COMMONWEALTH of VIRGINIA

DEPARTMENT OF ENVIRONMENTAL QUALITY
Street address: 629 East Main Street, Richmond, Virginia 23219
Mailing address: P.O. Box 1105, Richmond, Virginia 23218
Fax (804) 698-4500 TDD (804) 698-4021
www.deq.virginia.gov

L. Preston Bryant, Jr.
Secretary of Natural Resources

David K. Paylor
Director

(804) 698-4000
1-800-592-5482

To: The Honorable Timothy M. Kaine

The Honorable Harvey B. Morgan, Chair
House Committee on Agriculture, Chesapeake and Natural Resources

The Honorable Patricia S. Ticer, Chair
Senate Committee on Agriculture, Conservation and Natural Resources

From: David K. Paylor

Date: October 21, 2008

Subject: Virginia Mercury Study

Attached for your review is a revised copy of the "Virginia Mercury Study." This report was prepared pursuant to Chapter 867 of the 2006 Acts of Assembly (House Bill 1055) and was originally provided to you on October 15, 2008. After the Department of Environmental Quality (DEQ) distributed the report, ICF Resources, LLC (ICF), the consultant that performed air quality modeling for the report, discovered an error in some of the calculations they performed for the study. The error was related to calculation of near-source contributions, which are now larger than first reported. This error, however, does not affect the primary conclusions of the report. ICF provided a corrected report to DEQ on October 20, 2008. The report has been revised as necessary to reflect these corrections. ICF's corrected report is Appendix A to the attached revised report.

The revised report, including the corrected Appendix A, is being made available at www.deq.virginia.gov/regulations/reports/html. If you have any questions concerning this report or if you would like a hard copy of this report, please contact Angela Jenkins, Assistant Director of Legislative and Legal Affairs at (804) 698-4268.

Virginia Mercury Study

A Report to the Honorable Timothy M. Kaine, Governor and the House Committee on Agriculture, Chesapeake and Natural Resources and the Senate Committee on Agriculture, Conservation and Natural Resources

Virginia Department of Environmental Quality

Revised October 21, 2008

Report Revisions

This report has been revised due to corrected information received from ICF, Resources, LLC on October 20, 2008.

Appendix A has been updated by ICF, Resources, LLC.

Table of Contents

List of Acronyms and Abbreviations

ACI - Activated Carbon Injection
AERMOD- AMS/EPA Regulatory Model
APC - Air Pollution Control
B-PAC - Brominated Powdered Activated Carbon (product name from Sorbent Technologies Corp, Twinsburg, OH)
CAIR- Clean Air Interstate Rule
CAMR- Clean Air Mercury Rule
CAVR- Clean Air Visibility Rule
CMAQ- Community multiscale air quality model
CS-ESP - Cold-side Electrostatic Precipitator
DEQ- Department of Environmental Quality (Virginia)
DGIF- Department of Game and Inland Fisheries (Virginia)
DOE- U.S. Department of Energy
EGUs- Electric Generating Units
EPA- U. S. Environmental Protection Agency
EPRI - Electric Power Research Institute
ESP - Electrostatic Precipitator
g/km^2- grams per square kilometer
FF - Fabric Filter (baghouse)
FGD - Flue Gas Desulfurization
FIP- Federal Implementation Plan
GDP- Gross Domestic Product
Hg- Mercury
HGP- particulate mercury
HG2- reactive gaseous mercury
HG0- elemental mercury
HS-ESP - Hot-side Electrostatic Precipitator
IC/BC- Initial condition/boundary condition
ICF- ICF Resources, LLC
IECM - Integrated Environmental Control Model
Kw-hr - Kilowatt per hour
MDN- Mercury Deposition Network
MW - Megawatt
NEI- National Emission Inventory
NETL - National Energy Technology Laboratory
NLSY- National Longitudinal Study of Youth
NOx - Nitrogen Oxides
NRC- National Research Council
PAC - Powdered Activated Carbon
PADEP - Pennsylvania Department of Environmental Protection
PM - Particulate Matter
ppm- parts per million
PPTM- Particle and precursor tagging methodology

PS - Particulate Scrubber
R&D - Research and Development
RfD- Reference Dose
RFP- Request for Proposal
SAPCB- State Air Pollution Control Board
SCR - Selective Catalytic Reduction
SDA - Spray Dryer Absorber
SDA/FF - Spray Dryer Absorber with downstream Fabric Filter
SEA - Sorbent Enhanced Additive
TMDL-Total Maximum Daily Load
ug/m^2 – micrograms per square meter
USGS - United States Geological Survey
VDH- Virginia Department of Health
VCU-CES Virginia Commonwealth University Center for Environmental Studies

EXECUTIVE SUMMARY

This report has been prepared pursuant to the requirements of Chapter 867 of the 2006 Acts of Assembly (House Bill 1055). The Act directs the Department of Environmental Quality (DEQ) to conduct a detailed assessment of mercury deposition in Virginia in order to determine whether particular circumstances exist that justify, from a health and cost and benefit perspective, requiring additional steps to be taken to control mercury emissions within Virginia. The assessment included (i) an evaluation of the state of mercury control technology for coal fired boilers, including the technical and economic feasibility of such technology and (ii) an assessment of the mercury reductions and benefits expected to be achieved by the implementation of the Clean Air Interstate Rule (CAIR) and Clean Air Mercury Rule (CAMR) regulations. An interim report was provided by DEQ in October 2007 that provided a status report on the assessment. The interim report is available at http://www.deq.virginia.gov/export/sites/default/regulations/pdf/2007statusofhgstudy.pdf.

DEQ used a contractor experienced with performing mercury deposition modeling to assist with identifying the mercury reductions and benefits to be achieved in Virginia as a result of implementation of the CAIR and CAMR. The analysis DEQ performed differed from the analysis the U.S. Environmental Protection Agency (EPA) performed for the CAMR. As part of Virginia's study, the emission inventory for sources in Virginia was reviewed and modified to reflect the most up-to-date information concerning mercury emissions from stationary sources located within Virginia. Additionally, ICF worked with electric generating units (EGUs) to obtain information on the specific pollution control equipment industry plans to install in the future and the predicted emission reductions related to the installation and operation of those pollution control tools. In contrast, EPA's analysis made general assumptions concerning future controls and associated mercury reductions without obtaining information on facilities' future plans from industry. Virginia's report also focuses more closely on impacts to Virginia fish, the number of fish consumption advisories issued for Virginia fish and the potential for reduced fish advisories in the future as a result of less mercury deposition occurring in Virginia waters.

This study began in 2006 once the regulatory details of CAIR and CAMR were known. In February 2008, the U. S. Circuit Court of Appeals for the District of Columbia issued an opinion vacating CAMR. In July 2008 the U. S. Circuit Court of Appeals for the District of Columbia issued an opinion vacating the CAIR. Although the D.C. Circuit recently issued opinions vacating CAIR and CAMR, the agency has continued to move forward with completion of the report pursuant to the requirements and direction of House Bill 1055. As directed, this report examines modeling results anticipated to be achieved through the implementation of CAIR and CAMR requirements. Any reductions of mercury deposition and average mercury fish tissue concentrations identified in this report are based on modeling results and may not ultimately be achieved.

Mercury Deposition Modeling

The mercury deposition modeling conducted by ICF used data from the years 2001 and 2002 to develop a baseline year estimate for mercury deposition occurring in Virginia and surrounding states. This baseline year estimates the mercury deposition occurring before implementation of CAIR and CAMR. Modeling was performed to estimate the deposition of mercury occurring in

2018, after CAIR and CAMR had been implemented. The modeling conducted for this study indicates overall mercury deposition for Virginia would be lower by 20.4 percent for 2018, when compared to the base year. The greatest reduction in deposition comes from EGU sources located outside of Virginia (in the 12-km modeling domain that encompasses several nearby states), and 61 percent of the reduction in mercury deposition for Virginia is attributable to reductions in emissions from EGU sources in these nearby states. In addition, 7.2 percent of the overall simulated mercury reduction for Virginia is attributable to reductions in the emissions from EGU sources located within the state, 5.7 percent is attributable to reductions in the emissions from non-EGU sources in the state, 4.6 percent is attributable to reductions in non-EGU sources in nearby states, and 2.8 percent is attributable to emissions reductions in the remainder of the United States.

Fish Tissue Impacts

After examining the reductions of mercury deposition predicted to occur in Virginia as a result of implementation of measures to comply with CAIR and CAMR, there may be reductions in the number of mercury fish consumption advisories in place within Virginia. Of the 13 mercury-sensitive waterbodies in Virginia with current fish consumption advisories due to mercury contamination, the fish mercury levels may be lowered enough in the future (to below the 0.5 parts per million (ppm) mercury level currently used by the Virginia Department of Health (VDH)) such that three or four of these advisories may no longer be warranted. In all but two of the advisory areas, at least one species of fish may have reduced mercury levels in the future that could allow for its removal from the fish consumption advisory and in one case, (Dismal Swamp Canal), the advisory area may be reduced. Under the projected reduced air deposition rates for the future, nine to 10 of the current fish consumption advisories will likely remain in place for at least one species of fish.

It will take time for any reductions in mercury deposition to be reflected in fish tissue samples because the ecosystem must readjust to the lower mercury levels in the environment. Each individual water body will react slightly differently due to natural variances in the chemical and physical conditions and differences in food web structure. Lakes are expected to respond quickest (within a few years to decades) to reduced mercury deposition, with wetlands requiring more time to equilibrate to the lowered mercury inputs.

The DEQ has proposed the adoption of a fish tissue criterion for mercury of 0.30 ppm, which is lower than the fish tissue mercury level used by the VDH to determine when fish consumption advisories are issued. If the State Water Control Board adopts this criterion, waterbodies with average fish concentrations greater than 0.30 ppm will be classified as impaired. Even though reductions in mercury deposition may occur and some fish consumption advisories may be removed, the waterbodies examined in this study could remain classified as impaired by DEQ if average mercury concentrations for at least one species of fish remain higher than 0.30 ppm.

Cost Benefit Analysis

Virginia coal-fired power plants vary in the amount and type of mercury control equipment installed. Currently, all Virginia coal-fired power plants burn a low-sulfur, low-mercury, and high-chlorine bituminous coal, and most of the plants also burn coal that has been initially

washed and processed after mining. Furthermore, some of the plants have technologies already in place to control nitrogen oxide (NO_x), sulfur dioxide (SO_2) and particulate matter (PM). As a result, a certain level of mercury (Hg) removal is achieved as a co-benefit of these controls; this report attempts to capture the costs of mercury control (costs of control technologies and also possible costs of control levels).

The costs of mercury control at coal-fired power plants are affected by a number of parameters, including what technologies are chosen, what regulations are in place, and the market-based determination of demand versus supply of energy. A number of options for reducing mercury emissions from coal-fired power plants are commercially available, and others are being developed. A number of control technologies for the reduction of mercury are available to coal-fired power plants, allowing the facility to choose the best fit in terms of cost-effectiveness. The DEQ cost assessment was based on a thorough review of existing and future projected mercury controls by Virginia-based electric generating units. Specifically, best available information on control technologies (performance, constraints, market prices of inputs and by-product disposal estimates) was used in this analysis. The results support the view, which is widely held by EPA, the U.S. Department of Energy (DOE), industry research and other state agencies, that mercury control is more cost-effective if coal-fired power plants adopt a multi-pollutant, post-combustion control technology sequence.

Fish Consumption Trends in Virginia's Waterways

As part of this study, DEQ contracted with Virginia Commonwealth University's Center for Environmental Studies (VCU-CES) to obtain Virginia-specific fish consumption data collected in areas where mercury fish consumption advisories are in effect. Additionally, VCU-CES was tasked with estimating the associated health risks from resulting methylmercury exposures. VCU-CES developed a fish consumption survey, and worked with DEQ staff to identify the launching and fishing locations where anglers could be surveyed. The survey was designed to obtain information on fishing behaviors, fish consumption, and demographic data on the anglers and families. During the summer of 2007, a team from VCU-CES administered the survey to 158 anglers at boat launching and fishing sites. Surveys were completed for anglers who were fishing at 17 locations on 5 rivers: the James River below Richmond, the Chickahominy, Pamunkey, Mattaponi, and upper Piankatank rivers. These rivers are affected by methylmercury contamination, have been surveyed in previous, similar investigations and are used by anglers for recreational fishing.

The surveys were administered to anglers predominantly on Friday, Saturday or Sunday. Approximately 44 percent of all respondents and their families consume the fish that they catch from these waters. Half (50 percent) of the anglers only, not family members, consume some fish that they catch, and more men (54 percent) than women (43 percent) were reported to consume the fish with elevated methylmercury levels. The most commonly consumed fish were catfish, spot or croaker, sunfish and largemouth bass; catfish and largemouth bass are two of the species on the fish consumption advisory. Catfish also represented the largest number of meals and total amount of self-caught fish consumed per year.

The data on fish consumption were analyzed with DEQ data on methylmercury concentrations in fish that had been collected in previous years to estimate the amount of methylmercury consumed in fish yearly. In order to estimate total methylmercury from all fish consumption,

canned tuna and purchased fish consumption were added to mercury exposures from self-caught fish. Mercury levels in tuna and purchased fish were taken from national data.

The methylmercury exposures determined from survey data and DEQ fish tissue levels were compared to the dose of mercury exposure that EPA has set (and the VDH uses) as the dose without appreciable health risks.

The analysis of the fish consumption and fish tissue concentrations was performed using a probabilistic computer program that is used for risk assessments. This program randomly selects certain values, as defined, to use in the equations for determining total mercury from all fish consumed. The analysis indicates that a significant number of anglers who regularly catch and consume significant amounts of catfish and large mouth bass from the affected waters are exposed to methylmercury at levels above the EPA reference dose.

Using the information obtained from various statistical methods, VCU-CES modeled the loss of IQ points from prenatal exposure to methylmercury through the maternal diet, specifically mercury from consumption of mercury-contaminated fish. To model the loss of IQ points from prenatal exposure to methylmercury through the maternal diet, the target population of interest is women of childbearing age. With the survey results and fish mercury concentrations from DEQ's fish tissue database, a probability distribution of ingested doses was created. Based upon the estimated maternal exposure to current fish mercury concentrations, the VCU-CES study estimated future levels of IQ changes due to 2010 and 2018 levels of mercury controls to result in average (mean) avoided IQ deficits of 0.03 IQ points.

Monetization of Human Health Risk Effects (IQ level)

This report attempts to quantify and monetize, to the extent feasible, the economic benefits associated with modeled avoided IQ deficits due to reduced exposure from the consumption of recreationally caught freshwater fish. The monetization of the human health risk effects (IQ being the human health effects of measurement) builds upon the findings of the VCU-CES study (Appendix B) and adopts the approach used by EPA to conduct the economic benefit analysis at the federal level (U.S. EPA 2005). This regional assessment focused on estimating the changes in exposures to women of childbearing age because adverse health effects in children have been linked to prenatal mercury exposures (Sorenson et al. 1999). This report builds on the VCU-CES study that focused on select counties of eastern Virginia where fish advisories for mercury existed and using consumption surveys, where IQ losses were estimated. IQ losses were then monetized to evaluate the economic benefit of mercury emission controls (or impacts of no reduction in emissions).

EPA's CAMR analysis indicated a monetized impact of $15 million solely due to power plant emissions over the entire United States (3 percent discount rate and Year 2000 dollars); however, such an analysis is not representative of Virginia, Virginia-specific individual consumption patterns and DEQ's fish tissue data. The DEQ assessment used 10 years of birth data for only the select counties where fish consumption patterns were surveyed to quantify economic impacts associated with average avoided IQ deficits of 0.03 IQ points found in the VCU-CES study and associated with methylmercury consumption through 2010 and 2018. Economic losses to the

exposed populations of interest involved an assessment of two scenarios – worst-case and most likely. Under the worst case scenario, the estimated net per capita income earning loss to children is $337.00, or $4.8 million across all 14,364 children born in the select counties. Under the "most likely" scenario, it was estimated that 6,104 pre-natal children (i.e., less than half of the 14,364 children born in the select counties) would be exposed to methylmercury and would thus have net income losses totaling $2.05 million. The two monetized scenarios are estimates of impacts for areas where risk assessment of methylmercury exposure due to fish consumption was undertaken.

Conclusions

As a result of conducting this study, specific information concerning mercury deposition in Virginia was obtained. Excluding background and natural sources of mercury, the largest percentage of mercury deposition within Virginia originates from EGUs in surrounding states (54 percent). The next largest geographic source contributing to mercury deposition in Virginia is EGUs located within Virginia (14 percent). Non-EGUs in surrounding states contribute to 13 percent of the deposition occurring within Virginia, and in-state non-EGUs contribute to 12 percent of the deposition occurring within Virginia.

As part of the mercury modeling conducted by ICF, emissions and deposition information from the 15 largest mercury emitters in the state was modeled using the AERMOD model to examine the direct impact these facilities have on the area within a three km area surrounding each source. This analysis yielded three key findings: (1) dry deposition is greater than wet deposition for all facilities, (2) maximum wet deposition tends to occur at locations closest to the facility, and (3) maximum dry deposition tends to occur farther away from the facility location. The AERMOD model also corroborated the findings of the regional-scale modeling. Specifically, individual facilities located in Virginia contribute to mercury deposition within the state, and the greatest impacts from the in-state sources are simulated near the source locations. This includes EGU sources and non-EGU sources.

As mercury deposition into waterbodies is reduced, each individual waterbody is expected to react slightly differently due to natural variances in the chemical and physical conditions and differences in food web structure. Lakes are expected to respond the most quickly (within a few years to decades) to reduced mercury deposition, with wetlands requiring more time to equilibrate to the lowered mercury inputs.

The VDH issues fish consumption advisories when average concentrations of mercury in fish exceed 0.50 ppm. Under the projected reduced mercury air deposition rates for the future, nine to 10 of the current fish consumption advisories will likely remain in place for at least one species of fish. The DEQ has recently proposed the adoption of a fish tissue criterion for mercury of 0.30 ppm, which is lower than the threshold concentration used by the VDH to issue fish consumption advisories. If the State Water Control Board adopts this fish tissue criterion for mercury, in the future DEQ may classify some waterbodies as impaired due to elevated mercury contamination in fish before the VDH would find it necessary to issue a fish consumption advisory.

Chapter 1- Introduction

Background

Human exposure to mercury is most commonly associated with the consumption of contaminated fish. Due to measured high levels of mercury in fish, at least 44 states have, in recent years, issued fish consumption advisories. These advisories may suggest limits on the consumption of certain types of fish or they may recommend limiting or not eating fish from certain bodies of water due to unsafe levels of mercury. States have identified more than 6,000 individual bodies of water as mercury-impaired and have issued mercury fish advisories for more than 2,000 individual bodies of water. Prior to 2002, significant mercury impairment of Virginia surface waters was known to affect only three rivers (the North Fork of the Holston River, the South River, and the South Fork of the Shenandoah River) with historic industrial releases. Since that time, however, state monitoring has identified impairment of a number of surface waters without readily identifiable sources of mercury releases.

Virginia expanded its mercury monitoring in 2002 based on an increasing scientific understanding of mercury's environmental chemistry and discoveries in other states (e.g., Florida and Maryland) of mercury pollution in waterbodies without direct source releases. The 2002 monitoring effort focused on rivers of the coastal plain, mostly to the east of I-95. As a result of this effort, Virginia found elevated mercury levels in some fish in the Blackwater River, the Great Dismal Swamp Canal, the Dragon Run Swamp and the Piankatank River. Consistent with findings from Florida and elsewhere, these waterbodies in Virginia possess characteristics favorable to the formation of methylmercury, the highly bio-accumulative form of mercury. These characteristics include low dissolved oxygen, high organic matter and low pH, and are most prevalent in "backwaters" of the southeastern portion of the Commonwealth.

The primary source of mercury to these waterbodies is suspected to be atmospheric deposition. Historically, there were three Mercury Deposition Network (MDN)[1] sites in Virginia located in the Shenandoah National Park, Culpeper[2], and Harcum. Data from these sites have contributed to DEQ's understanding of the regional characterization of mercury transport and deposition throughout the state. Additional monitoring at the Harcum site in 2005 revealed that dry deposition of reactive gaseous (divalent) mercury along the Piankatank River (near the Chesapeake Bay) and in upstream areas is an important contributor to the high mercury levels observed in the water and fish in the area. Global, regional and local sources of mercury emissions contribute to the deposition; therefore, understanding these contributions is an important step toward identifying measures that will effectively reduce mercury deposition and environmental mercury levels.

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[1] The Mercury Deposition Network (MDN) is the mercury wet-deposition monitoring arm of the National Atmospheric Deposition Program (NADP). The NADP is a cooperative monitoring program comprised of federal and state agencies, academic institutions, Native American tribal governments and private organizations.

[2] The Culpeper site, which had been funded by the United States Geological Survey, was shut down at the end of 2006 due to lack of funding.

Objectives

The second enactment clause of HB 1055 (2006) provides:

> That the Department of Environmental Quality shall conduct a detailed assessment of mercury deposition in Virginia in order to determine whether particular circumstances exist that justify, from a health and cost and benefit perspective, requiring additional steps to be taken to control mercury emissions within Virginia. The assessment shall also include (i) an evaluation of the state of mercury control technology for coal-fired boilers, including the technical and economic feasibility of such technology, and (ii) an assessment of the mercury reductions and benefits expected to be achieved by the implementation of the CAIR and CAMR regulations. The Department shall complete its preliminary assessment as soon as practicable, but not later than October 15, 2007, and shall report the final findings and recommendations made as a result of the assessment to the Chairmen of the House Committee on Agriculture, Chesapeake and Natural Resources and the Senate Committee on Agriculture, Conservation and Natural Resources as soon as practicable, but no later than October 15, 2008.

In response to this mandate, Virginia-specific mercury emissions inventory data was compiled, verified and utilized to perform a comprehensive mercury deposition modeling analysis. Both the data analysis and modeling components were intended to examine and quantify the contribution of regional and local emissions sources to mercury deposition throughout the Commonwealth, and to provide information to support further analysis of the impact of mercury deposition on the environment.

For each of the bodies of water listed as impaired by Virginia, the Clean Water Act calls for the calculation of a Total Maximum Daily Load (TMDL). TMDLs identify the pollutant reductions or limits that are needed in order to achieve water quality standards. TMDLs must also allocate the reductions to the different sources of pollution, including air sources. Thus, another key objective of the data and modeling analyses is to provide information that will enable DEQ to conduct TMDL studies.

Finally, the results of this study are being used to support DEQ's evaluation of available measures to reduce mercury emissions in Virginia. Specifically, the data analyses and modeling have allowed DEQ to evaluate the effectiveness of selected control measures and support the development of management strategies for meeting water quality criteria and protecting human health.

Initial Steps and Preliminary Information

DEQ identified the largest emitters of mercury in the Commonwealth and in August 2006 sent letters to 75 industrial facilities in Virginia requesting estimated mercury emissions for calendar years 2002 and 2005. The facilities chosen for this request were the largest known mercury emitters in Virginia. Information received from each of the facilities was used to estimate future-year emissions. The future-year estimates were then used in the air quality modeling and

deposition analysis. In order to assess the mercury reductions and benefits expected to be achieved by the implementation of the Clean Air Interstate Rule (CAIR) and the Clean Air Mercury Rule (CAMR) regulations, DEQ staff issued a Request for Proposal (RFP) on September 25, 2006, for a detailed assessment of mercury deposition in Virginia. The scope of the RFP included an analysis of mercury air emissions data and an assessment of mercury deposition modeling, as well as the development of information on the human health risks from consuming methylmercury contaminated fish.

In February 2007, two contracts were awarded for the assessment. One contract was awarded to ICF Resources, LLC (ICF), for work on the mercury emissions data analysis and deposition modeling portions of the study. Specifically, ICF conducted mercury deposition model simulations to be used by DEQ to examine:

1. Air deposition as a contributor of mercury to Virginia's impaired waterbodies and other mercury sensitive waters;
2. Impacts of emissions from Virginia's electric generating units (EGUs) on mercury deposition in Virginia, including an evaluation of the benefits of CAMR and other federal and state programs which may impact or reduce mercury emissions;
3. Contributions of Virginia's non-EGUs to mercury deposition in Virginia; and
4. The individual impact of a selected number of Virginia facilities to local and regional scale mercury deposition.

DEQ also awarded a contract to the Center for Environmental Studies at the Virginia Commonwealth University (VCU) to assess the human health risks from consuming methylmercury contaminated fish. The study focused on understanding the risks of consuming methylmercury through ingestion of freshwater fish by sensitive sub-populations (such as children and pregnant women) in Virginia. This study used DEQ's fish tissue database and on-site fish consumption data to estimate risks to human health. These estimates of risks to human health were needed for DEQ to be able to monetize the potential economic benefits and costs of current levels of mercury and potential future reductions.

Data was collected from internal and external sources on control technologies used at all of Virginia's coal-fired power plants in order to understand expected mercury removal rates and costs of controls. This information was used to develop estimates that distinguish the portion of such control costs that can be ascribed to mercury from the co-benefits of controlling other pollutants. The team then analyzed the costs associated with mercury-specific control technologies for coal- fired power plants.

Virginia Mercury Symposium

Complementing the Virginia Mercury Study, the State Air Pollution Control Board and DEQ organized and hosted the Virginia Mercury Symposium on November 28-29, 2007, in Newport News, Virginia. In addition to providing a progress report on the status of the Virginia Mercury Study, the Symposium brought together regionally- and nationally-recognized speakers to provide information and perspectives on various aspects of the science, technology, economics and policy aspects of mercury emissions, abatement and impacts.

Conference attendees included a wide range of Virginia stakeholders, including representatives of state and local environmental and health agencies; nongovernmental organizations (NGOs); coal, utility and manufacturing sectors; seafood interests; vendors of pollution controls; academic researchers and the policy research community.

The goal of the symposium was to promote awareness of the multiple issues surrounding mercury. There was no attempt to develop a set of consensus findings or conclusions from the Symposium. Information presented at the symposium has been posted on DEQ's website at http://www.deq.virginia.gov/info/symposium.html for all interested parties to review and use.

Chapter 2- Summary of Differences Between Virginia's Study and EPA's CAMR Analysis

Prior to releasing CAMR, EPA performed its own analysis on the rule. In some ways, this report utilized similar approaches to those taken by EPA. The goal of this report was to specifically examine mercury as it relates to Virginia, which included mercury deposition modeling and impacts to Virginia waterways from such deposition, as well as potential impacts to Virginia citizens. The differences between EPA's analysis and this report are explained in this section of the report.

Revised Inventory

Prior to releasing the CAMR, EPA conducted an analysis on the impact mercury from coal-fired power plants in the United States has on the environment. DEQ's mercury deposition modeling utilized Virginia-specific information and differed from the emission inventory utilized in EPA's analysis. When conducting the mercury deposition modeling for this report, the emission inventory information utilized by EPA was updated and revised to reflect the most current information concerning sources in Virginia emitting mercury. This included verification of the total emissions, stack locations and stack parameters.

Individual Sources

In addition to utilizing a revised emission inventory, DEQ's modeling analysis not only examined the mercury deposition occurring within Virginia, but also estimated the mercury deposition occurring as a result of individual sources that operate within the Commonwealth through the use of source tagging. In order to predict the behavior of mercury emissions from individual sources, modeling was conducted utilizing a smaller grid size (12 km x 12 km) to examine impacts within Virginia. Therefore, DEQ's study contained a more narrow focus on the deposition of mercury occurring within areas of the state.

Fish Tissue Data

When EPA conducted its analysis of the CAMR, information on fish tissue samples was gathered from across the United States. Approximately 20 tissue samples from two types of fish from Virginia were utilized in EPA's analysis. In this study Virginia-specific fish tissue information was used to review the impacts mercury has on Virginia fish. This included over 2,100 samples that had previously been obtained by DEQ's fish tissue monitoring program.

Cost Analysis

The cost analysis conducted in this study focused on Virginia-specific information. Virginia power plants vary in the amount and type of mercury control equipment installed. All plants burn a low sulfur, low mercury, and high chlorine bituminous coal, and most of the plants also burn coal that has been initially washed and processed after mining. Furthermore, some of the plants have technologies already in place to control nitrogen oxide (NO_x), sulfur dioxide (SO_2), and particulate matter (PM). This information was utilized when examining the cost benefits of the different control technologies.

Additionally, the cost of IQ points lost as a result of consumption of mercury contaminated fish was able to be projected for a portion of river basins impacted by mercury contamination in

Virginia. This allowed an estimate of the monetary impacts of IQ losses for a select population of Virginians.

Human Health Impact to Virginia Citizens

EPA's analysis was not representative of the Commonwealth alone and did not take into account Virginia-specific individual consumption patterns and DEQ's fish tissue data. DEQ contracted with VCU to obtain information on recreational fishing and fish consumption patterns in areas of Virginia with mercury fish consumption advisories. This information enabled VCU to estimate the associated health risks from resulting methylmercury exposures by consumption of mercury contaminated fish.

Recent Federal Court Actions Concerning CAIR and CAMR

The EPA promulgated the Clean Air Interstate Rule (CAIR) and Clean Air Mercury Rule (CAMR) in the spring of 2005. CAIR established a cap-and-trade program to reduce emissions of NO_x and SO_2 from power plants in affected states to reduce interstate emissions contributing to fine particulate and ozone nonattainment. CAMR was designed to reduce emissions of mercury from coal-fired power plants through a cap-and-trade program. Because control technologies for NO_x and SO_2 may also reduce emissions of mercury, CAIR and CAMR were expected to work together to achieve mercury reductions.

The State Air Pollution Control Board (SAPCB) adopted its final regulation to implement the federal CAIR program on December 6, 2006. On January 16, 2007, the State Air Pollution Control Board adopted its final regulation to implement the federal CAMR program in Virginia.

In two separate actions during the spring and summer of 2008, the U.S. Circuit Court of Appeals for the District of Columbia issued decisions vacating the federal CAIR and CAMR. EPA's request for a rehearing on CAMR was denied and EPA currently is evaluating its options for appeal to the United States Supreme Court. With respect to CAIR, EPA has petitioned the D.C. Circuit Court for rehearing of the case. Because of the significant impacts of the Court's CAIR ruling, stakeholders, including the affected states and industry, have asked Congress to take action to legislatively reinstate CAIR in some form. These efforts are still underway.

The D.C. Circuit Court's very recent opinions vacating both the CAMR and the CAIR occurred after the air quality modeling and studies for this report had been completed. As a result, this report provides information on the predicted environmental changes that were expected to occur as a result of implementation of both CAIR and CAMR. This information will be a valuable resource for predicting environmental changes that may occur as a result of emission reductions occurring in the future.

Chapter 3- Emission Data Analysis and Mercury Deposition Modeling

The reliability of the mercury deposition assessments, including the modeling, is partially dependent on the quality and completeness of the emission inventory data. Thus, a key objective of the emissions data analysis component of the study was to assess and improve, as needed, the reliability of the mercury emissions data. The data analysis focused on the review and refinement of the mercury emissions data from a variety of source categories, including coal-fired utilities, medical waste incinerators and municipal waste incinerators. The emissions data analysis also required the reliable projection of these data to three future years (2010, 2015 and 2018), taking into account implementation of federal and state laws impacting emissions of mercury.

The modeling analysis included development of a conceptual description of mercury deposition, which improves the overall understanding of mercury impacts and the relationships between meteorology and mercury deposition. The modeling results provide a basis for quantifying the contribution of emissions sources to mercury deposition and examining the fate of mercury emissions from selected sources. For environmental planning purposes, modeling was used to examine the effectiveness of control measures in reducing mercury concentrations in contaminated bodies of water and improving or maintaining water quality within the designated areas of interest in Virginia. By quantifying deposition, the modeling results also provide a link between the analysis of mercury emissions and the assessment of the impacts of airborne mercury on fish tissue and human health.

Mercury Emissions Data Analysis

Literature Review

A literature review was conducted by ICF of recent research into atmospheric chemistry and reactivity, mercury deposition mechanisms, and physical and chemical characteristics of mercury as part of this study. Reports addressing mercury emissions issues, deposition modeling and modeling studies were reviewed to compile estimated global background values of mercury. Estimates of global background vary widely in the current literature, and outputs from various global models have been used in recent modeling studies as input for continental-scale mercury modeling studies. These findings were summarized as part of the interim report provided by DEQ in October 2007. This information is included in Attachment A of the interim report which is available at:
http://www.deq.virginia.gov/export/sites/default/regulations/pdf/2007statusofhgstudy.pdf

Virginia Point Source Mercury Inventory

DEQ solicited the 75 largest known point sources of mercury for updated mercury emission estimates for 2002 and 2005 as part of this study. Of those that provided updated information, some sources prepared emissions estimates based on measurements (stack tests), while others based their estimates on standard process-based emission factors for various source types (e.g., AP-42). Still others may have estimated emissions using alternative methods. For each facility, a thorough technical review of the emissions estimates was conducted, taking into account the important factors that affect mercury emissions such as process-type, boiler type, fuel type, equipment type and stack parameters (e.g., flow rate, exit temperature, exit velocity, etc.). For each facility, the accuracy of the emissions estimates and all of the facility-specific information

including location, stack parameters, hours of operation, maintenance schedules and estimated daily operating profiles were reviewed for accuracy. An investigation also was conducted to determine whether any emission control or other equipment was installed or replaced between 2002 and 2005 and whether there were plans to change/update equipment in the near future. Any new pollution control equipment or other equipment expected to be installed beyond 2005 was accounted for in the future year emission estimates.

Other Inventories – National Emission Inventory
In addition to the Virginia point source inventory, the EPA compiles and maintains the National Emission Inventory (NEI), which includes mercury emissions data. As part of this analysis, the latest version (Version 3) of the NEI mercury inventory was obtained from EPA. This inventory contains information for point sources and "non-point" sources, also referred to as area sources. These include various other types of fuel combustion sources. The NEI inventory was used in the modeling deposition portion of the study to account for other influences, such as mobile sources and landfills, affecting mercury deposition in Virginia.

Revisions to the Emissions Data Since the Interim Report
The interim report included an emission inventory for sources within Virginia. Since the publication of the interim report, Jewel Coke Company, L.P., provided revised information pertaining to the company's mercury emissions. The revised mercury emission information was submitted as a result of Jewel Coke Company's having performed coal analyses to determine the mercury content of the coal utilized at its facility. When calculating the revised mercury emissions, an assumption was made that 100 percent of the mercury content of the coal was emitted during the company's process. For the base year, emissions were estimated based on the actual coal throughput. Future year projections were calculated by using the permitted coal throughput limit for the facility. No other revisions were made to the emission inventory included in the interim report.

Interim Report
ICF submitted a report to DEQ in September 2007 titled, "The Virginia Mercury Study: Review and Assessment of Virginia Mercury Emissions Data and Recent Mercury Studies." This report summarized ICF's review and analysis of the sources of atmospheric mercury emissions located within the Commonwealth of Virginia and surrounding areas. This report also included a summary of recent mercury studies that were reviewed as part of the literature review. A copy of the report is available from DEQ's website at
http://www.deq.virginia.gov/export/sites/default/regulations/pdf/2007statusofhgstudy.pdf

Mercury Deposition Modeling

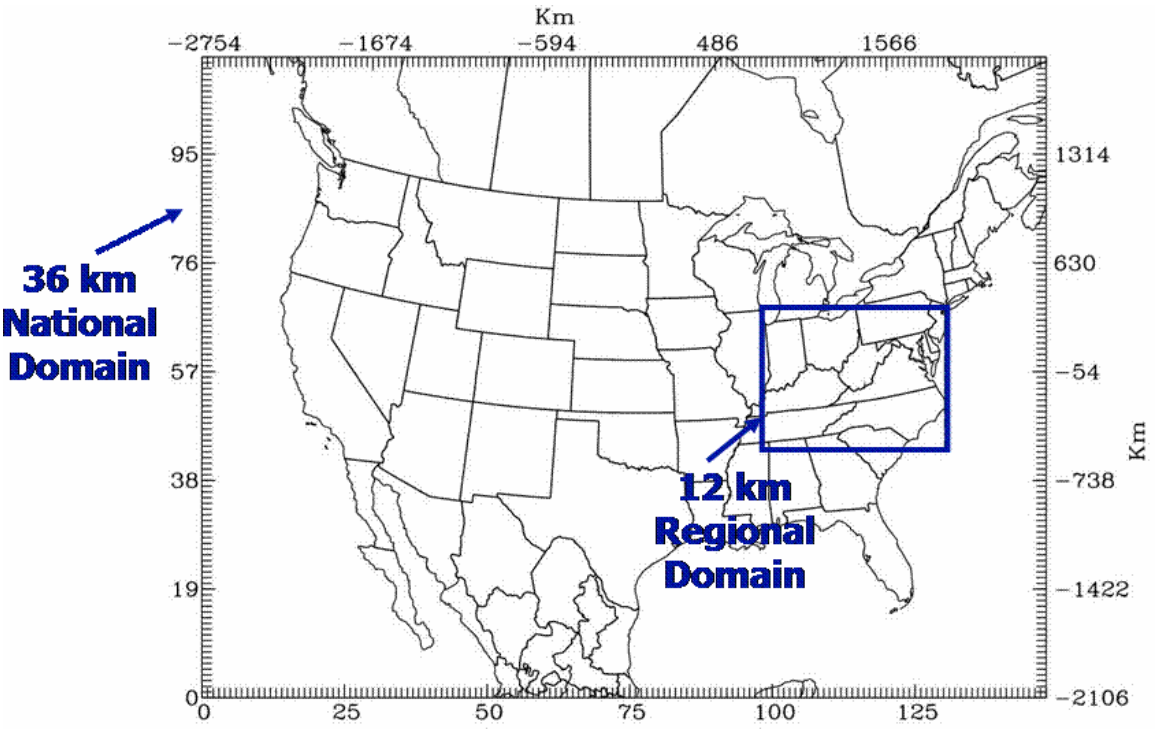
Overview
Atmospheric modeling is a tool that can predict how mercury behaves in the atmosphere and how the mercury will be deposited from the air to the land or water. Mercury deposition can be attributed to global, national, regional and local sources. As a result, several different types of modeling tools were considered in the development of the modeling methodology for this study. Modeling tools differ in terms of numerical formulation [e.g., grid based (Eulerian), trajectory (Lagrangian), plume (Gaussian) formulations], treatment of mercury chemistry and other

processes (such as deposition and the effects of meteorology), and applicable scales (e.g., global, regional, local). In addition, data analysis techniques such as receptor modeling have also been used to study mercury deposition. A portion of the literature review summarizes the ongoing development of mercury capabilities in air quality modeling and some recent national- and regional-scale applications.

The atmospheric modeling methodology for this study consists of two components: (1) regional-scale modeling and (2) local-scale modeling. Regional-scale modeling can provide information on the sources contributing to the deposition in a large geographical area (e.g., United States, Mid-Atlantic Region, Virginia) as a result of global, national, regional and local emissions sources. ICF utilized the Community Multi-scale Air Quality (CMAQ) model, a grid-based model, to conduct regional-scale modeling. The version of CMAQ includes the Particle and Precursor Tagging Methodology (PPTM), which is a feature that can track the contribution of emissions from selected sources (e.g., individual facilities), source categories (e.g., EGUs, non-EGUs), and/or source regions (e.g., nearby states, geographic regions) to simulated mercury (total, wet and dry) deposition.

CMAQ was selected for this study for several reasons. One of the primary goals of this study was to assess the contribution of various geographical regions and source categories to mercury deposition in Virginia. Grid-based models such as CMAQ are designed to simulate the physical and chemical processes that govern the formation, transport and deposition of gaseous and particulate species in the atmosphere. CMAQ is considered a "state-of-the-science" air quality model for mercury deposition and has been used by EPA and others for national- and regional-scale regulatory assessments. CMAQ specifically supports the detailed simulation of the emissions, chemical transformation, transport, and wet and dry deposition of elemental, divalent and particulate forms of mercury.

CMAQ uses grid patterns to assist with establishing boundaries in which air quality is evaluated and examined. The regional-scale modeling conducted for this study utilized two different-sized, horizontal grid patterns, 36 km x 36 km and 12 km x 12 km. The air quality model being utilized, the information available to be used in the modeling, as well as the size of the area being modeled all play a role in determining which grid size is utilized. The mercury deposition modeling performed by ICF used 36 km x 36 km grids to examine the deposition occurring over the entire continental United States. Next, modeling was performed using 12 km x 12 km grids over Virginia and surrounding states, which provides more specific, detailed information on the deposition that is occurring. The following figure displays the geographic areas and the grid sizes used in the modeling.



As previously mentioned, local-scale modeling also was conducted as part of this study. AERMOD, a Gaussian dispersion (or plume) model, was used to simulate the local-scale dispersion and deposition of pollutants for the top 15 mercury-emitting facilities (which make up approximately 85 percent of mercury point source emissions within the state) in Virginia. AERMOD was selected for this study for several reasons. AERMOD is currently the most widely-used Gaussian dispersion model for regulatory applications. It is designed to simulate the local-scale dispersion of pollutants from low-level or elevated sources in simple (i.e., terrain below stack-top elevation) or complex (i.e., terrain above stack-top elevation). It is an EPA "preferred" dispersion model and recent versions of AERMOD also include algorithms for simulating deposition of gaseous and particulate pollutants such as mercury. The model also can be used to simulate the effects of local emission changes for selected areas and sources.

Model Uncertainty

As with any modeling study, there are several areas of potential uncertainty that can affect the reliability of the modeling results. For the regional-scale CMAQ modeling, these include: (1) the representation of emissions (including natural emissions), boundary conditions (global emissions) and meteorology; (2) uncertainties in the chemical reaction rates; (3) representing the dispersion and chemistry in plumes; and (4) accounting for the deposition of elemental mercury and re-emission of mercury.

Uncertainties in the local-scale AERMOD modeling include: (1) AERMOD does not include a chemical mechanism for mercury. That is, AERMOD can be used to simulate the dispersion and deposition of mercury, but not the chemical transformation of mercury. However, this may not

be an important limiting factor for near-source assessments. (2) Gaussian models such as AERMOD use a relatively simple representation of the meteorological conditions (important but complex meteorological features cannot be represented). Representing the effects of mountainous terrain (such as that found in western Virginia) and land use are also sources of uncertainty.

Other Modeling Techniques

Other modeling techniques were considered for use in this study including trajectory and receptor models. Trajectory models (e.g., CALPUFF and HYSPLIT) are alternatives to grid-based models. Although trajectory modeling has been used in other studies, it was not selected for this study because it is generally not well-suited for simulating contributions from distant sources. Specifically, the uncertainty of trajectory models increases with the time and distance between the source and location where concentrations are estimated.

Receptor models were also considered for use in this study. These models (e.g., PMF and UNMIX), are statistical-based tools that use a combination of observed wet deposition data, air quality data, meteorological data, and information about emissions source characteristics (e.g., location, emissions process, speciation) to identify potential sources or source categories that may be contributing to observed deposition. This approach was not selected because of the following: (1) meteorological conditions are generally not considered or are represented by a few simple parameters;(2) source-receptor models include the need for very high-resolution, comprehensive data to establish the contributing source profiles and reliance on statistical, rather than physical and chemical, relationships to infer source attribution.

Lastly, receptor modeling has been combined with trajectory modeling as a way to better incorporate the effects of meteorology and narrow down the source-receptor relationships. However, as noted earlier, the uncertainties associated with trajectory modeling, which increase with distance from the receptor location, may also add to the uncertainties in the hybrid source-receptor modeling results.

Conceptual Description of Mercury Model

Prior to conducting modeling, a conceptual description of a mercury model was developed to assist with understanding the project and the issues to be considered when working on the project. Issues such as data availability, accuracy of the data and potential sources that contribute to mercury deposition were studied. This included reviewing mercury deposition data, meteorological data, emission inventory information and recent mercury deposition modeling results. During the development of the conceptual model, issues such as which factors contribute to mercury deposition in Virginia, variations of mercury deposition over a period of time, variations of deposition from location to location, and impacts the variations in meteorology have on deposition were examined. A more in-depth discussion has been included as an attachment to ICF's final report provided in Appendix A of this report.

Modeling Protocol

The purpose of a modeling protocol is to document in detail how a modeling analysis will be performed and how the results will be presented. ICF submitted a modeling protocol to DEQ in April 2007. This protocol document outlined the methods and procedures to be followed in conducting mercury deposition modeling for the study. The protocol provided a basis for DEQ to

review and comment on all aspects of the modeling analysis, including the modeling tools and databases, modeling domain and simulation period, modeling procedures, quality assurance procedures, schedule, and communication structures. The protocol was used to guide the progress of the modeling analysis and needed decisions to be made as the work progressed. Although there are no current EPA guidelines for mercury deposition modeling, the modeling protocol and the modeling practices were designed to be consistent, wherever applicable, with current EPA guidelines for other regional modeling applications [e.g., ozone and fine particulate matter (PM-2.5)]. The modeling protocol document has been included as an attachment to ICF's final report provided in Appendix A of this report.

Model Sensitivity Analysis

A sensitivity analysis is the process of varying model input parameters over a reasonable range (range of uncertainty in values of model parameters) and observing the relative change in model response. Sensitivity analyses were conducted for both the regional- and local-scale modeling. The regional-scale sensitivity analysis included an evaluation of meteorological data. It is widely understood that changes in the meteorological conditions input to a simulation have the potential to affect simulated mercury deposition in a variety of complex ways. This study did not include a detailed assessment of the differences between the meteorological inputs and their effects on simulating deposition. Instead, the assessment focused on whether use of a different simulation period (and its associated meteorological conditions) would produce very different CMAQ results. The results of the sensitivity analysis indicate that the model is sensitive to rainfall and possibly other meteorological conditions. One conclusion from this analysis is that the ability of CMAQ to simulate deposition is dependent on the ability of the meteorological inputs to represent key meteorological conditions, such as rainfall.

The local-scale AERMOD sensitivity analysis evaluated the sensitivity of the model to changes in mercury deposition parameters. The sensitivity analysis also included varying surface characteristics (e.g., land use), emission rates and stack parameters. One conclusion of the analysis is that the deposition simulated using AERMOD is sensitive to changes in stack parameters. For example, increasing stack height and exit velocity of particles tends to reduce the amount of deposition near the emission source.

The sensitivity results are provided in Appendix A to this report.

Model Performance Evaluation

A model performance evaluation was conducted for the regional-scale CMAQ modeling as recommended by EPA guidance. The CMAQ model is a multi-pollutant model and certain of the non-mercury species, especially ozone and other oxidants, may influence the simulation of mercury. In addition, examining model performance for a variety different species and for both air concentrations and deposition may aid the overall evaluation of the model results and specifically the identification of biases or deficiencies for certain regions, time periods and/or meteorological (or other) conditions. Thus, the evaluation of model performance for CMAQ considered concentration and deposition of both mercury and non-mercury species.

The model performance evaluation examined (1) whether the CMAQ model was able to replicate observed (and estimated) mercury deposition data, and (2) whether the response of the model to changes in mercury emissions was reasonable.

Overall model performance for mercury (wet deposition) and other modeled species (e.g., ozone) appears reasonable, especially when evaluating annual deposition. Differences between the modeled and observed values are attributable to a number of factors, including the numerical approximations and physical parameterizations used in the CMAQ model, imperfect representation of the meteorological conditions (in particular, the timing and amount of rainfall), uncertainties in the emission inventory and boundary condition estimates and even uncertainties in the measurements. Nevertheless, the simulated annual wet deposition mercury amounts on average are within 10 percent of the observed values for both the 36- and 12-km modeling domains. The complete model performance evaluation is provided in Section 5 of Appendix A to this report.

Modeling Simulations

ICF used the CMAQ model to examine regional-scale mercury deposition and the sources contributing to deposition for each river basin and the entire State of Virginia. AERMOD was used to evaluate local-scale deposition for the top 15 mercury-emitting facilities in Virginia (i.e., within a three-km radius of each plant).

CMAQ simulations were used by DEQ to:

1. Examine the contributions from mercury air emissions sources in (a) Virginia, (b) the remainder of the 12-km modeling domain, which includes several neighboring states, (c) all other U.S. states (outside of the 12-km domain), (d) Canada and Mexico, (e) global emissions sources, and (f) natural emissions.

2. Quantify the contributions from Electric Generating Unit (EGU) and non-EGU facilities in Virginia and the surrounding states, including (a) all of Virginia's EGU sources, (b) all of the Virginia non-EGU sources, (c) all EGU sources in the surrounding states (i.e., the remainder of the 12-km grid), and (d) all non-EGU sources in the surrounding states. The results were used to quantify and compare the contributions from the EGU and non-EGU source sectors to mercury deposition for any location (grid cell or group of grid cells) within Virginia and the 12-km modeling domain.

CMAQ modeling simulations were conducted for the baseline year (2001/2002) as well as three future projection years (2010, 2015 and 2018). The CMAQ PPTM methodology was applied to each of the two groups of scenarios listed above for the baseline year and one future year (2018). Future-year modeling inventories accounted for the impacts of federal and state laws to reduce emissions. Results of the modeling simulations were used as inputs into the other portions of the study.

Finally, local-scale modeling using AERMOD was applied for the 15 facilities in Virginia with the greatest mercury emissions. Average mercury deposition was calculated for the 3-km area surrounding each facility. AERMOD simulations were conducted for the baseline year as well as

for three future projection years (2010, 2015 and 2018). Future-year modeling inventories for each of the individual facilities accounted for the impacts of federal and state laws to reduce emissions.

Differences from EPA's Regional-Scale Mercury Modeling Study

This report used some of the same procedures that EPA used when performing its CAMR analysis. EPA performed its analysis for CAMR by utilizing the CMAQ model. The modeling performed by ICF, however, utilized a different version of the CMAQ model - version 4.6 with PPTM. Additionally, in order to more closely examine the mercury deposition occurring within Virginia, a smaller grid size was used in part of this study. EPA utilized a 36 km x 36 km grid when it performed modeling for the CAMR analysis. ICF's use of the 12 km x 12 km grid size allowed more detailed historical Virginia meteorological information to be used. Revisions to emission estimates were made as part of this study, so the emission estimates used in this study differed from those used by EPA. Additionally, ICF was able to use PPTM modeling to quantify the contributions from several emissions categories located in Virginia and to examine the transport of mercury emissions from emissions categories outside Virginia.

Chapter 4- Mercury Deposition Modeling Results

The CMAQ modeling simulations conducted by ICF provided information on where mercury deposition is occurring, the predicted trends of mercury deposition, and predicted future mercury deposition in each of Virginia's major river basins. More detailed information on the modeling results can be found in the final report provided by ICF, which is included as Appendix A. The following is a summary of the results of ICF's study.

Sources of Mercury Deposition in Virginia

Base Year Regional-Scale Modeling Results

Mercury deposition occurring within Virginia originates from many places, from places around the globe to sources located within the state. The mercury deposition modeling conducted by ICF included PPTM, which allowed the contribution of mercury emissions from different geographic regions to be estimated. The modeling categorized the origin of the mercury deposition as global, national, regional, natural or Virginia emission sources. In general, global background refers to mercury that is circulated around the earth. Global background will include mercury emitted from sources outside of the continental United States, such as those in Asia. National emissions sources are those sources that are located within the continental United States and portions of Canada and Mexico that are near the United States border. Regional emission sources are located within the 12-km grid and include emissions from states surrounding Virginia. Natural sources include those mercury emissions caused from such things as volcanic activity. Virginia emissions sources include all emission sources that are located within the state of Virginia. The breakdown of the geographic areas contributing to mercury deposition in Virginia during the base year for this study is shown in Figure 4-1 below. Deposition is given in terms of the grams of mercury deposition per square kilometer. The base year was established by using 2001 and 2002 emissions inputs. Throughout the report, the base-year scenario is referred to as either the "base year" or the "2001/2002 base year." The first pie chart illustrates that 74 percent of the annual deposition in Virginia for the base year can be attributed to global background and 26 percent of the deposition occurring in Virginia is from emission sources. The pie chart labeled "Contribution by Geographic Area" provides the breakdown of the origin of the emission sources that contribute to mercury deposition within Virginia. For example, 3 percent of the mercury deposition occurring within Virginia can be attributed to EGUs located within Virginia. The third pie chart labeled "Contribution by Geographic Area w/o background and natural sources" further illustrates the contribution of emissions by geographic area that contribute to mercury deposition within Virginia without the inclusion of global background and natural emissions. This pie chart redistributes the 26 percent emissions contribution in the first pie chart (i.e., "Contribution by Geographic Area"). Specifically, this pie chart illustrates that of the 26 percent attributed to emission sources, 54 percent is attributed to EGUs in surrounding states, 14 percent is attributed to Virginia EGUs, 13 percent to non-EGUs in surrounding states and 12 percent to non-EGUs located in Virginia.

Figure 4-1. Summary of CMAQ/PPTM Mercury Contribution Results for Virginia for base year.

Simulated Annual Hg Deposition for 2001 for Virginia: 22.69 g/km²

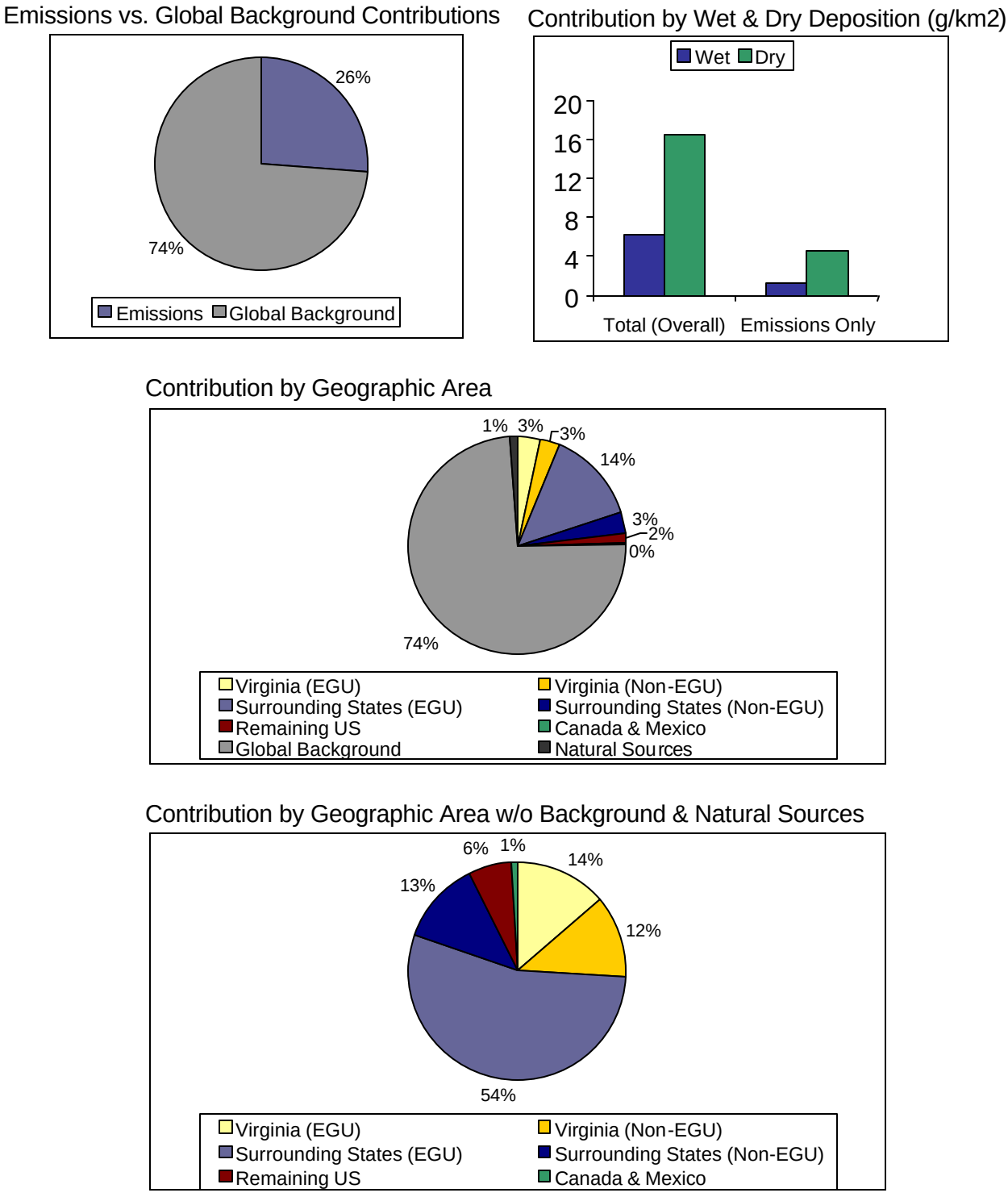


Figure 4-1 provided by ICF

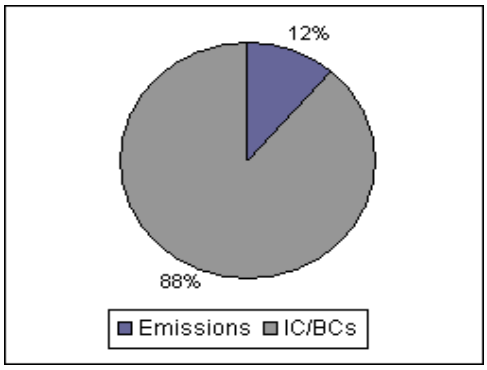
Future Year Regional-Scale Modeling Results

Once the base year mercury deposition modeling was completed, modeling was conducted to identify the mercury deposition estimated to occur in future years. Figure 4-2 below illustrates the breakdown of the origin of the emission sources that contribute to mercury deposition within Virginia that is expected to occur in 2018 after the implementation of CAIR and CAMR requirements. It is important to note that the pie charts in Figure 4-2 do not depict the change in the amount of deposition that is expected from the baseline year to 2018. These changes in mercury deposition are discussed below and illustrated in Figure 4-3.

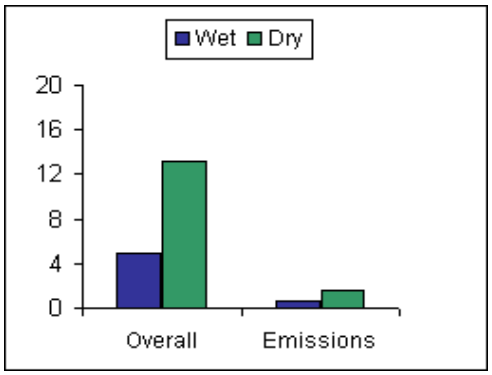
Figure 4-2 Summary of CMAQ/PPTM Mercury Contribution Results for Virginia for 2018.

Simulated Annual Hg Deposition for 2018 for Virginia: 18.07 g/km2

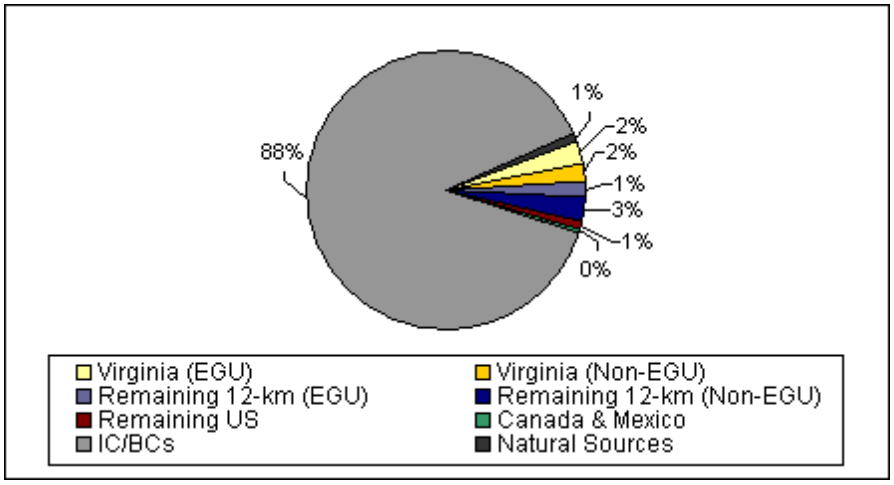
Emissions vs. Global Background Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Geographic Area



Contribution by Geographic Area w/o Background & Natural Sources

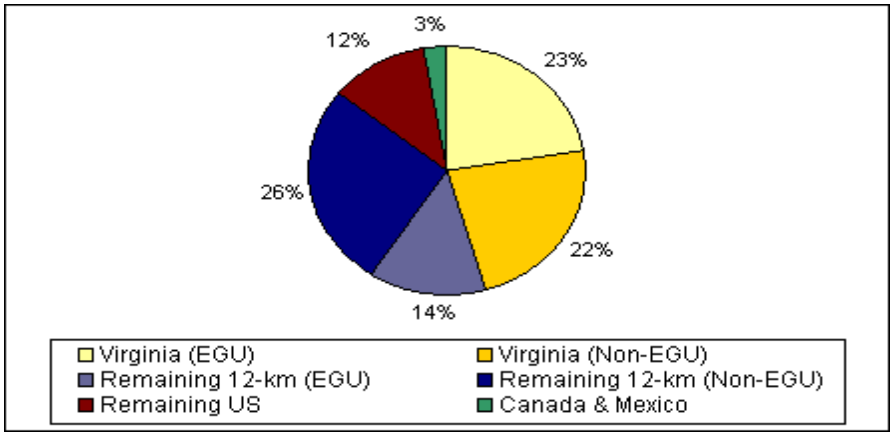


Figure 4-2 provided by ICF

Modeling predicts that a decrease in mercury emissions in all geographic categories (excluding natural sources) will occur in response to implementation of CAIR and CAMR requirements. The largest percentage of mercury deposition in Virginia in the baseline year is from global sources, and the largest percentage of mercury deposition in Virginia is predicted to continue to originate from global sources in 2018.

Figure 4-3 below illustrates the change in mercury deposition anticipated to occur as a result of implementation of CAIR and CAMR requirements. Figure 4-3 compares the mercury deposition occurring within Virginia in the base year and in 2018. This figure illustrates that, as a result of implementation of CAIR and CAMR, deposition in Virginia will decrease. Virginia will benefit from reductions in mercury emissions at EGUs located in surrounding states.

Figure 4-3 CMAQ/PPTM 12-km Mercury Contribution Results for Virginia for 2001/2002 and 2018.

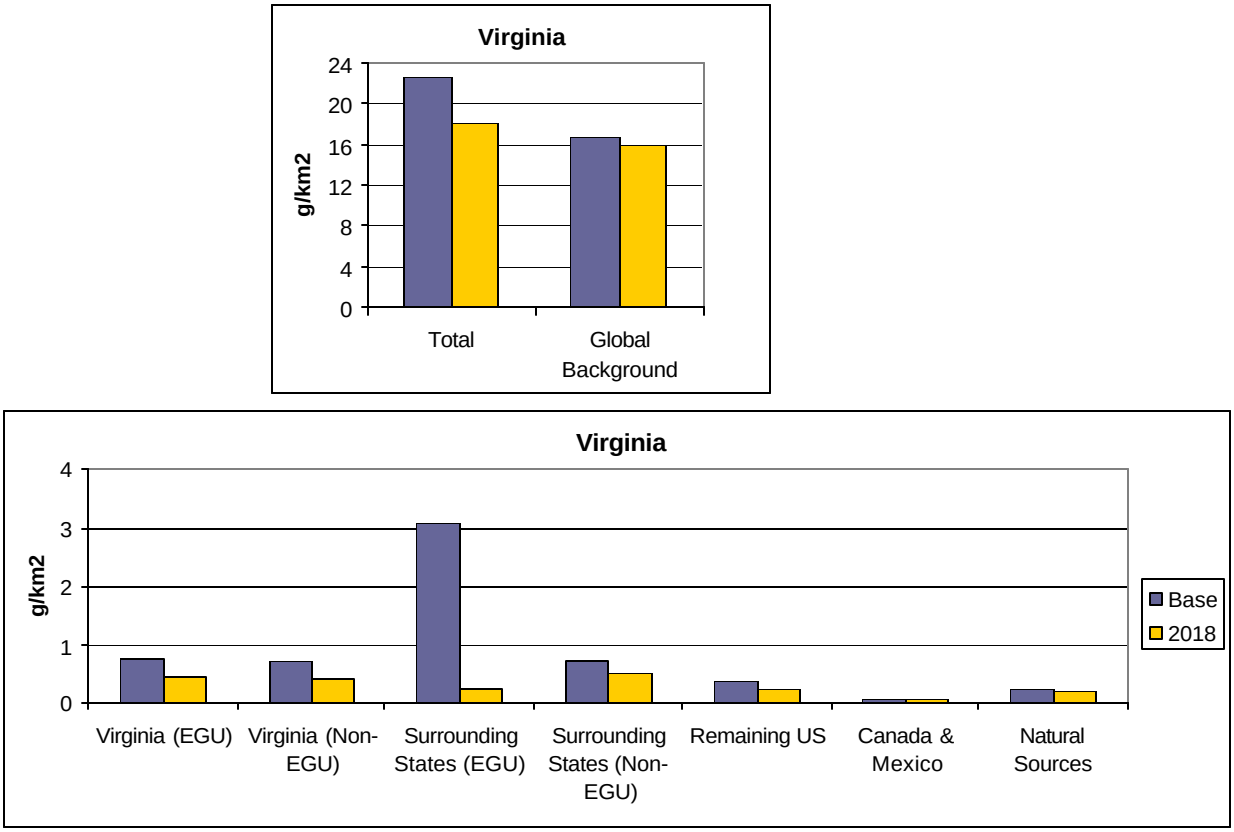


Figure 4-3 provided by ICF

The modeling conducted for this study indicates overall mercury deposition for Virginia is lower by 20.4 percent for 2018, when compared to the base year. The greatest reduction in deposition comes from EGU sources located outside of Virginia (in the 12-km modeling domain that encompasses several nearby states), and 61 percent of the reduction in mercury deposition for Virginia is attributable to reductions in emissions from EGU sources in these nearby states. In addition, 7.2 percent of the overall simulated mercury reduction for Virginia is attributable to

reductions in the emissions from EGU sources located within the state, 5.7 percent is attributable to reductions in the emissions from non-EGU sources in the state, 4.6 percent is attributable to reductions in non-EGU sources in nearby states, and 2.8 percent is attributable to emissions reductions in the remainder of the United States.

CAIR regulates both EGUs and non-EGUs; however, CAMR regulates only EGUs. Some controls that are utilized to meet regulatory requirements of CAIR have the co-benefit of reducing mercury emissions. The decrease in mercury emissions will provide some benefit as far as reduced mercury deposition; however, there is not a one-to-one ratio between the reduction in mercury emissions and mercury deposition. Meteorological conditions, the type of mercury emitted, stack height, as well as other factors, influence where mercury is deposited.

In addition to examining the mercury deposition that is predicted to change within Virginia as a result of implementation of CAIR and CAMR, ICF also examined the change in deposition that is predicted to occur in Virginia waterways. This is important because Virginia currently has many waterways with fish consumption advisories that are assumed to be related to the deposition of mercury from the atmosphere. Table 4-1 below illustrates the percent reduction in mercury deposition anticipated to occur in Virginia and in individual river basins as a result of implementation of CAIR and CAMR. All river basins within Virginia are predicted to see decreases in mercury deposition by 2018.

Because each of the source regions and categories contribute different amounts to the total mercury deposition, it also is interesting to attribute the overall change in total deposition to the change in contribution from each geographic region or category. This information is summarized in Table 4-1.

Table 4-1. Portion of Overall Percent Reduction in Mercury Deposition for 2018 Attributable to Each Source Region and Category, for Virginia and the Ten Major River Basins.

Region	Virginia (EGU) (%)	Virginia (Non-EGU) (%)	Remaining 12-km (EGU) (%)	Remaining 12-km (Non-EGU) (%)	Remaining US (%)	Canada & Mexico (%)	IC/BCs (%)	Natural Sources (%)
Virginia	7.2	5.7	61.0	4.6	2.8	0.0	18.0	0.8
Chesapeake Bay	7.4	1.4	62.7	3.1	2.6	0.1	20.0	0.7
Chowan River Basin & Dismal Swamp	9.2	13.9	45.1	10.4	2.3	0.0	16.6	0.7
James River Basin	8.4	8.5	54.9	3.5	2.7	0.1	20.4	0.8
New River Basin	0.6	2.4	55.6	5.0	5.4	0.1	28.9	1.2
Potomac River Basin	14.8	4.2	68.8	0.8	1.1	0.0	9.0	0.4
Rappahannock River Basin	5.1	3.3	72.1	1.2	1.9	0.0	15.1	0.7
Roanoke River Basin	0.6	5.2	68.7	2.5	2.8	0.0	18.8	0.8
Shenandoah River Basin	0.9	3.4	73.6	3.7	2.0	0.0	15.2	0.7
Tennessee & Big Sandy River Basins	12.2	1.2	44.3	9.9	6.4	0.1	23.8	1.0
York River Basin	11.1	5.1	62.3	1.0	2.0	0.0	16.6	0.7

Table 4-1 provided by ICF

The reductions to mercury deposition listed above are mainly predicted to be achieved from control technology installed as a result of CAIR and CAMR. There are some reductions that may be achieved from non-EGUs as a result of other requirements that were not included in the air quality modeling. For example, sources that are electric arc furnaces that melt scrap metal for recycling now may only process scrap metal free of mercury switches. More information on this federal requirement is available at: http://www.epa.gov/ttn/oarpg/t3/fact_sheets/eaf_fs_121707.html. Prior to this federal requirement, Virginia adopted a vehicle mercury switch removal program in 2006, which requires a good faith effort to be made to remove mercury switches from end-of-life vehicles. To date, removal and recycling of mercury switches from vehicles in Virginia has prevented over 35 pounds of mercury from being released into the environment. Automakers have ceased using mercury switches in new vehicles and as newer cars replace older vehicles, the number of vehicles in operation with mercury switches is decreasing, which will reduce the amount of mercury that potentially could be released into the environment from the recycling of old automobiles.

Local-Scale Mercury Deposition Attributable To Individual Facilities
As part of the mercury modeling conducted by ICF, emissions and deposition from the 15 largest mercury emitters in the state were modeled using the AERMOD model to examine the direct impact these facilities have on the area within a three-km area surrounding each source. This analysis yielded three key findings: (1) dry deposition is greater than wet deposition for all facilities, (2) maximum wet deposition tends to occur at locations closest to the facility, and (3) maximum dry deposition tends to occur farther away from the facility location.

Through working with facilities, ICF obtained information on future controls that these facilities plan to install and then modeled the associated changes in mercury emissions and average annual deposition occurring as a result of operation of these facilities. For all facilities, the changes in simulated deposition track the changes in emissions quite closely. As with the regional-scale modeling results, the largest reductions in both emissions and deposition tend to occur between the base year and 2010, with some variability between facilities. Emission increases are associated with some of the facilities in 2015 and 2018, and these changes result in corresponding local deposition increases for the future years.

The type of mercury emitted was also examined as part of this modeling exercise, and the modeling results indicate that most of the local-scale mercury deposition is in the form of reactive gaseous mercury (HG2).

Detailed information on the baseline and projected future mercury emissions for the 15 largest mercury emitters and the corresponding predicted mercury deposition is provided in Section 6 of Appendix A of this report.

Summary of Modeling Results
The modeling conducted by ICF indicates the following:

- Mercury sources located outside of Virginia contribute to the mercury deposition occurring within the state. Global sources are responsible for the largest amount of mercury being deposited within the state.

- Mercury deposition is predicted to decrease statewide in future years as a result of implementation of emission controls in use to meet requirements of the CAIR and the CAMR. Virginia benefits from mercury reductions occurring in surrounding states, particularly emissions reductions from EGUs.

- Emission sources located in Virginia contribute to mercury deposition within the state, and the greatest impacts from the in-state sources are simulated near the source locations. This includes EGU sources and non-EGU sources.

- Examining deposition patterns for EGU and non-EGU sources indicates that, in general, EGU sources tend to impact a larger area, compared to non-EGU sources. This is likely due to shorter stack heights and lower exit velocities at non-EGU sources, which result in less dispersion of mercury.

- The modeling results were calculated by using requirements that must be met under the CAIR and the CAMR. The Washington, D.C. Circuit Court of Appeals has recently issued opinions vacating both of these rules.

Chapter 5- Analysis of Mercury Deposition Modeling – Impact on Fish Tissue Concentrations

DEQ used the information provided by the ICF model about projected reductions in mercury deposition rates to estimate the potential for reductions in fish mercury concentrations in the future, once these reductions in mercury had occurred. In order to do this, information available from the scientific literature as well as experiences in other parts of the country were reviewed to determine what effect might be expected from reductions in mercury deposition into the waterbodies with current fish consumption advisories due to mercury contamination. The differences in mercury deposition rates estimated for 2010 and 2018 were compared to the estimates for the base year utilized in ICF's modeling. Relative proportional reduction factors were calculated for each of the watersheds with fish consumption advisories. These reduction factors were used to estimate the potential for lowered concentrations of mercury in fish from these waterbodies, after the projected reductions in air deposition of mercury have occurred. These estimated, future fish mercury contamination levels were reviewed to assess the potential for removal or relaxations of the existing fish consumption advisories, should future monitoring show that the fish contamination has been reduced to below levels of concern.

Literature Review

Scientific literature was reviewed to gather information to help estimate future fish mercury concentrations, given the reductions in mercury air deposition rates projected by the ICF model.

A large amount of information has been generated in the last 15 years on mercury contamination of fish and the linkages between air emissions of mercury, its cycling in the environment, conversion to methylmercury and eventual bio-accumulation in fish tissue where it can pose a potential risk to humans and wildlife who consume it. Some of the more important and most recent information is briefly discussed below. The emphasis on this summary review is to provide information that will help answer the question, "If we reduce the rates of mercury deposited by air sources into a waterbody that has mercury-contaminated fish, can we expect to see the contamination levels of the fish decrease in response to the decreased rates of air deposition?"

A considerable amount of sophisticated research has been conducted in the Florida Everglades and in experimental lakes in Ontario, Canada, where mercury was added to the waterbody and then traced as it was cycled in the environment to become accumulated in fish tissue. Actual field experiences in Florida and in Massachusetts also provide important information.

Summary of Findings of Literature Search

- Mercury emitted into the air from combustion sources is present in a variety of chemical forms, some of which can be deposited within miles of the emission site, while other forms of mercury can be transported tens to hundreds of miles away from the original source.

- Once deposited in a waterbody, mercury can be transformed into methylmercury by certain bacteria species commonly found in soil or sediments.

- Once converted into methylmercury, it quickly enters the food chain, and concentrations of methylmercury increase in fish, often reaching the highest concentrations in fish species that eat other fish.

- Methylmercury is the most toxic form of mercury and can pose potential risks to human consumers of those fish.

- The amount of mercury being added to an ecosystem and the rate at which this mercury is converted into methylmercury in the ecosystem are the most important factors that determine whether or not fish in a waterbody will accumulate mercury to high levels in any particular waterbody.

- Environmental conditions that favor the bacteria communities that produce methylmercury are known to include waterbodies with low dissolved oxygen, low pH (slightly acid conditions), high organic matter and moderate concentrations of sulfates. These conditions are common to swamps, wetlands and some lakes or reservoirs.

- Newly added mercury appears to be most active in an ecosystem and is quickly converted into methylmercury under favorable environmental conditions.

- Mercury added to lakes can be expected to be converted into methylmercury and begin to enter the food chain relatively quickly, being found in fish within a few months or years of being deposited into the waterbody.

- Mercury deposited onto forested uplands is thought to be relatively unavailable to the aquatic ecosystem. This mercury will enter the waterbody slowly, only after many years of cycling through vegetative decay and erosion of the soils, probably taking many decades to centuries to be transported into the waterbody where it can be accumulated by fish.

- Wetlands appear to respond to changes in mercury deposition and accumulation into the fish in an intermediate time frame involving years to decades.

- Available evidence from both experiments and actual field experiences indicate that although each waterbody will react to changes in mercury inputs differently, it is reasonable to anticipate that if mercury inputs into an ecosystem are decreased, there will be a proportional decrease in the fish contamination levels.

- It is reasonable to accept an assumption of an equal proportional decrease (1:1) in fish concentrations after a reduction in mercury deposition into the waterbody has been achieved; that is, if mercury input is lowered by 20 percent%, we can expect

to see the fish mercury concentrations lowered by 20 percent after the ecosystem equilibrates to the new, lower amounts of mercury available in the ecosystem.

- The time frame for the ecosystem to come into equilibrium after the reductions in mercury deposition takes place will be variable and different for each waterbody.

- Lakes will be expected to react most quickly to changes in mercury deposition reduction, showing reduced mercury in fish tissue within a few years to decades.

- Wetlands will be expected to react in an intermediate time frame to changes in mercury deposition reduction, showing reduced mercury in fish tissue possibly within several years to several decades, and probably dependent on how well connected the shallow wetlands are to the nearby river channel.

More detailed summaries of information reviewed as part of the literature review are provided below.

Mercury-Fish Contamination Field Experiments, Everglades

The mercury contamination of fish in the Florida Everglades has been subject to intense studies since the 1980's when elevated levels of mercury were found in fish there. This prompted widespread research and mercury reduction efforts and a development of a Total Maximum Daily Load (TMDL) to try to identify and control the sources of mercury to this area. One of the key findings of the Everglades TMDL study (Florida DEP, 2003) was that there is a linear relationship between mercury deposition and levels of mercury in fish, and when atmospheric deposition of mercury is reduced, levels of mercury in fish also show a decline with a relationship of almost 1:1. Local air emission rates of mercury, primarily from medical waste incinerators and municipal waste incinerators, have declined by over 90 percent since the late 1980s to early 1990s. This has resulted in a corresponding decline of about 80 percent in mercury in largemouth bass and fish-eating birds in the affected area of the Everglades. The changes in fish mercury concentrations occurred relatively rapidly after reduction in local emissions. Fish mercury concentrations were reduced by about 50 percent in about 10 years and by 90 percent within 25 years.

Also, along with the reductions in local air emissions of mercury, reductions of sulfates into the area's waters were achieved, which also could have contributed to the corresponding decreases in mercury levels in the local fish (Gilmore, etal., 2003). Decreases in sulfates in a waterbody have been shown to lessen the methylation efficiency rates of the bacterial community responsible for the mercury methylation cycle, which reduces the potential for fish to accumulate methylmercury. The TMDL report notes that the Everglades is a unique ecosystem, and that other waterbodies may not react the same way, but this experience does demonstrate the potential for linkage between deposition rates and corresponding reductions in fish contamination. The report notes that even after reductions in mercury air-deposition rates, the fish will have some remaining mercury due to remaining mercury in the sediments and continuing, but lower levels of air-deposited mercury.

Mercury-Fish Contamination Field Experiments, Canadian Lakes

A series of long-term experiments (Harris, R. et al.,2004), (Branfireun, et al., 2005), (Patterson, et al., 2006) in experimental lakes in Northwest Ontario, Canada were conducted in 2001-2003, where lakes were dosed with specific isotopes of mercury, and the fate and transport of this mercury was followed. This allowed the researchers to distinguish between mercury already in the water system and the "new" mercury. The mercury isotopes were added to the lake itself, nearby wetlands and an upland forested area. An extensive series of papers has been published on these experiments. A recent publication in the Proceedings of the National Academy of Science in October 2007 titled, "Whole-ecosystem study shows rapid fish mercury response to changes in mercury deposition" (Harris et al., 2007) provides a good synopsis of this work. This 2007 paper concluded that concentrations of methylmercury in fish in the experimental lake rapidly increased as mercury deposition rates were increased over the first 3 years of the study. Mercury added to the lake showed the most rapid conversion into methylmercury and was detected in the fish within months of deposition; continued to increase in the fish tissue during the three years of the experiment; and had not yet reached a steady state. Mercury deposited to a nearby wetland took much longer to appear in the lake waters, reflecting a lag time as the mercury was bound up in the vegetation and cycled through the wetland's vegetation growth and decay cycles and slowly found its away into the lake water. Mercury added to the forested upland area took even longer to be detected in the lake water. The authors concluded that as mercury emission controls are instituted and atmospheric deposition of mercury decreases, there is the expectation that a decrease in atmospheric mercury deposition will result in lower fish mercury concentrations. There will be some lag time before the ecosystem and fish concentrations of mercury become equilibrated to the lower mercury inputs. The effects are expected to occur in two phases, an initial rapid decline in fish mercury concentrations after reductions in direct deposits into the waterbody occur, followed by a more prolonged reaction as mercury previously deposited in wetlands or on the upland ecosystems become re-equilibrated. Lakes that receive most of their mercury from the atmosphere could be expected to respond within years to approximately a decade, while wetlands may respond less rapidly, and waterbodies that receive mercury after being deposited to forested, upland ecosystems would take longer (decades and possibly up to centuries).

Although this experiment found a long lag time in transport of the mercury from the wetlands to the lake, the report also noted that other types of wetlands could export newly deposited mercury and impact fish mercury concentrations on a much shorter time scale than what was seen in this particular lake. Much depends on the connectivity of the wetland to the waterbody where the fish reside. Other related experiments, in another lake and wetland, have shown the mercury deposited in wetlands is rapidly methylated and can be transported by shallow flow to the nearby lake within a relatively short time. The northern wetland in this experiment may not act the same as other wetlands because of differences in hydrologic connectivity, the type of moss vegetation and the colder climate with a short warm season. When wetlands are hydrologically well-connected to nearby lakes or rivers, as is often the case in southern coastal plain swamps as in Virginia, it can be expected that the shallow wetlands bordering the channel of the river flowing through the swamp will act as a site of increased methylation, and the methylmercury can be readily transported via the water flow through the system.

Additional experiments in the Florida Everglades and the group of experimental lakes in Canada (Hintelmann et al., 2002), have provided evidence that "new" mercury that has been recently added to an ecosystem is much more likely to be converted into methylmercury and bio-accumulated into the local fish as compared to "older "mercury that may already be in the local environment from previous deposits. The newly added mercury appears to be more environmentally active than the older mercury, possibly due to the mercury becoming bound with sulfates in the sediments over time. It has been shown that even with previously contaminated ecosystems, newly added mercury is even more active than previously existing, "older" mercury. Recently-added mercury shows up in fish tissue in a relatively short period of time. Mercury deposited into waterbodies or wetlands is most active and quickly finds its way into fish tissue, while mercury added to forests or upland sites did not show up in fish tissue during the course of the experiments. This information suggests that "new" mercury deposited into the water or wetlands is most important to methylation and resulting fish contamination. The bioaccumulation of the new mercury takes place relatively quickly, showing up in the fish tissue within months of adding it to the lakes or wetlands. After time, months to years, mercury in sediments appears to be stabilized, possibly bound up with reduced sulfur compounds in the sediments and is not as available to the biota as newly added mercury. This has implications that suggest that if the ecosystem is capable of responding relatively quickly to increases in inputs of mercury, then reductions in the amount of mercury deposited into the ecosystem should result in lowered fish contamination levels within a relatively short time frame, too. If a way can be found to decrease the amount of "new mercury" being added to the ecosystem, then a decrease in fish mercury contamination levels may be observed.

Findings of the International Conference on Mercury as a Global Pollutant

A recent international meeting of mercury specialists, the 8th International Conference on Mercury as a Global Pollutant, was held in Madison, Wisconsin, in 2006. Panels of mercury experts were charged with addressing several important questions regarding mercury fate and transport issues. One panel was given the question, "How would methylmercury levels in fish respond to reduced anthropogenic emissions of mercury?"

The panel concluded (ICMGP 2006) that the concentrations in methylmercury in fish will decrease in response to mercury-load reductions. The magnitude, rate and lag time of that reduction will vary significantly, depending on site-specific factors that affect the amount of methylmercury available to the food web. The most mercury-sensitive ecosystems have several characteristics in common: efficient delivery of mercury to zones of methylation, high rates of methylation of mercury in these zones, and efficient uptake of the methylmercury into the food web.

The rate of recovery of a fishery in a specific waterbody depends, in part, on the transport of mercury that has accumulated in the watershed area. Increased transport of mercury from the terrestrial zone to the waterbody is associated with shallow surface deposits of mercury, decomposition rates in the soil, high organic content of the soil and land disturbances and soil erosion that lead to a washing of the mercury into the waterbody.

Very similar conclusions were reached in a recent publication that reviewed the available information on recovery of mercury contaminated fisheries (Munthe, R.A. et al., 2007).

EPA Total Maximum Daily Load Guidance for Mercury Impaired Waters

The EPA has recognized that the primary potential risk posed to humans by mercury released to the environment via air emissions involves the complex events that lead to deposition of the mercury onto a waterbody, the conversion of the mercury into methylmercury and the uptake and bioaccumulation of methylmercury into fish tissue, where it can pose a risk to the human consumers. Once a problem is identified with mercury contamination of fish, a waterbody is classified as impaired by a state and plans are made to identify the sources of the mercury and control them by developing a Total Maximum Daily Load (TMDL) that apportions allowable releases of mercury so that the fishery in the waterbody can recover. EPA recognizes the difficulties involved with trying to control mercury deposition when some sources may be outside the jurisdiction of the state where the contamination occurs. EPA has developed guidance for dealing with these issues (EPA 2007).

In this mercury-TMDL guidance, EPA recommends that states estimate the range of percent-reductions in air deposition needed to achieve the acceptable fish-tissue mercury concentration. EPA does not expect complex modeling is needed to develop these estimates, and that the estimates can be based on steady-state assumptions such as a 1:1 linear relationship between reductions in air loadings and reductions in methylmercury in fish tissue. Such a linear relationship has been used in EPA-approved TMDLs for Georgia.

The Massachusetts Experience

New England states also have discovered elevated levels of mercury in fish, especially in lakes and ponds. In response to these mercury levels, the states have entered into regional agreements that have resulted in increased controls on mercury emissions and decreased mercury emissions in the region. Expanded fish monitoring was conducted to evaluate the initial effectiveness of these efforts. The Massachusetts Department of Environmental Protection published a report in 2006 entitled, "Massachusetts Fish Tissue Mercury Studies: Long-Term Monitoring Results, 1999-2004" (Mass DEP, 2006). This report describes long-term monitoring of changes in mercury concentrations in edible tissues of two species of freshwater fish in a series of lakes and provides data to help evaluate the effectiveness of state and regional mercury reduction programs in Massachusetts lakes and especially in an area in northeastern Massachusetts with modeled, higher mercury deposition. This area of higher modeled deposition was caused by local and regional air emissions of mercury, mainly from incinerators. Controls on these local and regional sources of mercury emissions had been implemented beginning in the late 1990s and during the course of the fish monitoring (1999-2004). Massachusetts reported that mercury emissions in New England and the Eastern Canadian Provinces decreased by about 54 percent between 1998 and 2003. During this period, emissions in Massachusetts decreased by about 70 percent, and those in the study area by about 87 percent.

Massachusetts also reported that during the period of the monitoring (1999-2004), consistent and substantial, statistically significant decreases in yellow perch and largemouth bass fish tissue

mercury concentrations occurred in most lakes sampled. For yellow perch, of 17 lakes monitored, mean mercury concentrations in this species decreased significantly in 13 of the waterbodies between the earliest and latest dates sampled. Nine of the lakes were located in the area in northeastern Massachusetts with higher modeled mercury deposition and in eight of these lakes, significant decreases in mercury concentrations in yellow perch were observed, ranging from -26.0 to -61.9percent. The mean change for all nine lakes was -32.4 percent. Five of the remaining eight lakes around the rest of the state also had statistically significant decreases in mercury in yellow perch ranging from 20.1 to 28.0 percent, with an overall mean change for all eight lakes of -15.4 percent.

The situation was similar for large mouth bass with mercury concentrations declining in 11 of 17 lakes throughout the state. Eleven of the lakes sampled were in the area in northeastern Massachusetts with the higher modeled mercury deposition, and mercury levels in largemouth bass from seven of those decreased significantly, ranging from -16.0 to -55.2 percent. Mercury levels in three of the four other lakes also decreased, but the changes were not statistically significant. The mean change in mercury concentrations in largemouth bass among all 11 of these lakes was -24.8 percent. Four of the remaining six lakes located around the rest of the state also had statistically significant, but smaller, decreases in largemouth bass tissue-mercury concentrations. The range of these changes was -15.9 to -36.4 percent, with an overall mean for all six lakes of -19.0 percent.

The Massachusetts report indicates that, given a reduction of air emissions of mercury of about 70-87 percent in the local area, the fish concentrations of mercury declined an average of 24.8 percent to 32.4 percent in a five-year period. This indicates that reductions in local emissions of mercury can have a direct and rapid effect in corresponding fish uptake of mercury in the local area. The ratio between mean declines in fish mercury concentrations and the mercury emissions declines range between 0.22 and 0.27 on a regional basis and 0.29 and 0.37 in the area with higher deposition. It is important to recognize this is based on declines in mercury <u>emissions</u> and <u>not deposition</u> estimates (which are not available). Typically, local deposition of mercury is a fraction of the mercury emitted to the air, so the ratios for declines in fish mercury compared to deposited mercury would be expected to be higher than the 0.22 to 0.37 observed based on emissions data only. Also, the period of investigation is only a few years, and it is expected that the ecosystem will take some period of time to re-equilibrate to the new, reduced mercury deposition rates.

Overall, this information from the Massachusetts study is very encouraging and indicates that a decline in deposited mercury to a waterbody will result in a corresponding decline in fish contamination, and that such a decline in fish mercury contamination can begin to occur within a few years of the changes in mercury deposition.

<u>Conclusions of the literature review</u>

The experiments in the Everglades and in the Canadian lakes where mercury was added to the test water demonstrated that mercury deposited from the air is quickly converted into methylmercury in these environments and can be found in fish tissue within a few months to

years. This demonstrates a fairly rapid response to added mercury. The time between addition of the new mercury to the waterbody and when it is found in fish tissue is quickest for lakes (months to years) and longest for mercury deposited to forested uplands (years to many decades or to maybe even centuries). Wetlands are expected to respond in an intermediate timeframe, depending on a variety of site-specific factors. Actual experience of the start of recoveries of fisheries in the Everglades and in Massachusetts demonstrated that, following reductions in air emissions of mercury in local and regional sources, within a few years the local fish also showed a corresponding decrease in mercury uptake.

In each waterbody, site-specific physical, chemical and biological factors affect the rate of conversion of mercury into methylmercury and its uptake into the food web. High rates of methylation are associated with sources of mercury in areas with high organic matter, low pH, and moderate concentrations of sulfates and sulfur, along with the presence or abundance of bacterial communities capable of methylation of mercury (Munthe, R.A. etal., 2007). Once methylmercury is formed, each waterbody will have a different food-web structure that also can influence the rate of bioaccumulation of mercury into fish in these waterbodies. While these various factors are understood to have effects on the rate of methylation and uptake on mercury, these processes are not understood well enough to allow for accurate predictions of rates of methylation or mercury bioaccumulation in the various waterbodies. This makes the construction of a reliable model for accurately predicting the effects that changing inputs of mercury will ultimately have on local fish contamination levels unworkable without a great deal of site-specific study and information. Thus, the development of such a model is impractical for all the different swamps, rivers, reservoirs and ponds in Virginia, all of which likely have different mercury cycling efficiencies and different food webs.

On the other hand, each waterbody may be considered as a dynamic system that will respond to changes in mercury input in a consistent manner once the ecosystem equilibrates to the changed conditions. Using this as a basis, it can be predicted that a reduction of any of the factors that has the potential to increase the amount of mercury in the waterbody, or that increases the rate of mercury methylation efficiency; should show a corresponding reduction in methylmercury contamination levels in fish. If the environmental conditions that affect the efficiency of mercury methylation in the soil or sediment are considered to be natural, ecological conditions that remain in some form of dynamic equilibrium, then the amount of change in mercury input can be expected to result in a proportional change in the fish tissue mercury concentrations once the ecosystem has become equilibrated to the changes in available mercury. Thus, it is assumed that if mercury deposition into a waterbody is reduced by a certain amount, a similar and proportional reduction in mercury concentration in fish in that waterbody is to be expected.

The available information indicates that when mercury deposition to a waterbody is reduced, it is reasonable to expect to see a corresponding decrease in fish contamination levels (Mass DEP, 2006), (Munthe, R.A. etal., 2007), (ICMGP, 2006), (Florida DEP, 2003). An assumption of a 1:1 relationship would be appropriate for estimating potential future fish mercury concentrations in relation to percent reductions in mercury deposition rates.

This assumption of a 1:1 relationship of a reduction in mercury input into an ecosystem to a corresponding reduction in fish bioaccumulation of methylmercury will be used to estimate

future fish mercury concentrations in Virginia waterbodies that are currently subject to fish consumption advisories and where the primary source of mercury is believed to be air deposition.

Mercury in Virginia Waterways

Two rivers in Virginia have been contaminated with mercury due to past industrial pollution incidents. These are the only known instances where significant discharges of mercury directly into Virginia waterbodies has occurred in the past and resulted in fish consumption advisories. The North Fork of the Holston River in southwest Virginia and the South River and the South Fork Shenandoah River in the Shenandoah Valley have fish with elevated levels of mercury caused by two past industrial pollution incidents. The North Fork of the Holston River became contaminated with mercury from the Olin Corporation's Saltville facility as part of a chlorine production process. Olin has been addressing contamination in the river with assistance from the EPA and DEQ since the 1980s. Mercury was used by a DuPont plant in Waynesboro in fiber production between 1929 and 1950. Mercury contamination in the South River was discovered in the 1970s and now extends to the South Fork Shenandoah River. DEQ, in partnership with the South River Science Team, regularly takes samples of water, fish tissue and sediments in the South River and the South Fork Shenandoah River with money from a trust fund established by DuPont Co. Until 2001, these two industrial sites were the only sites with fish consumption advisories due to mercury in Virginia.

Monitoring of Mercury-Fish Contamination

The DEQ Fish Tissue and Sediment Monitoring Program is used to monitor for fish contamination issues that could pose potential risks to human consumers. DEQ's fish monitoring efforts have always been directed toward investigating waterbodies with the highest probability of chemical contamination, and most of these monitoring efforts have focused on waterbodies that receive permitted discharges from major industrial and municipal facilities. Until about the year 2000, there was little reason to monitor fish in many of Virginia's swamps or wetland-dominated rivers, because most of these waters do not have significant industrial municipal discharges. In the late 1990s, however, many other states and other countries began discovering fish with high levels of mercury in lakes and wetlands in areas without any significant known sources of mercury discharges into the affected waterbodies. An understanding developed that some types of waterbodies, such as lakes and wetlands, might be predisposed to fish mercury contamination issues, even if they were not subject to any significant, direct source of mercury discharges. DEQ began to investigate this possibility by expanding the monitoring of fish in some rivers that are influenced by wetlands. Results of this monitoring showed that several of Virginia's waterbodies do contain fish with elevated levels of mercury, even where there were no known significant industrial or municipal dischargers into the waterbody.

Summary of Mercury-Sensitive Waters

Fish with elevated levels of mercury have been found in some waterbodies, even when there are no known local sources of mercury that discharge into the water. Some aquatic ecosystems have

natural environmental conditions that make them more sensitive to even small amounts of mercury, allowing rapid and efficient uptake of mercury into the food chain and accumulation in fish. These aquatic ecosystems have environmental conditions that allow certain bacteria in the sediment to convert mercury into methylmercury in a highly efficient manner. This increases the rate at which added mercury can be converted into methylmercury and accumulated by the fish in these waterbodies. The important environmental conditions that create the right conditions for these types of bacteria include low dissolved oxygen, low pH (slightly acidic waters) and high levels of organic matter. These environmental conditions are common in swamps, wetlands and some lakes or reservoirs. This helps explain why some waterbodies have elevated levels of mercury in fish, even when there are no direct sources of mercury into the waterbody except for low levels of mercury deposited from the air. This phenomenon of some waterbodies being especially sensitive to mercury contamination will be described in more detail below.

Detailed Discussion of Environmental Conditions of Mercury Sensitive Waters

During the 1990s scientists began to better understand the extent of mercury contamination of fish in lakes and other waterbodies in many parts of the world. Many of these waterbodies, including the Everglades in Florida and isolated lakes in the southeastern and northern United States, Canada and Scandinavia had little or no direct discharges of wastewater from industries or wastewater treatment plants, yet the fish in these waterbodies showed elevated levels of mercury. As more research was conducted, it became apparent that some waterbodies have physical and chemical characteristics that promote the uptake of mercury into the food chain and this leads to the accumulation of mercury in some species of fish, especially the top predator fish, such as bass.

In order to become readily taken into the food chain, mercury must be chemically combined with a methyl molecule (CH_3) to form methylmercury ($Hg\text{-}CH_3$). Some species of naturally occurring bacteria commonly found in soil or sediment are capable of absorbing mercury in a variety of forms and converting it to methylmercury, thereby making the mercury more biologically active. This "methylation" by bacteria in soils of mercury into the toxic form methylmercury is a key step in the process that most dramatically influences whether or not mercury may become accumulated in fish to high enough concentrations that it could present a potential risk to consumers if eaten in an unrestricted fashion.

Methylmercury can easily pass through cell membranes and is much more toxic than elemental mercury. Once converted into methylmercury, mercury is much more likely to be easily absorbed by living things and, as these are eaten by other aquatic animals, the methylmercury is accumulated to higher levels in each step up the food chain. The top predators in the ecosystem, generally the fish species that eat other fish, such as bass, often have the highest concentrations of mercury.

As research continued in the 1990s, it became clear that certain environmental conditions were associated with the observed high levels of mercury in fish. In general, high levels of mercury in fish were seen in waterbodies that were more acidic, contained high levels of organic matter and had low levels of dissolved oxygen, all of which are often natural characteristics of some types

of lakes, swamps or wetlands. Under these environmental conditions, the types of bacteria that can convert mercury into methylmercury are more likely to be present and active.

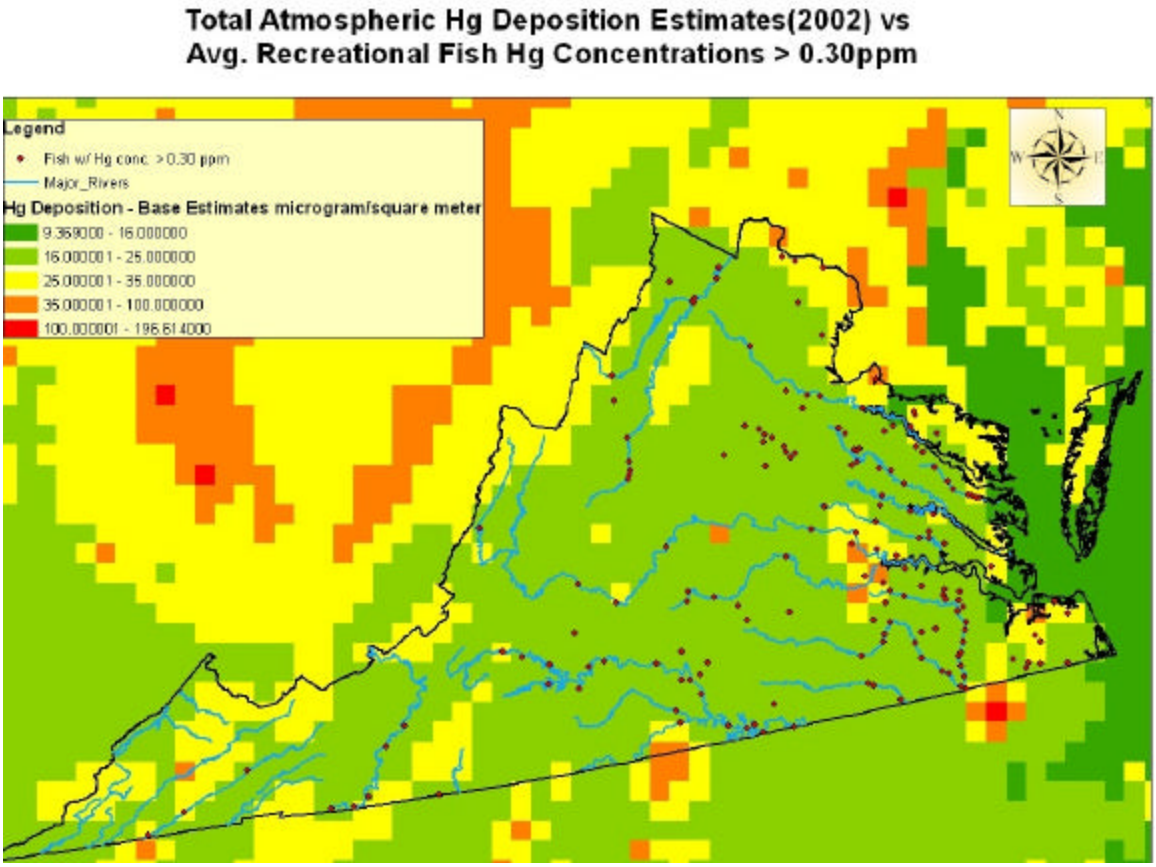
These waterbodies are considered "mercury sensitive waters" because their natural environmental conditions [low dissolved oxygen, low pH (a measure of acidity) and high amounts of organic matter] make them more likely to promote the methylation of any mercury that enters these ecosystems. In other words, if the same, small amount of mercury is added to a swamp water and a free-flowing stream or river, the fish in the swamp are more likely to accumulate higher levels of mercury.

Mercury coming out of combustion stacks can be in three general forms: elemental mercury as a vapor, ionic mercury as inorganic compounds (mostly mercuric chloride) and particulate-bound mercury as organic compounds. Elemental mercury (as a vapor) is generally transported great distances, becoming part of the global air mercury reservoir, while particulate-bound mercury is deposited locally, and ionic mercury is transported and deposited intermediate distances. The ionic forms of mercury are very water-soluble and can quickly become incorporated into the mercury methylation cycle and quickly enter into the food chain.

The journey between air emissions of mercury to fish contamination involves photochemical processes, deposition and conversion of mercury compounds into methylmercury at the water-sediment surface interface. The conversion into methylmercury is performed by a class of bacteria known as sulfur-reducing bacteria, which are very common in soil and sediments. These bacteria are found in soil and in sediments in waterbodies where the environment changes between oxygen-rich to oxygen-poor. As mercury compounds and sulfates are deposited onto the surface of the sediment, they diffuse into the bacteria-rich zone and are converted into methylmercury by the bacteria.

Figure 5-1 illustrates the predictions of air-mercury deposition rates for the base year of 2002 from the ICF study. Superimposed on the map of Virginia are locations in waterbodies where the average concentrations of mercury in recreationally important fish species were greater than 0.30 ppm (the proposed fish criterion for fish tissue in Virginia).

Figure 5-1



DEQ has found that fish in at least 11 waters in eastern Virginia are contaminated with mercury. Sampling results triggered fish consumption advisories in the Great Dismal Swamp Canal (including Lake Drummond), portions of the Blackwater River and Dragon Run Swamp, as well as eight other rivers and small lakes. These waters appear to be mercury-sensitive, meaning that they are more likely than other waters to have natural conditions that are favorable for the conversion of mercury into methylmercury. The waters share three characteristics: low levels of oxygen, high amounts of organic matter and low pH, which indicates that they are acidic. These traits are common in swamps, streams and rivers in Virginia's coastal areas as well as in some lakes or reservoirs. Another chemical constituent that appears to be important to the increased potential for mercury methylation in the environment is sulfate. Moderately elevated levels of sulfate appear to increase the potential for methylation of mercury. Extremely high concentrations of sulfate, however, seem to have a dampening effect on the methylation process. It is thought that sulfate helps to stimulate the bacteria that are responsible for the mercury methylation. Information from the Florida Everglades (Florida DEP, 2003) study indicates that some of the reduction of mercury in fish tissue in those sites is attributable to joint reductions of mercury deposition following control of local air emissions as well as reductions in local inputs of sulfates into the waterbody.

Monitoring of Fish Contamination in Virginia

The DEQ - Office of Water Quality Programs' Fish Tissue and Sediment Contaminants Monitoring Program conducts routine studies of fish tissue and sediment samples in state waters. The fish monitoring program collects fish and sediment samples from selected sites in Virginia waters and has them analyzed for selected toxic contaminants that are likely to be found in fish tissue. These contaminants include a variety of organic chemicals such as pesticides and poly-chlorinated biphenyls (PCBs), as well as metals, including mercury. The sites where the fish and sediment are collected are selected based on a variety of reasons, but these sites are targeted mostly because of a proximity to industrial or municipal discharges into the waterbodies, or other potential sources of toxic chemical contaminants that are likely to bioaccumulate in fish tissue.

The monitoring program is designed to sample sites in the river basins in Virginia, rotating the monitoring around the state in each major river basin every three to five years, depending on the availability of sufficient resources. Depending on available resources (staff and funds for contaminant analysis), between 70 and 100 sites have been monitored each year since 1998. Fish and sediment samples are collected between April and September of each year, the chemical analysis is performed during the winter, results are reported to DEQ beginning in February of the following year, and all data are due no later than June 30. All data are shared with the Virginia VDH and also posted on the DEQ website soon after receipt from the lab.

At each monitored site, five to ten individual fish for each of three to five different species of fish are collected. These fish species are selected to represent different feeding habits and positions in the food chain and will include a bottom feeder like a catfish, an insect-eating fish like the sunfish species and an upper-level predator species like a bass. By collecting these different species, DEQ can determine if a toxic chemical may accumulate in one level of the food chain.

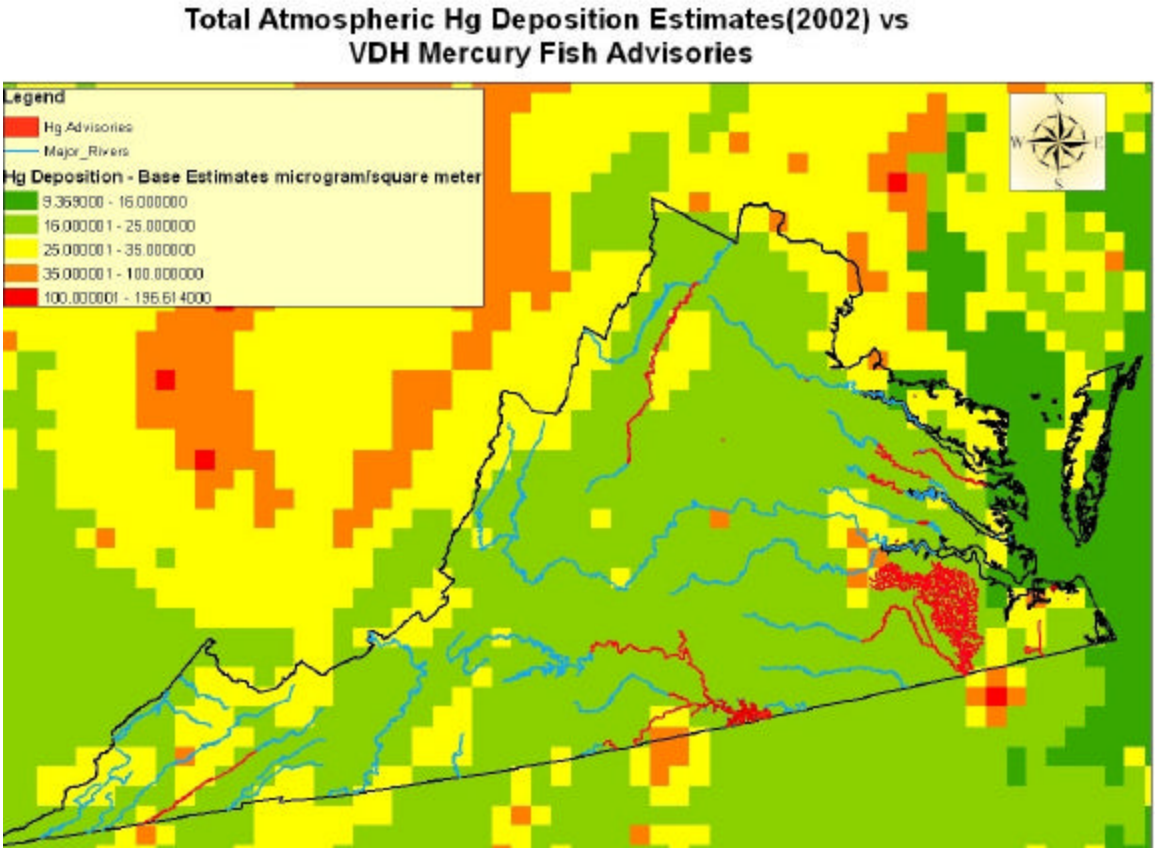
The concentrations of toxic contaminants detected in the fish are assessed to determine the potential for human health risks for individuals who may consume fish from state waters and to identify impaired aquatic ecosystems. The VDH uses the data generated by the program to determine the need for issuing fish consumption advisories. DEQ and other state and federal agencies also use the data to assess the environmental quality of Virginia's waters. Along with the fish, at least one sediment sample is collected at each station where fish tissue are sampled and analyzed for a suite of bioaccumulative chemical contaminants.

Fish Consumption Advisories Due To Mercury-

In Virginia, DEQ is responsible for monitoring fish for bio-accumulative chemicals and assessing if a waterbody is impaired due to elevated levels of toxic contaminants. DEQ shares all these data with the VDH staff who review the fish contamination data to determine whether a fish consumption advisory is warranted and, if so, VDH issues the advisory. For each waterbody, all available data on the contamination levels of each toxic contaminant are reviewed and the different species of fish are assessed separately.

Figure 5-2 displays the current (as of 2007) fish consumption advisories for mercury issued by VDH and the corresponding modeled mercury deposition for the base year.

Figure 5-2



The VDH uses 0.5 mg/kg or 0.5 ppm of methylmercury in fish filet tissue as a trigger level for the issuance of a fish consumption advisory. If average tissue concentrations of mercury are below 0.5 ppm, the VDH will conclude that a fish consumption advisory is not warranted. When a fish species' tissue average concentration of mercury is between 0.5 and 1.0 ppm, VDH will recommend limiting consumption of the contaminated species to two, eight-ounce meals per month and that young children, pregnant women and nursing mothers should not consume the contaminated species of fish. If the average concentration of mercury in a species of fish is between 1.0 and 2.0 ppm, the VDH will recommend limiting consumption to one, eight-ounce meal per month. If the average mercury concentration in fish exceeds 2.0 ppm, the VDH will recommend that the contaminated species of fish not be consumed.

Based on these VDH guidelines for issuing fish consumption advisories because of mercury, a fish consumption advisory that has been issued by the VDH can be expected to remain in place until the average concentration of mercury in the affected species has been reduced below 0.5 ppm. It is expected that at least two years of monitoring data that show average fish mercury

concentrations below 0.5 ppm in the species of fish previously known to be contaminated will be needed to show that such a reduction in fish mercury contamination has occurred and a removal or relaxation of the fish consumption advisory is warranted.

The VDH trigger value of 0.5 ppm applies to methylmercury in edible fish filet tissue. The analytical lab used by DEQ to analyze fish contaminants reports concentrations of total mercury in fish tissue rather than methylmercury. This is a cost-saving issue as methylmercury analysis is more expensive. This is standard practice for analyzing mercury in fish tissue and most of the mercury in fish tissue is, in fact, methylmercury. It has been shown in numerous studies that in larger, predator fish (the species most likely to bioaccumulate mercury to higher levels), approximately 90 percent to more than 95 percent of the total mercury detected is methylmercury. Risk assessments on total mercury concentrations in fish is conducted with recognition that this may involve a potential 5 to 10 percent overestimation of the methylmercury included in the total mercury concentration in fish tissue. The use of this methodology is a conservative approach that is utilized to account for variability in the amount of mercury that may bioaccumulate within a fish. This potential difference of 5 to 10 percent between measured total mercury and methylmercury is rarely an issue except in a few cases where the concentration of total mercury in fish sample is just above 0.5 ppm. In such borderline cases, VDH may postpone issuing a fish consumption advisory until additional monitoring is conducted to better confirm whether the average concentrations of methylmercury in the affected species of fish are above the level of concern.

Summary of Calculation of Waterbody Specific Mercury Reduction Factors Used to Estimate Changes in Future Fish Contamination

One of the important issues investigated in this report is the potential for reductions in mercury concentrations in fish after the projected reductions in mercury deposited by air into the watershed has occurred. In order to do this, estimates were needed of the reductions in air-deposited mercury that were projected by the air-mercury deposition model for the watersheds of the mercury sensitive waterbodies. The ICF model produced estimates of mercury deposition rates for the base year as well as projected estimates of deposition rates for 2010, 2015 and 2018. These estimates of past and future mercury deposition rates were used to predict the proportional reductions of inputs of mercury into the watersheds of the mercury sensitive waterbodies in Virginia after the years 2010 and 2018.

These estimated reductions in deposited mercury were used to estimate the proportional amount of reduction in mercury in fish that might be expected after the reductions in air deposition had taken effect. These reductions in air deposition rates were averaged across the watershed of each affected waterbody to produce a "reduction factor" that could be used to estimate potential future fish mercury levels in that waterbody. It was assumed that a reduction in mercury deposited into the watershed would result in an equal amount of reduction in fish tissue mercury.

Details of Method of Calculation of Reduction Factors

The ICF deposition model projected mercury deposition rates after the projected reductions in air deposition into the watershed will have occurred. The ICF deposition model produced estimated mercury-air deposition rates for the entire state of Virginia and surrounding areas for the base year and projected mercury deposition rates for the years 2010, 2015 and 2018. These mercury deposition rates were estimated for wet deposition (deposited in rainfall), dry deposition (particulate) and total mercury deposition rates. These estimates were supplied for cells overlaid on a map of Virginia and the surrounding states. The square cells are 12 kilometers (7.4564 miles) on each side, and cover 144 square kilometers, or about 55.6 square miles. The model predicted a total mercury deposition rate for the base year for individual cells which was considered to be representative of the atmospheric deposition rate that contributed to the mercury fish tissue concentrations detected in DEQ's fish monitoring program between the years 2002 and 2006, which is the period during which DEQ expanded fish monitoring to more extensively sample swamp waters unrelated to known potential human impacts.

The rate of total mercury deposition predicted for 2010 by the model for a cell was divided by the deposition rate in the base year to get an estimate of the relative proportion of the 2002 mercury deposition that would remain in 2010. For example, if the total mercury deposition rate in 2002 was estimated by the model to be 20 micrograms per square meter (ug/m^2), and the model's estimate for 2010 was 16 ug/m^2, then the total mercury projected to be deposited in that cell in 2010 is 16/20 = 0.80. That is, 80 percent of the mercury that was estimated by the model to have been deposited in the base year of 2002 is expected to be deposited into that cell in 2010, representing a 20 percent decrease in mercury input to that cell.

This example calculation produces a "reduction factor" of 0.80 that, when multiplied by the average concentration of mercury of a species of fish collected in the past from that waterbody, can be used to estimate the potential fish mercury concentrations in the future after the ecosystem responded to the reduced mercury deposition rates predicted by the model for 2010. The same calculations were performed for the projected 2018 reductions in total mercury deposition rates. In general, the major projected reductions in mercury deposition rates were predicted by the model for 2010, with an additional reduction of only one to three percent by 2018. The projected reductions for 2015 were intermediate between the estimates for 2010 and 2018, but were not calculated in every case because they were within approximately one percent of the 2018 model predictions. The reduction factors calculated for 2010 and 2018 were used to assess potential, future fish mercury concentrations in the mercury-sensitive waters where fish consumption advisories are currently in effect in Virginia. These predictions were made using the results of ICF's deposition modeling which provided the mercury deposition to occur as a result of emission reductions required by CAIR and CAMR.

Comparisons were made between the ICF model's estimates of total mercury deposition rates for the base year of 2002 and for future deposition rates for 2010 and 2018 for each model cell that overlaid the Virginia river basins that are considered to be mercury-sensitive due to environmental conditions and where a current fish consumption advisory exists due to elevated levels of mercury in fish. These are the Dragon Run Swamp, Mattaponi River, Herring Creek, Pamunkey River, Chickahominy Lake, Blackwater River, Nottoway River, Meherrin River, and

the Dismal Swamp Canal and Lake Drummond, the Kerr Reservoir, Lake Gordonsville, Harrison Lake, Motts Run Reservoir and Chandler's Mill Pond. All of these waterbodies are thought to be mercury-sensitive because they are either isolated lakes or are river systems that are significantly influenced by connected swamps or wetlands, and they generally do not have any significant sources of human discharges into the waterbody that are a likely source of mercury. A few other rivers or lakes also have fish with levels above 0.30 or 0.50 ppm mercury, but these have significant human activity within their watersheds which could provide other sources of mercury, and these waterbodies are not connected to wetlands or other zones of increased mercury methylation.

For each cell that overlaid these waterbodies, proportional estimated reductions in total mercury deposition rates were calculated for 2010 and 2018 as described above. Because the model's predictions of deposition rates are not considered to be exactly delineated along the borders of the 12 kilometer squares, the cells surrounding the actual cells overlaying the river basins were also reviewed to determine if any of these border cells showed significantly different deposition rates. This was done to evaluate if a nearby area with predicted higher mercury deposition was in close enough proximity to the river basin to possibly influence the river's drainage area. If any of these border cells showed a difference in total mercury deposition rates of greater than 10 percent compared to the cells actually overlaying the waters in the river basin, projected proportional reductions were calculated for the border cells as well as the cells actually overlaying the river system and average reduction rates were calculated including the border cells' data.

These potential areas of higher mercury deposition were evaluated separately to see if this could be a potential for significant, different estimates of effects on future changes in fish mercury contamination levels. In general, none of these potential areas of higher mercury deposition showed a difference in mercury deposition reduction factors of greater than 10 percent of the average reduction factor for the entire river basin's watershed. One of the greatest differences was at the headwaters of the Blackwater River, with a reduction factor of 0.7492 for the three headwater streams compared to the average of 0.8296 (a relative difference of 9.7 percent) for the rest of the Blackwater watershed. The other greatest difference in deposition rates occurred at the Virginia border with North Carolina at the confluence of the Blackwater River and the Nottoway River, where the overall average reduction factor for the Blackwater River basin was 0.8296 and the reduction factor for the downstream border cells in North Carolina was 0.6745, for a relative difference of 19 percent.

In most cases, the proportional reduction factors for the cells along a river system were fairly uniform in value, generally differing by only a few percentage points, and an average reduction rate was calculated for the entire river basin. These reduction factors were used to estimate the potential for changes in fish mercury concentrations by multiplying the average mercury concentration in a species of fish from that river by the projected reductions in mercury deposition for the river basin for both 2010 and 2018.

The modeled reductions in total mercury deposited into the individual rivers' watersheds were used to calculate the relative amount of mercury deposition that was projected to continue to occur in future years in comparison with the baseline mercury deposition rates estimated for the

base year. The modeled deposition rates for the base year are considered representative of the conditions that were responsible for the fish mercury concentrations that were detected during the DEQ fish monitoring between 1998-2006. This information was used to calculate a "reduction factor" for future years representing the remaining air-deposited mercury compared to the rates of deposition in the base year. For example, the air model predicted that after the 2010 anticipated emissions reductions had taken effect, the average air deposition rate of total mercury onto the watershed of the Dragon Run Swamp would be 82.01 percent of the mercury deposition rate in the base year. This represents an estimated 17.9 percent reduction in the air deposition rate for total mercury after 2010, compared to the deposition rate of the base year. This produces a "reduction factor" of 0.8201 estimated for this watershed based on projected 2010 deposition levels. The reduction factor for the river basin can be used to estimate future fish mercury concentrations levels in response to reduced mercury deposition.

It was assumed by DEQ that the fish mercury concentrations in an ecosystem are in dynamic equilibrium with mercury inputs to that watershed and that a reduction in mercury deposition will result in a proportional reduction in fish mercury concentrations after the ecosystem re-equilibrates to the lowered inputs of mercury. Under this scenario, the reduction factor for the watershed can be multiplied times the fish mercury concentrations observed in previous monitoring (which are assumed to be a result of deposition rates represented by the base year) to estimate future mercury fish concentrations after the projected reductions in mercury deposition rates have occurred. For example, if previous samples of largemouth bass from the Dragon Run Swamp contained an average concentration of mercury of 1.0 ppm, then after the projected 2010 reductions in air deposition rates take effect, future concentrations in this species may be estimated to average 1.0 ppm mercury x 0.8201 (the river-specific reduction factor based on 2010 estimated remaining mercury deposition) = 0.8201 ppm mercury.

The reduction factors represent the proportional amount of mercury deposition to the watershed based on the estimated deposition rates for the base year that the model estimated will continue to occur after the 2010 and 2018 anticipated reductions have taken effect in mercury-air deposition for the modeled years 2010 and 2018. The reduction factors generally decrease slightly numerically between 2010 and 2018, which reflects slight additional reductions in the air deposition rates. For comparison purposes, a lower value of a reduction factor indicates that a greater amount of mercury from air deposition is expected to occur in the watershed, i.e., a greater percent reduction was estimated by the model.

The average projected reduction factors in total mercury air deposition estimated for 2010 and 2018 for the mercury-sensitive river basins important to this fish consumption and risk assessment study are shown in Table 5-1.

Table 5-1 Mercury Deposition Reduction Factors for Advisory Waterbodies(compared to base year)

		2010	2018
		Reduction Factor	**Reduction Factor**
River Basin		**Year 2010**	**Year 2018**
Dragon Run Swamp		0.8201	0.7972
Mattaponi River		0.8120	0.7853
Herring Creek		0.8120	0.7972
Pamunkey River		0.8063	0.7830
Chickahominy Lake		0.8096	0.7885
Harrison Lake		0.7647	0.7635
Blackwater River		0.8296	0.8145
Nottoway River		0.8332	0.8079
Dismal Swamp Area		0.7808	0.7711
(potential alternate for canal)			0.7332 (see text)
Kerr Reservoir (Roanoke River)		0.8110	0.7765
Chandler's Mill Pond		0.7215	0.6995
Motts Run Reservoir		0.7910	0.7700
Lake Gordonsville		0.8433	0.8289

The ICF air deposition model's projected future changes in mercury deposition rates were used to estimate the potential for changes in fish concentrations of mercury in response to the projected reductions in mercury input into the ecosystem via reduced air emissions and corresponding reductions in air deposition of mercury into the watersheds.

Assumptions Used in Analysis

It was assumed that, given a reduction in mercury deposition into the waterbody system, there would be a corresponding and proportional reduction in mercury in the ecosystem available to be methylated and taken up into the food chain. It was assumed that there would be a one-to-one relationship between reduced mercury deposition and the resulting fish concentrations in that

waterbody; that is, if the amount of mercury deposited into the ecosystem is reduced by 20 percent, a potential reduction of 20 percent in the concentration of mercury in the local fish tissue would result. This assumes that, once there is a reduction in mercury input, the ecosystem will have less mercury to process by methylation in the sediment into methylmercury, and less uptake of methylmercury into the food chain and magnification of the mercury concentrations in fish tissue as it moves up the food chain. All these processes within an ecosystem are assumed to be in balance and, if the initial key amount of mercury is reduced, then correspondingly lower concentration in fish tissue will eventually result.

As discussed previously, available evidence from a variety of sources suggests that this is a reasonable assumption, after the ecosystem processes this mercury and the methylation process and food-chain uptake occurs. The time frame necessary for the ecosystem to readjust to the reduced mercury inputs and come to equilibrium, however, will be site-specific and each waterbody is likely to react somewhat differently. It is unknown what time frame may be necessary for the ecosystem to adjust to the reduced mercury available and when the fish tissue concentrations of mercury may be lowered to correspond to the reduced mercury inputs. The process may vary from a few years to several decades or longer.

Summary of Estimated Changes in Fish Mercury Concentrations in Response to Decreased Mercury Deposition Rates in 2010 and 2018

The reduction factors described in the previous section were used to predict the potential for reduced fish mercury concentrations in the future. These estimates of future fish mercury concentrations are based on the estimates of reduced air-mercury deposition rates predicted for 2010 and 2018. After these projected future reductions in mercury depositions have been achieved, the ecosystems are expected to equilibrate to the lowered inputs of mercury and this is expected to result in a proportional lowering of fish mercury concentrations in the future.

The timeframe for the ecosystem to adjust to the lowered mercury levels and for the fish to reach the predicted lower mercury concentrations will depend on how quickly the specific waterbody will equilibrate to the new, lower mercury levels. This will probably be on the order of a few years to decades, with lakes responding more quickly and wetlands requiring some additional time. The fish already contaminated will continue to show mercury levels due to earlier mercury deposition levels until they die. Many of these fish species may live five or more years, so significant changes in adult fish in these waterbodies may not be detectable for at least that time period. Changes in fish mercury contamination levels might be more readily detected in younger fish at one to two years of age, after the predicted changes in mercury deposition have had a chance to occur.

Use of Reduction Factors to Estimate Future Fish Mercury Concentrations

The DEQ data set of fish tissue mercury concentrations reported for fish from selected waterbodies was reviewed to determine if the reductions in mercury deposition projected for 2010 and 2018 by the air deposition model could be expected to result in reduced fish tissue

concentrations in these waterbodies and especially to evaluate whether these reductions might result in a relaxation or removal of the fish consumption advisories.

Two "screening values" of mercury concentration in fish tissue were evaluated. The level of concern used by the VDH to issue a fish consumption advisory is 0.50 ppm. The data were examined to evaluate whether or not the levels of mercury could be expected to decrease to a level below this 0.50 ppm level, and the possibility of relaxing or lifting the current fish consumption advisories. The data were also examined using 0.30 ppm as a criterion. This is the fish methylmercury criterion recommended by the EPA, and this has been proposed for adoption in Virginia during the current triennial review of water quality criteria.

The historical fish mercury concentration data were collected for all the fish collected by DEQ's fish monitoring program between 2002 and 2006, which is the period of time when DEQ expanded the monitoring of fish into these swamp waters. The data were separated for each waterbody affected by current mercury-caused fish consumption advisories and the average concentration of mercury was calculated for each fish species collected in the waterbody. These average mercury concentrations were compared to the 0.50 advisory thresholds and to the potential future 0.30 ppm water quality criterion. The results of the analysis are presented below for the mercury-sensitive waters listed in Table 5-2.

Summary of Predictions of Changes in Fish Contamination Levels

As of 2007, there are thirteen waterbodies with fish consumption advisories that are considered mercury-sensitive waters and which have very little direct human impact attributable to the mercury-related fish consumption advisories. The estimates for reduced deposition rates of mercury after 2010 and potential effects on future fish contamination levels suggest that there is a possibility that three to four of the thirteen fish consumption advisories might become unnecessary and at least one fish species might be removed from the advisories in all but two of the advisory waterbodies.

A summary of the important findings of this analysis of the potential for reduced levels of mercury fish contamination following reduced rates of mercury-air deposition rates includes:

- Most of the expected reductions in mercury deposition will occur due to the emissions reductions projected for 2010. The additional reductions projected for 2018 are only an additional one to three percent.

- Estimated reductions in mercury deposited into the affected waterbodies and consequently into fish tissue vary from about 17 to 30 percent.

- Applying the reductions in air deposited mercury projected for 2010 and 2018 to the average fish mercury concentrations in the fish consumption areas, there is a possibility of the affected fish species' containing less than the concentration of mercury necessary to issue a fish consumption advisory. It was estimated that the average mercury concentration in the affected fish species could drop below the VDH trigger value (0.50

ppm) for issuing a fish consumption advisory for all species of fish included in the advisory in 3 of the 13 advisory waterbodies, and that this is a borderline possibility in one other waterbody. If this were to be the case, the current advisories may be removed from these three or four waterbodies. In addition, the Dismal Swamp Canal and Lake Drummond may be affected such that one of the two contaminated fish species can be removed from the advisory and the advisory area may also be reduced in size.

- In 11 of the 13 advisory waterbodies, at least one species of fish was estimated to have a potential for containing mercury concentrations less than 0.50 ppm in the future, after the 2010 reductions take effect. If this were to prove true, then these fish species may be removed from the advisories in the future.

- Almost all fish species currently included in the various fish consumption advisories will remain above the Proposed Virginia Fish Tissue Criterion of 0.30 ppm, with only one exception in one waterbody.

- The time frame necessary for the waterbodies' ecosystems to respond to the reduced mercury inputs and the resulting expected reduction in fish tissue mercury concentrations will vary for each waterbody. Reservoirs and lakes will likely respond within a few years to decades, while wetlands will likely respond more slowly, but possibly within years to decades, or longer.

This analysis suggests that, after the expected controls on mercury air emissions required by CAIR and CAMR projected for 2010 and 2018 have taken effect and the ecosystems respond to the reduced mercury deposited into them as a result, several fish consumption advisories will still be considered warranted.

The results of the assessment for potential changes to existing fish consumption advisories for these waterbodies due to the effects of the estimated lower mercury deposition rates are summarized in Table 5-2.

Table 5-2. Potential for Future Changes in Fish Consumption Advisories

Waterbody	# Fish Species Affected by Advisory	# Fish Species < 0.30 ppm	# Fish Species < 0.50 ppm	Potential for Removal of Species	Potential for Removal of Advisory
Dragon Run Swamp	**1**	**None**	**1**	**Yes**	**Yes**
Mattaponi River	**1**	**None**	**None**	**No**	**No**
Herring Creek	**2**	**None**	**1 of 2**	**Yes**	**No**
Pamunkey River	**1**	**None**	**None**	**No**	**No**
Chickahominy Lake	**3**	**None**	**1 of 3**	**Yes**	**No**
Harrison Lake	**4**	**None**	**2 of 4**	**Yes**	**No**
Blackwater River	**7**	**None**	**3 of 7**	**Yes**	**No**
Nottoway River	**8**	**None**	**4 of 8**	**Yes**	**No**
Dismal Swamp Canal **& Lake Drummond**	**2** **2**	**1 of 2** **1 of 2**	**2 of 2** **1 of 2**	**Yes** **Yes**	**Possible reduced advisory area (see text)**
Kerr Reservoir	**2**	**None**	**1 of 2**	**Yes**	**No**
Chandler's Mill Pond	**1**	**None**	**1 of 1**	**Yes**	**Yes**
Motts Run Reservoir	**1**	**None**	**1 of 1**	**Yes**	**Yes**
Lake Gordonsville	**1**	**None**	**1 possible**	**Yes**	**Possible (see text)**

Details of Estimated Changes in Fish Mercury Levels in Individual Waterbodies

The following section provides the details of the review of each of the fish consumption advisory waters in mercury-sensitive waters.

Dragon Run Swamp

The current fish consumption advisory for the Dragon Run Swamp applies to largemouth bass only. Mercury deposition rates for the watershed of the Dragon Run Swamp were similar in all cells along its length, with projected reduction factors varying by less than 5 percent. The average projected reduction factor estimated for 2010 was 0.8201. That is, 82.01 percent of the mercury estimated to have been deposited in 2002 was estimated to be still deposited in 2010. This is the same as an estimated reduction of 17.99 percent. The projected reduction factor for 2018 is 0.7972.

These reduction factors for 2010 and 2018 were multiplied by the average mercury concentrations for largemouth bass collected from the Dragon Run Swamp and contained in the DEQ's fish contamination data set. The results are shown in the table below:

Dragon Run Swamp	Average Fish Concentration of Mercury	Projected Mercury Fish concentration	Projected Mercury Fish concentration
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.49	0.4018 ppm	0.3906

These estimated concentrations are below the 0.50 ppm trigger value used by the VDH to issue fish consumption advisories. If future monitoring of largemouth bass from the Dragon Run Swamp show mercury levels this low, the removal of the current fish consumption advisory for this waterbody could result. However, these estimated mercury concentrations are still above the fish tissue target value of 0.30 ppm that is recommended by EPA and which DEQ has proposed for adoption in 2008 as a fish tissue quality criterion, as part of Virginia's water quality standards regulation.

Mattaponi River

The current fish consumption advisory for the Mattaponi River applies to largemouth bass. Mercury deposition rates for the watershed were similar in all cells along its length, with projected reduction factors among the cells varying by less than 5 percent. The average projected reduction factor estimated for 2010 was 0.8120, and the projected reduction factor for 2018 is 0.7853.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species, estimated mercury concentrations in largemouth bass from the Mattaponi River are estimated as shown below.

Mattaponi River	Average Fish Concentration of Mercury	Projected Mercury Fish concentration	Projected Mercury Fish concentration
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.856	0.6953 ppm	0.6722 ppm

Under this scenario, the estimated reductions in mercury deposition in the Mattaponi River basin are not expected to result in sufficiently reduced contamination in the largemouth bass to allow for a removal of the current fish consumption advisory.

Herring Creek (tributary to the Mattaponi River)

The current fish consumption advisory for Herring Creek applies to bluegill sunfish and yellow bullhead catfish. Projected total mercury deposition rates for the watershed were similar in all cells along its length, with projected reduction factors varying by less than five percent. The average projected reduction factor estimated for 2010 was 0.8120, and the projected reduction factor for 2018 is 0.7972

Applying these reduction factors to the average concentrations of mercury found in the affected fish species, the projected future mercury concentrations in bluegill sunfish and the yellow bullhead catfish are shown below:

Herring Creek	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep. Reductions**	**After 2018 Air-Dep. Reductions**
Bluegill Sunfish	0.591 ppm	0.4798 ppm	0.4711 ppm
Yellow Bullhead Catfish	1.017 ppm	0.8255 ppm	0.8108 ppm

These estimates for the sunfish are below the VDH fish consumption advisory trigger value and could result in a relaxation of the current advisory by removing bluegill sunfish from the consumption advisory. The estimated future concentration in the catfish species, however, is still above the trigger value for a fish advisory, so it is probable that this catfish species will continue to warrant the advisory. Also, both species are projected to remain contaminated at levels greater than the proposed Virginia fish tissue criterion of 0.30 ppm.

Pamunkey River

The current fish consumption advisory for the Pamunkey River applies to blue catfish. Mercury deposition rates for the watershed of the Pamunkey River were similar in all cells along its length, with projected reduction factors among the cells varying by less than 5 percent. The average projected reduction factor estimated for 2010 was 0.8063, and the projected reduction factor for 2018 is 0.7830.

These reduction factors for 2010 and 2018 were multiplied by the average mercury concentration for blue catfish collected from the Pamunkey River, and the resulting projected concentrations are shown below.

Pamunkey River	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Blue Catfish	0.730	0.5886 ppm	0.5716 ppm

These estimated future mercury concentrations in blue catfish remain above the 0.50 ppm trigger value used by VDH to issue fish consumption advisories. Under this scenario, the estimated reductions in mercury deposition in the Pamunkey River basin are not expected to result in sufficiently reduced contamination in the blue catfish to allow for a removal of the current fish consumption advisory.

Chickahominy Lake

The current fish consumption advisory for the Chickahominy Lake applies to largemouth bass, chain pickerel and bowfin. Mercury deposition rates for the watershed of the Chickahominy Lake were similar in all cells along its length, with projected reduction factors among the cells varying by less than 5 percent. The average projected reduction factor estimated for 2010 was 0.8096, and the projected reduction factor for 2018 is 0.7885.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from the Chickahominy Lake, estimated mercury concentrations are estimated as shown below.

Chickahominy Lake:	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.67	0.5424	0.5283
Chain Pickerel	0.63	0.51	0.4968
Bowfin	1.15	0.931	0.9066

Under this scenario, the estimated reductions in mercury deposition in the Chickahominy Lake basin are not expected to result in sufficiently reduced contamination in the bowfin to allow for a removal of the current fish consumption advisory. However, the projected reduced concentrations in the largemouth bass and chain pickerel are less than 10 percent above the fish consumption trigger value, so there appears to be some potential for possible changes for these species.

Harrison Lake

The current fish consumption advisory for Harrison Lake (Charles City County) applies to redear sunfish, largemouth bass, chain pickerel and bowfin. Mercury deposition rates for the watershed of Harrison Lake produced a projected reduction factor estimated for 2010 of 0.7647, and the projected reduction factor for 2018 is 0.7635.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from the Harrison Lake, estimated mercury concentrations are shown below.

Harrison Lake	**Average Fish Concentration of Mercury (ppm)**	**Projected Fish Mercury (ppm) Concentration**	**Projected Mercury (ppm) Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Redear Sunfish	0.53	0.4053	0.4047
Largemouth Bass	0.93	0.7112	0.7101
Chain Pickerel	0.61	0.4665	0.4657
Bowfin	1.02	0.78	0.7788

Under this situation, the estimated reductions in mercury deposition in the Harrison Lake basin could be expected to result in sufficiently reduced contamination in the redear sunfish and chain pickerel to potentially allow for a removal of these two fish species from the current fish consumption advisory. However, the projected reduced concentrations in the largemouth bass and bowfin remain above the fish consumption trigger value, so these two species are predicted to continue to warrant a fish consumption advisory, and all four species are predicted to remain above the 0.30 ppm proposed fish tissue criterion.

Blackwater River System

The current fish consumption advisory for the Blackwater River applies to largemouth bass, redear sunfish, bowfin, chain pickerel, white catfish, redhorse sucker and longnose gar.

Mercury deposition rates for the watershed of the Blackwater River were similar in most cells along its length, with projected reduction factors among the cells varying by less than 5 percent with the following exceptions. There is a modeled zone of slightly elevated mercury deposition for 2002 baseline deposition rates in a few cells that overlay or surround the headwaters of the Blackwater River system, just to the east and south of Petersburg. The cells surrounding the headwaters of the Blackwater River in this area show modeled elevated total mercury deposition rates for the baseline year of between 26.057 and 52.81ug/square meter (mean of 33.05), which are slightly higher than the average deposition rates that are estimated for cells along the main portion of the Blackwater River, which range from 24.427 to 19.48 with a mean of 22.029 ug/square meter. There is also another zone of slightly elevated mercury deposition that coincides with the mouth of the Blackwater River. The reductions in deposition rates for 2010 and 2018 estimated by the model for this local area of elevated baseline deposition rates consequently results in calculating a lower reduction factor for the area of the small headwaters; that is, the model predicts a greater percent reduction in mercury deposited into this headwater area in comparison with the majority of the watershed. This small area of elevated total mercury was assessed and a localized reduction factor of 0.7492 was calculated for the uppermost headwaters of the Blackwater River system. However, this was not assessed separately from the

rest of the Blackwater River system because the potential area of local influence on these small headwater streams is very small compared to the rest of the Blackwater River watershed, which was relatively homogeneous in modeled deposition rates. Calculated reduction factors for the other cells that overlay the Blackwater River are also homogeneous and range between 0.8108 and 0.8407 (based on 2010), with a mean of 0.8296, which was used to assess the Blackwater River system in its entirety. If this local area at the headwaters with estimated elevated baseline deposition rates and the subsequent lower reduction factor is considered to potentially affect the entire Blackwater River system (approximately 100 miles in length), it could have a potential effect of approximately an additional 1 to 2 percent reduction at most in fish tissue mercury in the future. This would not significantly change the conclusions reached by the analysis shown below, which are based on the assumption that this small, local area would not influence the entire Blackwater River system.

Using the deposition rates for the cells that directly overlaid the watershed for the Blackwater River system, the average projected reduction factor estimated for 2010 was 0.8296, and the projected reduction factor for 2018 is 0.8145. Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from the Blackwater River, estimated mercury concentrations are estimated as shown below.

Blackwater River and Tributaries	**Average Mercury Concentration in Affected Species**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.676 ppm	0.561 ppm	0.5506 ppm
Redear Sunfish	0.524 ppm	0.4347 ppm	0.4268 ppm
Bowfin	1.090 ppm	0.904 ppm	0.8878 ppm
Chain Pickerel	0.510 ppm	0.4129 ppm	0.4154 ppm
White Catfish	0.651 ppm	0.540 ppm	0.5302 ppm
Redhorse Sucker	0.579 ppm	0.4688 ppm	0.4716 ppm
Longnose Gar	0.705 ppm	0.585 ppm	0.5742 ppm

Based on this analysis, the estimated reductions in mercury deposition in the Blackwater River basin are not expected to result in sufficiently reduced contamination in the various species of fish to allow for the removal of the current fish consumption advisory. This analysis does suggest that the mercury contamination levels in redear sunfish, chain pickerel and sucker species could be expected to diminish over time, possibly to levels lower than the trigger value for fish consumption advisories. This presents the possibility that these species might be removed from the current advisory in the future. However, bass, bowfin, white catfish and gar are expected to remain at mercury levels where a fish consumption advisory is warranted. Also, all of the estimated fish mercury concentrations are projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion.

Nottoway River

The current fish consumption advisory for the Nottoway River applies to largemouth bass, smallmouth bass, sunfish species, bowfin, chain pickerel, channel catfish, redhorse sucker species and longnose gar.

Mercury deposition rates and projected reduction factors among the cells for the watershed of the Nottoway River were similar in most cells along its length; however, similar to the Blackwater, the Nottoway River is intersected with an area of slightly elevated mercury deposition rates at the conjunction of the Nottoway River with the Blackwater River, at the North Carolina border.

Using the deposition rates for the cells that directly overlaid the watershed for the Nottoway River system the average projected reduction factor estimated for 2010 was 0.8332, and the projected reduction factor for 2018 is 0.8079.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from the Nottoway River, estimated mercury concentrations are shown below.

Nottoway River	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.724	0.6093	0.5849
Smallmouth Bass	0.579	0.4824	0.4678
Sunfish species	0.503	0.4191	0.4059
Channel Catfish	0.572	0.4766	0.4621
Bowfin	0.946	0.7882	0.7575
Chain Pickerel	0.920	0.7665	0.7433
Longnose Gar	0.888	0.7399	0.7174
Redhorse Sucker species	0.545	0.4541	0.4403

Based on this analysis, the estimated reductions in mercury deposition in the Nottoway River basin are not expected to result in sufficiently reduced contamination in the various species of fish to allow for the removal of the current fish consumption advisory. This analysis does suggest that the mercury contamination levels in sunfish, smallmouth bass, channel catfish and sucker species could be expected to diminish over time, possibly to levels lower than the trigger value for fish consumption advisories. This presents the possibility that these species might be removed from the current advisory in the future. However, largemouth bass, bowfin, chain pickerel, and longnose gar are expected to remain at mercury levels where a fish consumption advisory is warranted. Also, all of the estimated fish mercury concentrations are projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion.

Dismal Swamp Canal and Lake Drummond

The current fish consumption advisory for the Dismal Swamp Canal and Lake Drummond applies to bowfin and chain pickerel.

Mercury deposition rates for the watershed of the Dismal Swamp were similar in most cells overlaying the swamp area and the length of the Dismal Swamp Canal. Using the deposition rates for only the cells that directly overlaid the watershed for the Dismal Swamp Canal system, the average projected reduction factor estimated for 2010 was 0.7808, and the projected reduction factor for 2018 is 0.7711. However, there are areas at the north end of the canal near Portsmouth, and also at the south end along the North Carolina border that the air-deposition model projected as areas of slightly elevated mercury deposition rates for the base year of 2002. These higher deposition rates for 2002 in these areas, combined with the projected reductions in future mercury deposition rates for 2010 and 2018, suggest that a relatively greater reduction in total mercury deposited into these areas could occur and result in slightly greater reductions in fish concentrations in these areas. These areas are within the drainage area of the canal and could influence the amount of mercury in the canal system and available to bioaccumulate in the fish. If the changes in deposition along the canal were averaged to include these neighboring cells (the areas with estimated greater mercury deposition rates for 2002), the projected reduction factors for future years would be lower, and the potential for reduced mercury loads in the fish could be greater in this area. To evaluate this possibility, a third reduction factor was calculated using the 2018 estimated reductions in air deposition rates of mercury by averaging the mercury depositions predicted along the length of the canal as well as the neighboring cells at both ends of the canal, where higher mercury base year deposition rates were indicated by the model. This third reduction factor was calculated to be 0.7332 for 2018 (compared to 0.7711 without including neighboring cells); would represent a more optimistic estimate of the amount of reduced mercury deposition in the watershed of the Dismal Swamp Canal; and, subsequently, could result in greater reductions in fish mercury concentrations.

Applying these three different reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from the Dismal Swamp Canal and Lake Drummond, estimated mercury concentrations are shown below.

Dismal Swamp Canal & Lake Drummond	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration (reduction factor 0.7808)**	**Projected Mercury Fish concentration (reduction factor 0.7711)**	**Most Optimistic Estimated Reduction Factor (0.7332)**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Bowfin (Canal)	0.49	0.38	0.38	0.36
Bowfin (Lake)	0.97	0.75	0.74	0.71
Chain Pickerel	0.32	0.25	0.25	0.23

Lake Drummond is connected to the Great Dismal Swamp Canal system by a dam which separates the fish populations. Available data indicate average concentrations of mercury detected in chain pickerel collected in the Canal, the Lake and other areas of the Dismal Swamp National Wildlife Refuge had the same average mercury concentration, so this fish species was assessed for all areas. The data indicated that the bowfin collected from Lake Drummond contain higher average concentrations of mercury than the bowfin in the Canal. Hence, the bowfin collected from the Lake and the Canal were assessed separately. Based on this analysis, the estimated reductions in mercury deposition in the Dismal Swamp Canal and Lake Drummond are not expected to result in sufficiently reduced mercury contaminations in bowfin in Lake Drummond to allow for the removal of the current fish consumption advisory for the Lake, even under the most optimistic levels of reductions in air deposition of mercury.

This analysis does suggest, however, that after projected reductions in mercury deposition rates occur, the mercury contamination levels in bowfin from the Great Dismal Swamp Canal and in chain pickerel throughout the lake, swamp and canal system could be expected to diminish over time to levels lower than the trigger value for fish consumption advisories. This is because the average concentrations of mercury in these two fish species were on the borderline with consumption advisory thresholds to begin with. In fact, by including the most recent mercury monitoring data, the average mercury concentration for the chain pickerel is now below the advisory threshold. This presents the possibility that these species might be removed from the current advisory in the future, at least for the Dismal Swamp Canal. In this case, the Dismal Swamp Canal may no longer meet the criteria for a fish consumption advisory and the Canal may be dropped from the advisory area. However, in Lake Drummond, the bowfin is expected to remain at mercury levels where a fish consumption advisory is warranted. This could result in removing the chain pickerel from the advisory and dropping the Dismal Swamp Canal from the advisory area, retaining only the advisory for the bowfin in Lake Drummond. However, the estimated fish mercury concentrations for bowfin in the Canal are projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion.

Kerr Reservoir, Dan River and Roanoke River

The current fish consumption advisories for the Kerr Reservoir, Dan River and the Roanoke River apply to striped bass and white bass. Both of these fish species spend most of their life in the Kerr Reservoir, but migrate in the spring up the Roanoke River and Dan River to spawn and then return to the reservoir for the rest of the year. It is presumed that these fish species concentrate most of their mercury load during their lengthy time spent in the Kerr Reservoir and were only caught in the Roanoke and Dan Rivers during spring spawning migrations. However, several significant industrial and municipal dischargers exist or have existed along the Roanoke River and Dan River, and these could represent other potential sources of mercury to the Roanoke River or Dan River in addition to air deposition.

Projected total mercury deposition rates for the watershed were similar in all cells along its length, with projected reduction factors among the cells varying by less than five percent. The average projected reduction factor estimated for 2010 was 0.8110, and the projected reduction factor for 2018 is 0.7765.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species, the projected future mercury concentrations in striped bass and white bass are shown below:

Kerr Reservoir (Roanoke and Dan River)	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Stripped Bass	0.7170	0.5815	0.5568
White Bass	0.6040	0.4898	0.4890

This analysis suggests that the mercury contamination levels in white bass in the Kerr Reservoir River basin could be expected to diminish over time, possibly to levels lower than the trigger value for fish consumption advisories. This presents the possibility that the white bass might be removed from the current advisory in the future. This analysis estimated future total mercury concentrations in the striped bass could be only 11 percent and 16 percent above the methylmercury consumption advisory threshold of 0.50 ppm methylmercury. This, along with the assumption that 90 to 95 percent of the total mercury in fish is methylmercury, suggests that striped bass may become close to mercury concentrations levels that are very near the threshold for requiring a fish consumption advisory due to mercury contamination. However, all of the estimated fish mercury concentrations are projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion.

Chandler's Mill Pond

The current fish consumption advisory for Chandler's Mill Pond in Westmoreland County applies only to largemouth bass. Mercury deposition rates for the watershed of Chandler's Mill Pond produced a projected reduction factor estimated for 2010 of 0.7215, and the projected reduction factor for 2018 is 0.6995.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from Chandler's Mill Pond, the estimated mercury concentrations are shown below.

Chandler's Mill Pond	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.591	0.4264	0.4134

This analysis estimated future total mercury concentrations in the largemouth bass from Chandler's Mill Pond could be below the methylmercury consumption advisory threshold of

0.50 ppm, raising the possibility that this advisory could be lifted in the future. However, the estimated fish mercury concentration is still projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion for assessment purposes.

Motts Run Reservoir

The current fish consumption advisory for Motts Run Reservoir applies to largemouth bass only. Mercury deposition rates for the watershed of Motts Run produced a projected reduction factor estimated for 2010 of 0.791, and the projected reduction factor for 2018 is 0.77.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from Motts Run Reservoir, the estimated mercury concentrations are shown below.

Motts Run Reservoir	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.557	0.4406	0.4289

This analysis estimated future total mercury concentrations in the largemouth bass from Motts Run Reservoir could be below the methylmercury consumption advisory threshold of 0.50 ppm, raising the possibility that this advisory could be lifted in the future. However, the estimated fish mercury concentration is still projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion for assessment purposes.

Lake Gordonsville

The current fish consumption advisory for Lake Gordonsville applies to largemouth bass only. Mercury deposition rates for the watershed of Lake Gordonsville produced a projected reduction factor estimated for 2010 of 0.8433, and the projected reduction factor for 2018 is 0.8289.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from Lake Gordonsville, the estimated mercury concentrations are shown below.

Lake Gordonsville	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.609	0.5136	0.5048

This analysis estimated future total mercury concentrations in the largemouth bass could be only 1 to 3 percent above the methylmercury consumption advisory threshold of 0.50 ppm methylmercury. With the assumption that 90 to 95 percent of the total mercury in fish is methylmercury, this suggests that after the predicted future reductions in air deposition of mercury, it is possible that largemouth bass from Lake Gordonsville may become eligible for consideration of a removal of the current fish consumption advisory. However, the estimated fish mercury concentration is still projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion for assessment purposes.

Summary of Overall Conclusions of the Review of Potential for Changes in Fish Mercury-Contaminations in Response to Reduced Mercury Air Deposition in Virginia:

- Based on available information from multiple experiments and field experiences, mercury that is air-deposited into aquatic ecosystems can be expected to contaminate fish.

- Lakes and wetlands are especially sensitive to even small amounts of added mercury because these environments are very efficient in transforming the mercury into a form that is readily accumulated by fish.

- Reduction in mercury inputs into a waterbody is expected to result in lowered concentrations of mercury in the fish after the ecosystem readjusts to the lower mercury levels in the environment.

- It is reasonable to expect a proportional lowering of fish tissue mercury concentrations over time in response to decreases in mercury deposition rates from the air.

- The time frame needed before these lowered fish concentrations could occur depends on how efficiently mercury is processed by the aquatic ecosystem and picked up by the fish.

- Each individual waterbody is expected to react slightly differently due to natural variances in the chemical and physical conditions and differences in food-web structure.

- Lakes are expected to respond quickest (within a few years to decades) to reduced mercury deposition, with wetlands requiring more time to equilibrate to the lowered mercury inputs.

- The projected reductions in mercury-air deposition rates after 2010 and 2018 estimated by the ICF model suggests that fish mercury levels may become lower in the future such that some species may no longer warrant a fish consumption advisory.

- The VDH issues fish consumption advisories when average concentrations of mercury in fish exceed 0.50 ppm.

- The DEQ has recently proposed the adoption of a fish tissue criterion for mercury of 0.30 ppm, which is lower than the current threshold concentration used by the VDH to issue fish consumption advisories. If the State Water Control Board adopts this fish tissue criterion for mercury, in the future DEQ may classify some waterbodies as impaired due to elevated mercury contamination in fish before the VDH would find it necessary to issue a fish consumption advisory.

- Of the 13 mercury-sensitive waterbodies in Virginia with current fish consumption advisories due to mercury contamination in fish, the fish mercury levels may be lowered enough in the future to below 0.5 ppm mercury used by the VDH such that three or four of these advisories may no longer be warranted.

- In all but two of the advisory areas, at least one species of fish may have reduced mercury levels in the future that could allow for its removal from the fish consumption advisory and in one case (Dismal Swamp Canal), the advisory area may be reduced.

- Under the projected reduced air deposition rates for the future, nine to ten of the current fish consumption advisories will likely remain in place for at least one species of fish.

- Average mercury concentrations for at least one species of fish could remain higher than 0.30 ppm, so all of these waterbodies could remain classified as impaired by DEQ.

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Chapter 6- Performance and Cost Assessment of Control Technologies at Coal-Fired Power Plants

Summary

This section of the report reviews the performance of mercury (Hg) control technologies and related costs of mercury reduction levels. Virginia coal-fired power plants vary in the amount and type of mercury control equipment installed. Currently, all Virginia coal-fired power plants burn a low sulfur, low mercury, and high chlorine bituminous coal, and most of the plants also burn coal that has been initially washed and processed after mining. Furthermore, some of the plants have technologies already in place to control nitrogen oxide (NO_x), sulfur dioxide (SO_2), and particulate matter (PM). As a result, a certain level of mercury removal is achieved as a co-benefit of these controls; this report attempts to capture the costs of Hg control (costs of control technologies and also possible costs of control levels).

This report provides an overview of commerically available technologies, their performance and their costs. Moreover, the estimated costs of adopting mercury control technologies are based on assumptions in terms of the data collected for the cost assessment and default performance measures, when actual data was lacking or unavailable due to intellectual property right laws. To overcome such data challenges, the Department of Energy's (DOE) approved simulation tool was used and populated with representative, Virginia-specific coal-fired power plants to assess the current versus future costs of adopting mercury control technologies.

This report provides calculated costs for two scenarios: (1) costs of mercury control technologies, if adopted under a mercury control scenario alone and no other control technologies were utilized and (2) costs of a multi-pollutant (NO_x, SO_2, PM) control system that, as appropriately as possible, captures the "net marginal costs" of mercury control alone, under a co-benefit scenario. For the identified Virginia coal-fired utilities, costs of Hg-specific air pollution control equipment was determined to be in the range of $1.50 - $12.14 per MW-hour. Costs of mercury control as part of a multi-pollutant air pollution control scenario was determined to be approximately $1- $7 per MW-hour.

These findings are within the range of estimates from published scientific and federal agency literature and confirm that mercury control through a multi-pollutant control technology scenario is more cost-efficient and feasible than adding mercury-specific controls only. Detailed review of the estimates also confirmed that older (and/or smaller power generating) power plants are less efficient than the newer and/or larger production capacity facilities. The results confirm economies of size and value of co-benefits.

Introduction

The most common characteristics of coal-fired power plants that influence mercury emissions (and thus performance and costs) are:

1. Mercury content of coal
2. Type of burners on the plant
3. Boiler operating conditions

4. Design and operation of particulate devices, and the design and operation of flue gas cleaners (and resulting energy loss associated with adoption of control technologies for emission controls).

Mercury is present in small quantities in coal, usually between 0.02 to 0.8 ppm, with an average of 0.09 ppm (USGS). Mercury in coal occurs in association with pyrite and other sulfide minerals that can be organically bound. Coal mercury is converted to gaseous Hg in the combustion flame; it becomes partially oxidized as the combustion gases cool (Pavlish, 2003). Mercury oxidation in coal boilers is controlled kinetically, homogeneous oxidation reactions are promoted by chlorine, and heterogeneous oxidation is promoted by fly ash and sorbents. Acid gases will have strong influences on the heterogeneous oxidation of mercury, particularly as it affects capture on sorbents (Pavlish, 2003).

The coal used in Virginia primarily is Appalachian bituminous coal with lower sulfur levels, lower mercury levels and higher chlorine levels. Low sulfur levels result in lower sulfur dioxide (SO_2) emissions. Mercury emissions levels are around 9.01 lbs/trillion BTU. These emissions levels are relatively low when compared to emissions from other coal sources; for example, coal burned in Ohio has levels of 17.1 lbs/trillion BTU. The presence of chlorine allows the mercury to more easily adsorb onto particles when entering the flue gas stream after coal combustion. This aids mercury control because the particles in the flue gas that have adsorbed the mercury (aided by the presence of chlorine) are then captured in the particulate control device.

As a result of the mercury found in coal, coal-fired power plants release mercury into the air. The amount released depends on the size of the plant, but a typical 500-MW coal-fired plant may emit up to 250 pounds per year (Change and Offen). In order to control emissions caused by coal combustion, post-combustion control technologies are commonly used. Examples of such control technologies are fabric filters (baghouses) and electrostatic precipitators (ESP) for particulate removal; wet and dry lime scrubbers for sulfur dioxide (SO_2) removal, which are often also described as flue gas desulfurization (FGD); and selective catalytic reduction (SCR) for the removal of nitrogen oxides (NO_X). A mercury-specific control technology is activated carbon injection (ACI), which is being examined for potential installation at various facilities across Virginia. Activated carbon injection is a form of sorbent injection.

Pre-combustion technology such as coal washing and crushing can remove some mercury from the coal before firing. Oxidation of Hg allows for Hg to be more easily adsorbed onto particles that will be removed from the flue gas stream. Post-combustion controls for particulate removal capture these particles, which have adsorbed the mercury from the flue gas stream. Post combustion NO_x and SO_2 controls also help to oxidize the mercury, making it easier to adsorb downstream. Finally, activated carbon injection is a mercury-specific technology that injects carbon particles into the flue gas stream to help collect mercury. These various controls can have mercury removal rates of 90 percent or greater, depending on the site-specific plant configurations.

Coal fired power plants in Virginia currently have a variety of pollution control devices installed to meet standards for sulfur dioxide (SO_2), nitrogen oxide (NO_x), and particulate matter (PM) emissions. These control devices also contribute to the reduction of mercury emissions as a "co-

benefit." Pollution controls can be either pre-combustion coal treatment processes or post-combustion flue-gas cleaning devices.

The section below describes how control devices used for bituminous coal, including mercury-specific technologies, contribute to mercury removal. Table 6-1 below shows how power plant technologies affect mercury emissions.

Table 6-1 Power Plant Controls Scenarios and mercury emission controls

POWER PLANT CONFIGURATION AND OPERATIONS STRATEGY	EFFECT ON MERCURY EMISSIONS	EFFECT ON MERCURY EMISSIONS
	Primarily Oxidized Mercury	**Primarily Elemental Mercury**
Coal Cleaning	Decreases emissions (highly coal-specific)	Decreases emissions (highly coal-specific)
Electrostatic Precipitator	Some decrease	Some decrease
Fabric Filter	Some decrease	Larger decrease in emissions
Scrubber	Decrease	No effect
Spray Dryer/fabric filter	Some decrease	Limited decrease
ACI	Decrease	Decrease

Pre-Combustion Controls

Pre-combustion controls decrease the amount of mercury in coal before it even enters the boiler. These types of control technologies consist of pre-cleaning the fuel before it enters the combustion chamber. As previously mentioned, typical bituminous coal used in Virginia power plants has about 9.01 lbs/trillion BTU of mercury, which is relatively low in Hg content. Virginia bituminous coals are well-suited to controlling mercury because the high chlorine content promotes mercury oxidation and results in a higher percentage of mercury capture.

Mercury in flue gas has two different forms, oxidized and elemental. The ability of control devices to capture mercury is dependent on the type of mercury that is in the flue gas. Elemental mercury is more difficult to capture than oxidized mercury. Bituminous coals can have approximately 14 percent of their mercury in elemental form (HG0), 52 percent in ionic form (HG2), and the remaining 34 percent is particulate-bound (HGP) (PADEP, 2006). These estimates are highly variable.

Coal cleaning

Performance:

The purpose of coal cleaning is to remove small particles of unwanted elements in the coal. The coal is finely ground until the small particles of unwanted substances can be removed. For high sulfur fuels, the pyritic compounds can be separated from the less dense coal using gravity. Removal of these compounds reduces SO_2 emissions and also has the added benefit of removing the mercury associated with the pyretic compounds (Luttrell, 2000). This process is most effective with high sulfur coal (Luttrell, 2000). The co-benefit of the mercury removal is not

generally included in the removal efficiency for the plant because mercury is removed from the coal prior to its entering the boiler.

Roughly 77 percent of all bituminous coals are washed for removal of pyritic sulfur and ash. Mercury removal for physical washing methods ranges from 0 to 60percent on bituminous coals that are washed (Pavlish, 2003). Advanced cleaning methods and hydrothermal treatment offer a higher percentage of removal but no more than 70 percent (Pavlish, 2003). Froth flotation, selective agglomeration, advanced cyclone design, and several different chemical methods are being researched but are not commercially available yet.

The cost-effectiveness of various types of coal cleaning used on bituminous coals ranges widely. In some cases, additional costs for mercury removal are not incurred since the coal is already washed for sulfur removal. On the other hand, coal cleaning can cost as much as $33,000/lb of mercury removed for washing methods like hydrothermal treatment. Table 6-2 below provides a summary of performance and costs of coal cleaning.

Table 6-2 Performance and cost overview of coal cleaning (Pavlish, 2003)

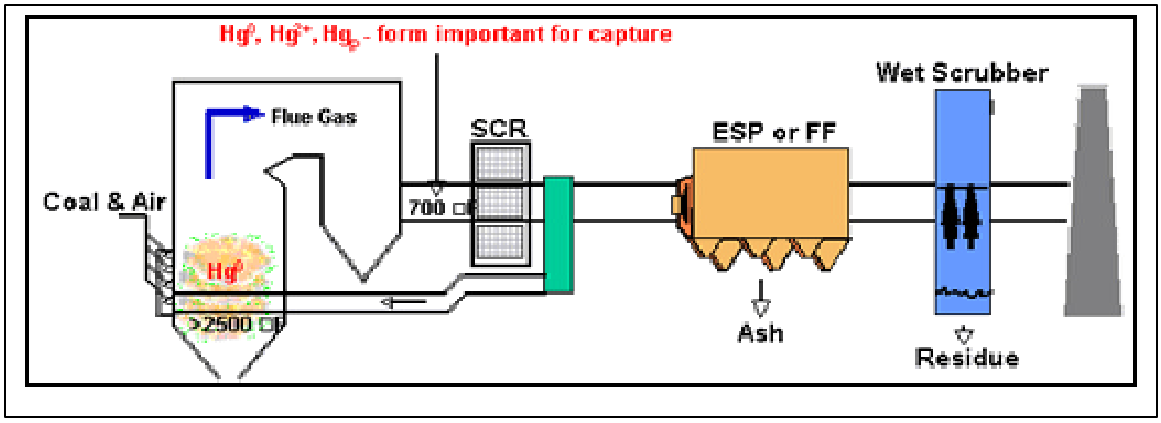
CONTROL TECHNOLOGY OPTION	STATUS	COST	CONTROL POTENTIAL	TECHNICAL IMPLEMENTATION ISSUES
Conventional	Commercial	Low	Low	70% eastern fuels already cleaned
Advanced	Near Commercial	High	Moderate	Not cost-effective
Hydrothermal	Developmental	Moderate	High	Not proven on a commercial level

Post-Combustion Controls

Post-combustion controls occur either within the boiler itself or as the flue gas stream passes from the boiler to the exhaust stack. Post-combustion controls aimed at controlling PM, SO_2 and NO_x also have a co-benefit for Hg control as explained earlier. ACI is a specific mercury control technology and is examined in this cost assessment. The following sections examine these controls, their performance and their costs. Figure 6-1 below shows a control system designed to remove PM, SO_2, and NO_X that also effectively controls mercury emissions. Such a control system can achieve 90 percent or greater mercury reduction.

Figure 6-1 (EPA, 2007).

Particulate Controls

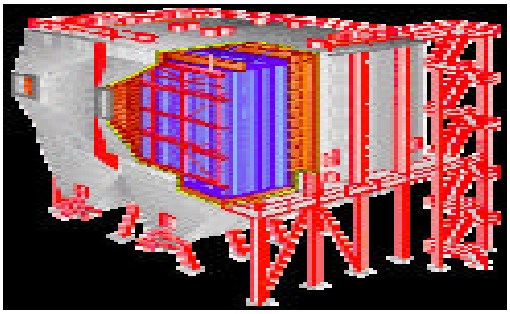


ESP (electrostatic precipitator)

Performance:

Electrostatic precipitators, as shown in Figure 6-2, remove particulate matter from the flue gas stream by charging particles and then collecting them on grounded plates. Electrostatic precipitators can be located either before the preheater at a temperature of 300-450°C (hot-side) or after the preheater at a temperature of 130-180°C (cold-side), with cold-side ESP being the most widely used (Clean Coal Technologies, 2007). U.S. power plants routinely achieve 99 percent or greater particulate removal.

Figure 6-2 (Courtesy of PA DEP)



ESPs aid in mercury capture as a co-benefit technology. In the flue gas, mercury is adsorbed onto the carbon in the fly ash, which is then removed by the ESP. According to Staudt (2003), the amount of mercury adsorbed onto the fly ash is dependent upon:

- the rate of mercury speciation (oxidized mercury adsorbs more readily than elemental mercury),
- the amount of fly ash in the flue gas stream,
- fly ash properties, including carbon content, and
- the temperature of the flue gas in the ESP.

In general, mercury is more easily adsorbed onto the fly ash when temperatures are lower. Mercury becomes gaseous at higher temperatures, and less contact between the mercury and the fly ash is possible in this phase (Air Pollution Prevention and Control Division, 2005). Therefore, cold-side ESPs are much more effective at mercury removal (about 29 percent removal efficiency) than hot-sided ESPs (about 11 percent removal efficiency). Since HG2 adsorbs more easily to carbon in fly ash than does its gaseous form (Staudt, 2003), the high

chlorine content of bituminous coal used in Virginia power plants also increases removal efficiencies. Chlorine acts as an oxidizing agent, increasing the amount of HG2, and therefore more mercury can be adsorbed and removed in particulate control devices.

Depending on the conditions of the flue gas, coal type, and specifications of the ESP, mercury capture for an ESP can range from 0 to 89 percent (Staudt, 2003). Mercury removal rates for Virginia utilities burning bituminous coal equipped with only cold-side ESPs are estimated to be about 29 percent. A case study comparing the costs of ESP's with fabric filters can be found at the end of the section on fabric filters.

Cost:

ESP capital costs range from $30 to $80/kW. A standard installation of an ESP will be at the lower end of this range. Operating costs range from $0.15 to $0.30/kW-hr (MIT, 2007). ESPs are standard on pulverized coal units so that they are usually considered to be part of the base cost.

Fabric Filter (FF)

Performance:

Fabric filters, sometimes known as baghouses, also remove particulate matter. Particles from the flue gas stream are deposited on filters, usually cylindrical fabric bags arranged in rows. Fabric filters can also use cartridges made of cintered metal or porous ceramic. Many rows make up a compartment, and several compartments make up the entire fabric filter system. The bags usually have internal wire mesh frames to keep them from collapsing (EPA, 2007). Fabric filters generally operate between 120-180°C (Clean Coal Technologies, 2007).

Figure 6-3. A fabric filter retrofit at a coal-fired power plant

Fabric filters remove mercury in the same manner as ESPs, by collecting particles onto which the mercury has adsorbed. As with ESPs, the speciation of the mercury in the flue gas stream will affect the collection of mercury by the fabric filter. However, the close contact between the gas and the collected particulate matter in a fabric filter leads to more mercury adsorption and a higher removal efficiency rate when compared to an ESP (Staudt, 2003).

Fabric filters remove about 99 percent of particulate matter from the flue gas stream (Clean Coal Technologies, 2007). They are also estimated to remove up to 90 percent of mercury when burning bituminous coal, as is used in Virginia (Staudt, 2003).

Cost:

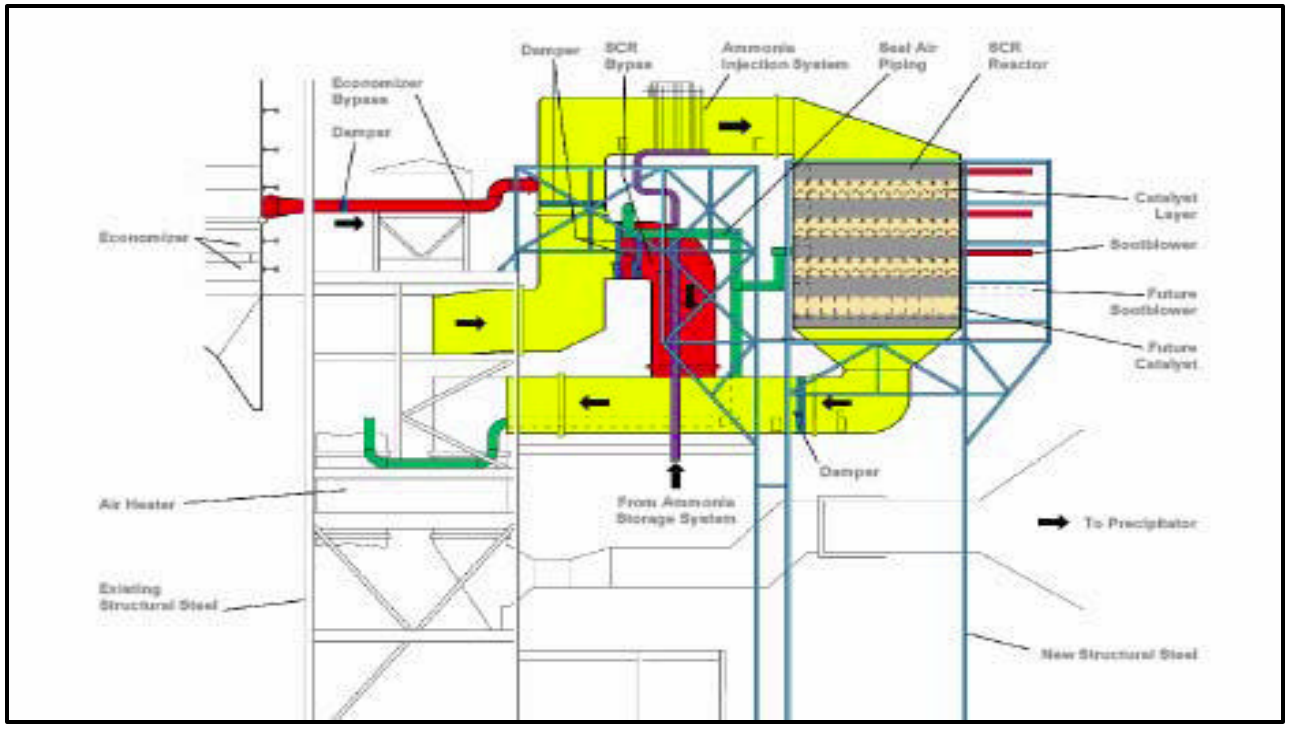
Although ESPs and FFs are both used to control particulate matter, they have different capital, maintenance, and operations costs. A case study from a plant in Southeast Asia has compared both devices in terms of U.S. dollars. The installation costs were found to be quite similar for both devices. However, there were significant differences in costs of operation and maintenance. The cost of bags and fan power consumption significantly increased the costs for FFs. In that case study, the ESP was chosen because the yearly accumulated extra cost for operating and maintaining fabric filters amounted to $16 million after 10 years of operation. Though a FF might be a more attractive option for controlling mercury emissions, it is clear that it can be a more expensive solution. Table 6-3 below shows costs from this case study (McIlvaine Company, Precip Newsletter, 2000).

Table 6-3 Cost Comparison between an ESP and a Fabric Filter

Scope of Activities	ESP	Fabric Filter
Capital Costs, Initial Investment (2000 dollars)		
Import Parts	3,309,000	3,750,000
Local Parts	1,044,000	903,000
Installation Costs	1,133,000	1,044,000
Total U.S. $	5,486,000	5,697,000
Maintenance Costs per year ($ / KW-hr)		
Normal operation	10,000	10,000
Bags (2 year life)	0	280,000
Total U.S. $	10,000	290,000
Operating Costs per year ($ / KW-hr)		
Pressure drop, mmWG	1,136	1,290
Power Consumption, fan, kW	3,535	4,005
Power Consumption, filter, kW	443	581
Total U.S. $	1,909,000	2,201,000
Summary U.S. $		
Installation Costs	5,486,000	5,697,000
Operation & Maintenance Costs / yr	1,919,000	2,491,000

NO_x Controls: SCR (selective catalytic reduction)

Figure 6-4 SCR Device, Courtesy of PA DEP



Performance:

Selective Catalytic Reduction (SCR) technology is used to reduce NO_x emissions by injecting ammonia vapor in to the flue gas stream. The ammonia vapor passes over a catalyst and reacts with the NO_x to form nitrogen gas and water. The SCR is usually located between the economizer and the preheater so that it may operate in the ideal temperature range of between 300°C and 400°C. This temperature is maintained in the SCR reactor by mixing the hot flue gas exiting the economizer with the cooler flue gas from the economizer bypass (Clean Coal Technologies, 2007). SCR units can achieve 90 percent NO_x reduction.

SCR technology can increase the mercury removal efficiencies of coal-fired power plants. As stated elsewhere in this document, mercury speciation has a significant impact on the amount of mercury removed. The oxidized form of mercury HG2 can form mercuric sulfide ($HgCl_2$), which is highly water soluble and can be captured in wet FGD systems. The catalysts used in SCR tend to oxidize elemental mercury from HG0 to HG2, making the mercury easier to capture downstream in a wet Flue Gas Desulfurization (FGD) system. The oxidation of mercury by the catalysts is thought to be affected by:

- the space velocity of the catalyst
- the temperature
- the ammonia concentration

- the catalyst age
- the concentration of chlorine in the flue gas stream

These interactions are complex and currently not fully understood. A higher chlorine concentration, a lower temperature, and a newer catalyst have been shown to result in a higher oxidation of mercury. There is still more to learn about the oxidation of mercury with SCR systems (Staudt, 2003).

When using SCR in conjunction with wet FGD and particulate control on a power plant burning bituminous coal, mercury removal efficiencies of 90 percent can be achieved. For plants with no wet FGD system the use of SCR did not affect mercury capture. (Staudt, 2003).

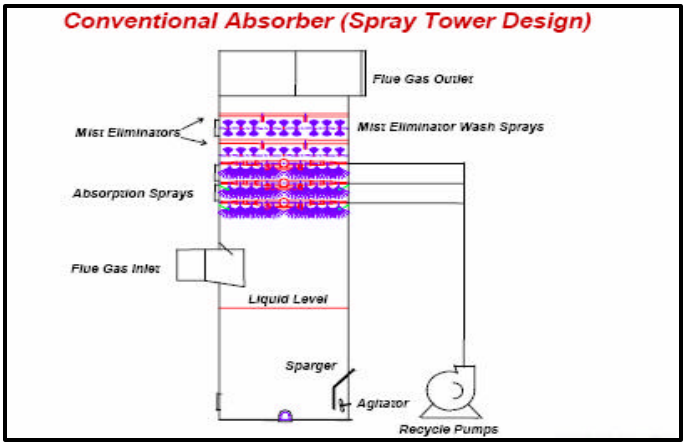
Cost:
One estimate shows that capital costs for SCR devices range from $40.88/kW to $91.51/kW. In this estimate the annual costs of operating and maintaining an SCR device range from $1,300,000 to $2,410,000 (McIlvaine Company, FGD and DeNOx Newsletter, 2000). Another study showed overall estimates of SCR installation to cost in the range of $100 to $200/kW. These estimates include costs for construction labor, equipment and material, project management, engineering and construction management. Construction labor costs were relatively constant for all size plants. However, economies of scale affect the material costs, making larger units cheaper. The average unit size in the study was 644 MW; the retrofit of a unit this size would cost in the range of $100 to $150/kW. Smaller units, around 300 MW, saw increased costs in the $200/kW range. The range continues to increase as unit size decreases (McIlvaine Company, FGD and DeNOx Newsletter, 2006).

A Massachusetts Institute of Technology (MIT) study estimated capital costs for SCR units to be roughly $20 to $40/kW for a new unit installation. For a retrofit unit installation, the capital costs increase in range to $50 to $90/ kW. Operating costs are in the range of $0.05 to $0.15 cents/kW-hr for SCR units according to this study.

SO_2 Controls

Performance:
Flue gas desulfurization controls SO_2 emissions. There are two types most commonly used by power plants in Virginia, wet scrubbers and spray dryers. Worldwide, wet scrubbers are the most commonly used device, followed by spray dry scrubbers and sorbent injection systems. The basic concept behind FGD systems is removal of the SO_2 gas from the flue gas stream by absorbtion into a liquid. These devices can achieve 95 percent success or better in SO_2 removal. Wet FGD units remove nearly 90 percent of HG2 but essentially none of the HG0 (Pavlish, 2003). Mercury removal can be enhanced in scrubbers if HG0 is converted to an oxidized form in or ahead of the scrubber using an SCR (see above).

Figure 6-5 FGD Device Courtesy PADEP



Cost:

As is typical with any control technology, FGD systems are much more costly when installed as retrofits rather than a new installation. Additional costs are incurred because the FGD systems must be fit within the existing site space and must be integrated with the existing plant and its structures. According to one study, retrofit costs for FGD systems can be as much as 20 to 40 percent more expensive than the cost for a new unit of similar size. For example, retrofitting a 170 MW unit averages $230/kW-hr whereas fitting a new 240 MW unit with an FGD system may cost $190/kW-hr. Both of these units use the same sorbent, both have fabric filters, and both have spray dryers, but the retrofit is more expensive. Another example shows the same result: a retrofit for a 180 MW unit costs $320/kW while control technologies on a new 430 MW unit costs only $150/kW (McIlvaine Company, FGD and DeNOx Newsletter, 2004). This large difference could be due to the scale of the units, but nonetheless the retrofits are more expensive.

A Massachusetts Institute of Technology study shows similar estimates. The study estimated capital costs for wet scrubbers range from $100 to $200/kW-hr. Operating costs ranged from $0.20 to $0.30/kW-hr with this estimate being heavily dependent on sulfur levels (MIT, 2007).

Wet FGD

Performance:

Wet flue gas desulfurization, also referred to as wet scrubbing, is the most widely used FGD technology for SO_2 control. The controls are usually installed upstream of some particulate matter control device, like a fabric filter or electrostatic precipitator. In a wet FGD system SO_2 is absorbed into a liquid, sometimes water, but often a chemical solution that absorbs the specific pollutant more readily. Calcium, sodium and ammonium-based solutions are commonly used as sorbents. Limestone and lime are the most common due to their availability and low cost. The lime or limestone and the SO_2 react with the oxygen in the air and eventually become gypsum, a by-product that can be sold to be used by other industries (Clean Coal Technologies, 2007). If gypsum is not produced, then the cost of treating and cleaning the water used in the wet FGD must be considered (EPA, 2007).

Wet FGD systems can achieve mercury removal co-benefits. Gaseous compounds of HG2 are soluble, meaning they can be absorbed in water or, in this case, the lime solution or slurry. However, HG0 is not soluble; therefore, the efficiency of the wet FGD in removing mercury is largely dependent upon which form of mercury is found in the flue gas. Mercury in the form of HG2 can react with the sulfur from the SO_2 already absorbed in the liquid to form mercuric sulfide (HgS) or the chlorides in the liquid to form mercuric chloride ($HgCl_2$), which becomes sludge and can be removed from the system.

Wet scrubbers can achieve a removal efficiency of SO_2 up to 99 percent (Clean Coal Technologies, 2007). The mercury removal efficiency of wet FGD systems can range from around 23 to 97 percent, depending upon the speciation of mercury in the flue gas stream and the type of particulate control used (Staudt, 2003). Virginia plants with both fabric filters and wet FGD controls are estimated to have a removal efficiency of over 90 percent.

Spray Dryer Absorbers

Performance:

Spray dry absorbers (SDAs) are another type of FGD system that requires a particulate control device. SDAs are similar to the wet scrubber in that the pollutant is absorbed into a liquid. Spray dryers use a spray mist of the slurry, however, instead of the bulk liquid. As with the wet FGD system, SO_2 is absorbed into the solution and forms calcium sulfite and calcium sulfate. Instead of becoming sludge, the heat of the flue gas evaporates the liquid and leaves dry particles. The particles are then collected by the particulate control downstream (EPA, 2007).

With respect to mercury removal, spray dryers are generally more efficient than wet scrubbers. Spray dryers can capture both HG2 and HG0, as HG2 can be absorbed in the spray droplets and both can be adsorbed onto the calcium sulfite and calcium sulfate particles. These particles are then collected downstream in the particulate control. If the particulate control is a fabric filter, there is an even greater potential for mercury capture as the flue gas passes through collected fly ash and dried slurry caked on the filter (Staudt, 2003).

In general, spray dryers can achieve SO_2 removal efficiencies of over 90 percent and up to 95 percent (Clean Coal Technologies, 2007) and over 98 percent, according to EPA. Since Virginia utilities burn bituminous coal with lower concentrations of HG0 and appropriate chlorine contents, the mercury removal efficiency for a SDA system followed by a particulate control system can reach 98 percent (Staudt, 2003).

Mercury Specific Controls
Activated Carbon Injection (ACI)

Figure 6-6 ACI before the PM Device (Courtesy PADEP)

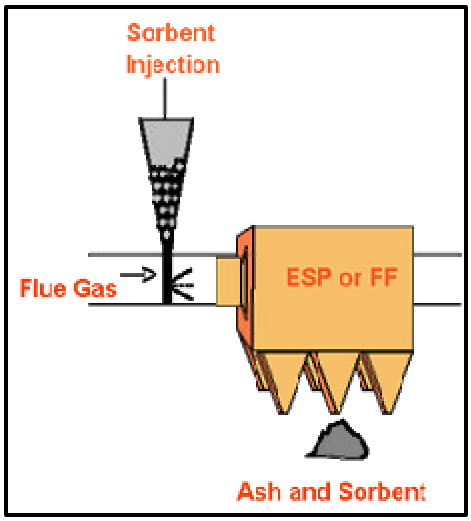
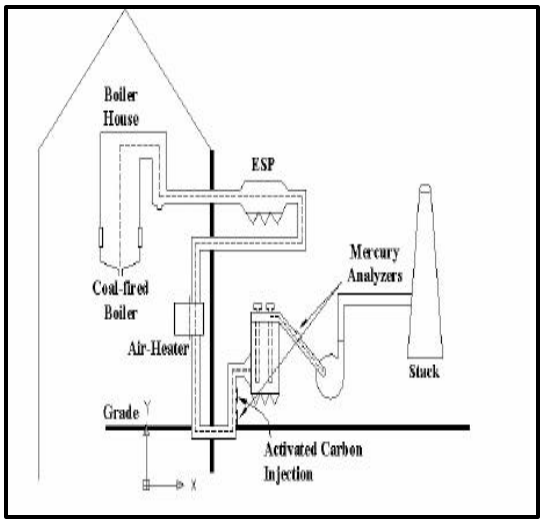


Figure 6-7 ACI after the PM Device (Courtesy PADEP)



Performance:
Activated carbon injection (ACI) is a technology used to specifically target and reduce mercury emissions. This technology is relatively new. It has not been installed in power plants in Virginia, although installation of ACI is planned for the new Virginia City Hybrid Energy Center in Wise County, Virginia. ACI has also been installed in municipal waste combustors for mercury control in the Northern Virginia area. ACI uses a powdered activated carbon sorbent that is injected into the flue gas stream at some point preceding or following the particulate control device. All forms of mercury can be adsorbed onto the carbon particles, which are then carried down the flue gas stream to be captured by the particulate control. As previously mentioned, fabric filters will capture more mercury than ESPs, because the carbon particles already captured by the fabric filter will adsorb additional mercury as the flue gas passes through the bags (EPA, 2007).

The performance of activated carbon injection is directly related to the carbon's physical and chemical characteristics. Important physical properties are surface area, pore size distribution, and particle size distribution. Mercury capture will increase with increasing surface area and pore volume. Properties of activated carbon should be selected to maximize mercury control. The injection of activated carbon ahead of an ESP or FF offers a technically feasible approach for the control of mercury emissions. Much of the cost for this technology depends on the rate of sorbent injection.

Several other sorbents, in addition to activated carbon, are being researched and developed. This research may lead to a reduction in cost and increase in performance of sorbent injection

technology for mercury removal (Staudt, 2003). One such sorbent injection technology is a halogenated ACI system. If the flue gas does not contain enough chlorine, a sorbent which also contains a halogen, such as chlorine or bromine, may be used to increase the oxidation of the mercury. As previously explained, this increases the ability of the mercury to adsorb to carbon particles. This technology has been shown to be just as effective as non-halogenated ACI. Less carbon will need to be injected as the oxidized mercury can also adsorb to fly ash particles, making this technology potentially less expensive. The Pennsylvania Department of Environmental Protection (PADEP) found that brominated-ACI along with an ESP device obtained 90 percent mercury removal (PADEP, 2006).

Another promising development for ACI has been developed by Praxair Technology, Inc. They have the technology to allow coal-fired power plants to produce activated carbon on-site. This allows for a secure supply, increased potential for revenue if a surplus is produced, and a reduction in costs against purchased carbon. The technology is best for Powder River Basin (PRB) and lignite coal but it also works for bituminous coal. Bituminous coal, however, does not always produce the best activated carbon. On-site ACI maybe an attractive option for power plants that want to use ACI, since producing the carbon on-site may reduce capital costs per pound of mercury removal. Praxair has estimated a 40 percent savings versus purchasing activated carbon offsite (Praxair, 2008).

A potential problem with ACI is the price of carbon, which is very volatile in today's international commodity markets. The price of carbon could increase and affect how cost-effective ACI technologies are in the market. Currently, standard powered activated carbon costs about $0.50/lb and halogenated powdered activated carbon costs about $1.00/lb (Srivastava, 2006). However, it is possible that carbon could reach $2/lb, resulting in specialty sorbents like brominated carbon becoming more competitive. (McIlvaine, 2008).

Cost:

In comparison to activated carbon, the brominated ACI, estimated by PADEP to result in 90 percent mercury capture, was much more expensive. The capital costs were cheaper at $4.9 to $9.8 million, but annual operating costs were much more expensive, estimated at $14.7 million. Total estimates came to between $15.4 to $15.8 million (PADEP, 2006).

Table 6-5 below shows cost estimates for both a 100 MW power plant and a 975 MW power plant that uses activated carbon injection to control mercury.

Table 6-5 (Pavlish, 2003). ACI design and cost

Carbon Injection System Design and Costs		
Reference power plant size (MW)	**100**	**975**
Bulk Carbon Density, lb/ft3	24	24
Carbon injection rate, lb/ft3	906	8,929
Silo Volume (15 day storage), ft3	13,600	134,000
Mass of Carbon, lb	326,000	3,210,000
Equipment Item Costs	**Thousands US $**	**Thousands US $**
Carbon Silo	143	1,722
Feed bin	6	24
Gravimetric feeder	10	12
Pneumatic conveyor	35	96
Carbon injection ports	25	36
Total equipment	291	2,526
Purchased equipment w/retrofit	379	3,283
Total Capital Costs	**889**	**6,139**

Other Sorbent Injection Technologies

Performance:

Other sorbent injection technologies exist that can be used to control mercury; however, they are typically not as effective as ACI. Development of low-cost, ultrafine sorbents would make injection technology a much more feasible option. Table 6-6 provides an overview of all sorbent injection technologies.

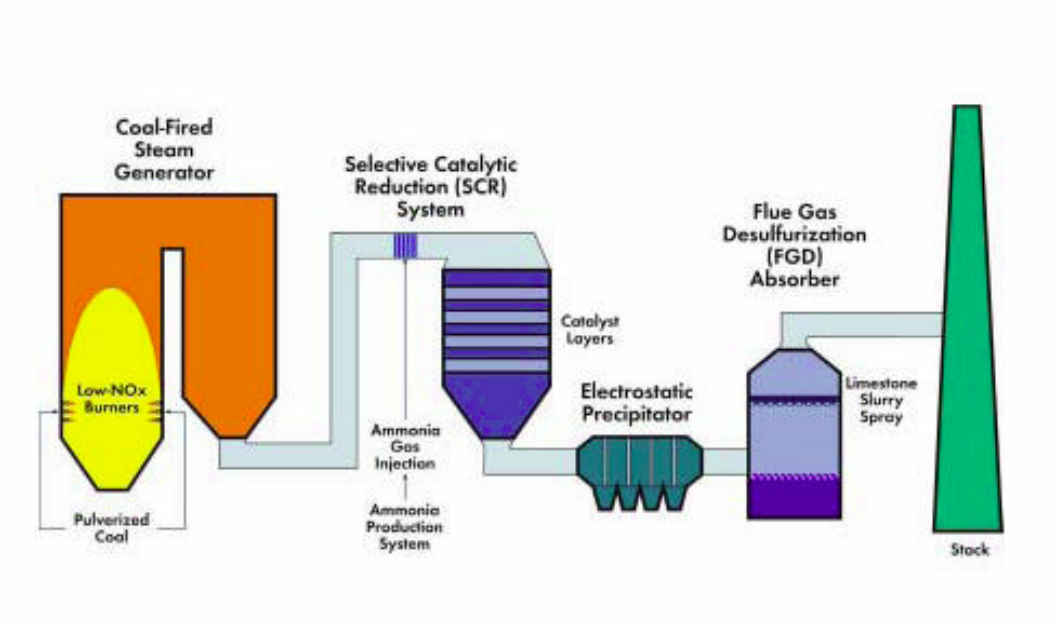
Table 6-6 (Pavlish, 2003). Sorbent Injection Technology

CONTROL TECHNOLOGY OPTION	STATUS	COST	CONTROL POTENTIAL	TECHNICAL IMPLEMENTATION ISSUES
Activated carbon	Commercial	Low-Moderate	Moderate-High	Separate Injection system required. Effectiveness very sensitive to temperature
Calcium-based sorbents	Commercial	Low-moderate	Moderate	Separate injection system required. Prep system may be needed.
Clay-based sorbents	Commercial	Low-moderate	Low	Separate injection system required
Sodium-based sorbents	Developmental-Commercial	Low-moderate	Low-moderate	Limited experience for Mercury Control. Separate injection system required
Metal oxide-based	Developmental-Commercial	Low-moderate	Moderate-high	Limited experience for mercury control. Separate injection system required

Co-Benefit Technologies and their Combinations

Many power plants already have existing mercury capture as a co-benefit of other air pollution control technologies for NO_x, SO_2 and PM. The PM control equipment captures particulate-bound mercury, and the FGD system captures the soluble form of mercury, HG2. As discussed above, the SCR technology used to control NO_x emissions can increase mercury removal efficiencies by oxidizing elemental mercury, making it easier to capture in an FGD system.

Figure 6-8 Typical Co-Benefit Configuration



Performance:

The SCR systems will enhance the oxidation of HG0 to its soluble ionic form of HG2, which results in increased removal by the FGD system (EPA, 2007). An SCR device combined with an ESP then followed by a wet scrubber, as shown in Figure 6-8 above, is an effective option for controlling mercury emissions. The three devices remove mercury with 90 percent efficiency for bituminous coal while maintaining their original primary functions (PADEP, 2006). Though these devices were not designed to remove mercury, their roles can be modified to increase mercury collection without degrading other emission control operations. The mercury removal process can be further aided by increasing the rate of slurry recirculation in scrubbers or injecting additives into the scrubber slurry (PADEP, 2006).

Cost:

Table 6-7 below shows cost estimates for each of the co-benefit technologies if they were to be installed separately; also included is their mercury control potential.

Table 6-7 Co-Benefit Technologies

CONTROL TECHNOLOGY OPTION	STATUS	COST	Hg CONTROL POTENTIAL
ESP	Commercial	Capital Costs – $5,486,000 Maintenance Costs – $10,000 Operation Costs – $1,909,000	36%
SCR	Commercial	Construction - $50/kW Equipment/Material - $100/kW Project Management - $150/kW Average Total Costs - $240-340/kW	0%
FGD	Commercial	Average Total Costs - $150-320/kW	30%
FF	Commercial	Costs included in FGD estimates	

Integrated Gasification Combined Cycle (IGCC)

Integrated Gasification Combined Cycle (IGCC) is a new technology for the production of electricity from coal. IGCC is a two-cycle process in which coal is treated by a gasifier to form 'syngas,' made primarily of hydrogen, carbon monoxide, and methane and other gaseous constituents. Next, the syngas is burned in a combustion turbine, which drives an electric generator (first cycle). Hot air from the combustion turbine is channeled back to the gasifier, while the exhaust is recovered and used to boil water, creating steam for a steam turbine-generator (second cycle).

IGCC has inherent advantages for emissions control because cleanup occurs in the syngas, which has not been diluted with combustion air. Removal of contaminants is more effective and economical than cleaning up large volumes of low-pressure flue gas (MIT, 2007). IGCC will enable the effective control of particulate matter, SO_2, NO_x, and mercury. IGCC systems remove mercury by running the syngas through carbon beds, thus removing as much as 95 percent of mercury. The mercury and other toxics captured in the carbon beds produce a relatively small amount of waste material. The amount is small enough that the waste can be managed to permanently remove mercury from the environment. The cost of this mercury removal has been estimated to be $3,412/lb Hg removed. Removing mercury will translate into an estimated cost increase of $ 0.025/kW-hr if IGCC is used. However, the current capital costs for IGCC systems are significantly higher than for comparably-sized, conventional pulverized coal technology.

Virginia DEQ's Cost Assessment of Control Technologies

This section summarizes DEQ staff's cost assessment of mercury control technologies for Virginia-specific representative coal-fired power plants.

Analytical Procedure and model:

Much literature exists regarding cost assessments for technologies controlling conventional Clean Air Act pollutants; however, not enough literature exists on the costs of Hg control through the Clean Air Interstate Rule (CAIR)- and the Clean Air Mercury Rule (CAMR)-based scenario. To better assess the costs of mercury removal by Virginia-specific, coal-fired power plants, an effort was made to collect the best possible information on existing and future controls (performance and cost) information that is representative of existing facilities in Virginia. This information was collected from Energy Information Administration (EIA) databases, EPA studies, and available permit and compliance data.

Analytical Procedure: The cost assessment was based on two key considerations:

1. **Co-benefits:** As explained above, the co-benefits of mercury control through CAIR-based control technologies is known and empirically measured. This study thus assessed the costs of a mercury controls only (CAMR-based) scenario and a multi-pollutant-based mercury removal scenario (CAIR-CAMR) scenario.
2. **Net marginal costs:** Net marginal costs of mercury control were assessed for emission control levels of 65, 80 and 90 percent. Most facilities in Virginia were achieving 65 percent level controls through the adoption of CAIR-based controls. About 65 percent mercury removal was also required through the passage of the Virginia General Assembly HB 1055. Additional control levels of 80 percent and 90 percent reflect typical mercury control levels as sought or evaluated by other states' model rules.

Model: Integrated Environmental Control Model (IECM)

The cost assessment was done simultaneously using a MS-Excel-based, cost-effectiveness calculation of existing and projected control technologies data (performance, removal efficiencies and costs) and, at the same time, through the use of a simulation tool called the Integrated Environmental Control Model (IECM). IECM is a simulation program that is approved by the DOE and was developed in collaboration with Carnegie Mellon University. IECM provides plant-level performance, emissions and cost estimates for a variety of environmental control options for coal-fired power plants specifically. The fundamental building blocks of IECM are a set of performance and cost sub-modules for individual technologies that can be linked together to configure a user-specified power-generating system. The process models employ mass and energy balances to quantify all system mass flows, including environmental emissions. For each technology module in the IECM, associated cost models are developed for total capital cost, variable operating costs and fixed operating costs. These elements are then combined to calculate a total annualized cost based on a consistent set of user-specified financial and lifetime assumptions. Normalized costresults, such as costs per kilowatt (or kilowatt-hour) of net capacity and cost per ton of pollutant avoided or removed, can also be computed.

Taking into consideration Virginia-specific bituminous coal and plant specifications, Virginia plants were modeled as accurately as possible, using information from permits and compliance records and, if plant specific data were not available, best possible market/industry estimates

were used. The IECM-based approach of cost estimation was compared to EPA, DOE and industry-level estimates of costs, and the estimates were found to be in close range.

Assumptions used:

Certain key assumptions were made in this cost assessment. Typical plant performance, gross and net energy production, and parasitic load estimates were used. Cost of coal, ash disposal, and electricity prices were based on market estimates and verified with professional scientists and vendors.

Cost estimation – approach and results:

Costs / MW-hour and costs/lb Hg removed were the two key measures of cost-effectiveness calculated by this study. Both estimates are in 2005 constant dollars and reflect market-based conditions. These measures were calculated using the following formulae:

$$\textbf{Net Costs / MW-hr} = \frac{\text{(Net Marginal Costs of Hg controls)}}{\text{MW generated* Total working hours * Capacity Factor}}$$

OR- mathematically, the cost assessment can be interpreted as:

$$\textbf{Net Costs / MW-hr} = \frac{\text{Net Marginal Costs of Hg controls}}{\text{MW generated} * 7580 * 0.80}$$

Costs / lb removed (X % level of Hg removal) =

$$\frac{\text{(Net Marginal Costs of Hg controls)}}{\text{lbs of Hg reduced by the Hg controls}}$$

Generally, Virginia facilities operate at about 80 percent of maximum capacity. However, variability on a plant-by-plant and unit-by-unit basis exists for this factor. Tables 6-8 and 6-9 below summarize the two measures of cost assessment for Virginia-specific coal-fired power plants.

Table 6-8 Costs of mercury control under CAMR-only scenario (Hg controls only)

Net Marginal costs of controls for varying levels of Hg control		**CAMR-only (if only mercury control technologies were retrofitted)**
Costs / MW-hr	**65% reduction**	$ 1.50 - $ 5.00
	80% reduction	$ 1.70 - $ 11.00
	90% reduction	$ 3.47- $ 12.14
Costs / lb removed	**65% reduction**	$ 51,772 - $ 162,381
	80% reduction	$ 41,535- $ 166,666
	90% reduction	$ 117,300 - $ 248,000

A review of Table 6-8 indicates that costs of retrofitting mercury-only (CAMR only) controls have a wide range. The costs range from $ 1.50 through $ 5.00 for achieving a 65 percent emission reduction (2015 levels of control) and the costs proportionately increase with higher levels of mercury control. Estimates of costs per pound removed show a range of $51,772 through $248,000, depending on the size of the power generating facility, quality and type of controls. ACI was the considered control technology chosen for the CAMR-only based scenario, and costs of the sorbent generally used in ACI ranged from $ 0.52 /lb through $ 0.89 / lb. Cost estimates as above are in 2005 constant dollars, thus allowing for ease of comparison across inflation.

Table 6-9 Costs of mercury control under a CAIR-CAMR scenario (co-benefits)

Marginal costs of controls under varying levels of Hg reduction		**CAIR-CAMR-based scenarios(co-benefits based)**
Costs / MW-hr	**65% reduction**	$ 4- $ 7
	80% reduction	$ 1- $ 3
	90% reduction	$ 1- $ 4
Costs / lb removed	**65% reduction**	$ 40,000 - $ 60,000
	80% reduction	$ 20,000 - $ 50,000
	90% reduction	$ 65,000 - $ 90,000

Table 6-9 clearly shows that Hg removal under a co-benefit scenario provides the most cost-efficient outcome. Costs range from a low of $ 1.00 to a high of $ 7.00. Costs per pound removed indicate that existing CAIR-based resources with Hg specific control upgrades allow for attainment of 65- 70 percent level of Hg removal. Once the 70 percent level of Hg removal threshold is reached, costs of achieving any additional level of Hg removal escalate and can reach as high as $ 90,000 per lb. A closer review of the data also indicated that older plants with no fabric filters, limited CAIR based controls, and poorer generation capacity were the facilities with higher costs of Hg removal ($ / MW-hour and $/lb removed). Such a cost pattern is in line with industry and academic research reports. EPA estimates that in order to achieve 90 percent mercury reduction using ACI costs would be between $ 5,000-$ 28,000/lb of Hg removed. On the other hand, DOE estimates it to be between $ 25,000-$ 70,000/lb of Hg removed.

Conclusions

- The costs of mercury control at coal-fired power plants are affected by a number of different parameters, including what technologies are chosen, what regulations are in place, and the market-based determination of demand versus supply of energy.

- A number of options for reducing mercury emissions from coal-fired power plants are commercially available, and others are being developed. A number of control technologies for the reduction of mercury are available to coal-fired power plants, allowing the facility to choose the best fit in terms of cost-effectiveness.

- The DEQ cost assessment was based on a thorough review of existing and future projected mercury controls by Virginia-based electric generating units. Specifically, best available information on control technologies (performance, constraints, market prices of inputs and by-product disposal estimates) was used in this analysis. The results support the view, which is widely held by EPA, U.S. DOE, industry research and other state agencies, that mercury control is more cost-effective if coal-fired power plants adopt a multi-pollutant, post-combustion control technology sequence. Specifically, a combination of SCR, FGD, Fabric Filter and ACI was found to have the most cost-effective configuration.

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Chapter 7- Human Health Risks Assessment

VCU-CES Recreational Fish Consumption Survey

As part of this study, DEQ contracted with VCU's Center for Environmental Studies (VCU-CES) to obtain Virginia-specific fish consumption data collected in areas where mercury-fish consumption advisories are in effect. Additionally, VCU-CES was tasked with estimating the associated health risks from resulting methylmercury exposures. VCU-CES developed a fish consumption survey and worked with DEQ staff to identify the launching and fishing locations where anglers could be surveyed. The survey was designed to obtain information on fishing behaviors, fish consumption, and demographic data on the anglers and families. During the summer of 2007, a team from VCU-CES administered the survey to 158 anglers at boat launching and fishing sites. Surveys were completed for anglers who were fishing at 17 locations on 5 rivers: the James River below Richmond, the Chickahominy, Pamunkey, Mattaponi, and upper Piankatank Rivers. These rivers are affected by methylmercury contamination, have been surveyed in previous similar investigations and are used by anglers for recreational fishing.

The surveys were administered to anglers from all 17 locations on all 5 rivers, predominantly on Friday, Saturday or Sunday. Approximately 44 percent of all respondents and their families consume the fish that they catch from these waters. Half (50 percent) of the anglers, not their family members consume some fish that they catch, and more men (54 percent) than women (43 percent) were reported to consume the fish with elevated methylmercury levels. The most commonly consumed fish were catfish, spot or croaker, sunfish and largemouth bass; catfish and largemouth bass are two of the species on the fish consumption advisory. Catfish also represented the largest number of meals and total amount of self-caught fish consumed per year. The data on fish consumption were analyzed with DEQ data on methylmercury concentrations in fish that had been collected in previous years to estimate the amount of methylmercury consumed in fish yearly. In order to estimate total methylmercury from all fish consumption, canned tuna and purchased fish consumption were added to mercury exposures from self-caught fish. Mercury levels in tuna and purchased fish were taken from national data.

The methylmercury exposures determined from survey data and DEQ fish tissue levels were compared to the dose of mercury exposure that the EPA has set (and VDH uses) as the dose without appreciable health risks, based on the reference dose or RfD. The RfD for methylmercury established by EPA is based on recommendations from the National Research Council (NRC), a body of the National Academy of Sciences. The NRC reported that there is evidence that the kidney, liver, cardiovascular and immune systems could be affected by methylmercury, but a NRC committee found that neurodevelopmental problems are the most appropriate basis for setting an exposure limit for methylmercury and that strong scientific evidence exists from human and animal studies to link certain levels of methylmercury exposure and neurological problems. These problems include poor performance on tests that measure attention and motor function, which are linked to IQ. Following the recommendations of the NRC, the RfD for methylmercury was established based on preventing adverse effects on neurological development in young children.

VCU-CES's analysis of the fish consumption and fish tissue concentrations was performed using risk assessment software that provided probabilistic levels of potential exposure to methylmercury. This program randomly selects certain values, as defined, to use in the equations

for determining total mercury from all the fish consumed. The analysis indicates that a significant number of anglers who regularly catch and consume significant amounts of catfish and large mouth bass from the affected waters are exposed to methylmercury at levels above the U.S. EPA reference dose of 0.1 ug/kg-day.

Utilizing the information obtained from various statistical methods, VCU-CES modeled the loss of IQ points from prenatal exposure to methylmercury through the maternal diet, specifically mercury from consumption of mercury-contaminated fish. To model the loss of IQ points from prenatal exposure to methylmercury through the maternal diet, the target population of interest is women of childbearing age. To approximate this group, the survey results were divided by gender and age group and the subsample from women 16 to 49 years old (n=52) was used for risk assessment. Two of the survey results used were from female anglers who had been interviewed; the remaining 50 survey results used were from anglers who reported women aged 16 to 49 living in their households who ate fish that the angler caught from the river where interviewed. Because information was not obtained on fish-meal frequency and meal size for family members, it was assumed that these 50 women had the same fish-meal frequency and size as their anglers. Using the survey results and fish mercury concentrations from DEQ's fish tissue database, a probability distribution of ingested doses was created through a Monte Carlo simulation process. Based upon the estimated maternal exposure to current fish mercury concentrations, the VCU-CES study estimated future levels of IQ changes due to 2010 and 2018 levels of controls to result in average (mean) avoided IQ deficits of 0.03 IQ points. The VCU study estimated change in IQ points to approximate a net loss of 0.03 as a result of exposure to mercury.

Note: the following chart is provided to help give some perspective on IQ scores.

Descriptive Classifications of Intelligence Quotients

IQ	Description	% of Population
130+	Very superior	2.2%
120-129	Superior	6.7%
110-119	High average	16.1%
90-109	Average	50%
80-89	Low average	16.1%
70-79	Borderline	6.7%
Below 70	Extremely low	2.2%

Source: From; Wechsler, David, WAIS-III Administration and Scoring Manual, San Antonio, Texas: Psychological Corporation, 1997.

The survey conducted by VCU-CES indicated that there are limitations with the study, including but not limited to:

- This survey obtained data from only a few women and no family members and further surveys would be needed to obtain direct fish consumption information on women and children in anglers' families;

- Language barriers prohibited some Spanish-speaking anglers from participating in the survey; and
- The risks of combined exposures to multiple contaminants in fish are unknown.

The above is a summary of the report prepared by VCU-CES. The entire report prepared by VCU-CES provides more detailed information on the sampling surveys, survey results, methods used to examine fish consumption and risks assessment. The report is included as Appendix B. Information obtained from the VCU-CES study was provided to DEQ to be utilized in the monetized economic analysis associated with avoided IQ deficits due to reduced exposure from the consumption of recreationally-caught freshwater fish, which is discussed in the next chapter of the report.

Chapter 8- Assessment Of Potential Monetary Benefits Of IQ Changes Associated With Reduced Methylmercury Consumption

Summary

This chapter of the report attempts to quantify and monetize, to the extent feasible, the economic benefits associated with modeled avoided IQ deficits due to reduced exposure from the consumption of recreationally-caught freshwater fish.

The monetization of the human health risk effects (IQ being the human health effects of measurement) builds upon the findings of the VCU-CES study (Appendix B) and adopts the approach utilized by EPA to conduct the economic benefit analysis at the federal level (U.S. EPA 2005). This regional assessment focused on estimating the changes in exposures to women of childbearing age because adverse health effects in children have been linked to prenatal mercury exposures (Sorenson et al. 1999). This report builds on the VCU-CES study that focused on select counties of eastern Virginia where fish advisories for mercury existed and using consumption surveys, IQ losses were estimated. IQ losses were then monetized to evaluate the economic benefit of mercury emission controls (or impacts of no reduction in emissions).

EPA's CAMR analysis indicated a monetized impact of $15 million solely due to power plant emissions over the entire United States (3 percent discount rate and Year 2000 dollars); however, such an analysis is not representative of Virginia, Virginia-specific individual consumption patterns and DEQ's fish tissue data. The DEQ assessment used 10 years of birth data for only the select counties where fish consumption patterns were surveyed to quantify economic impacts associated with the average (mean) avoided IQ deficits of 0.03 IQ points found in the VCU-CES study and associated with methylmercury consumption through 2010 and 2018. Economic losses to the exposed populations of interest involved an assessment of two scenarios – worst case and most likely. Under the worst-case scenario, the estimated net per capita income earning loss to children is $337.00, or $4.8 million across all 14,364 children born in the select counties. Under the "most likely" scenario, it was estimated that 6,104 pre-natal children (i.e., less than half of the 14,364 children born in the select counties) would be exposed to methylmercury and would thus have net income losses totaling $ 2.05 million. The two monetized scenarios are estimates of impacts for areas where risk assessment of methylmercury exposure due to fish consumption was undertaken.

Introduction

This chapter sets forth the analysis of economic monetary benefits (impacts) of implementing mercury emission controls (or not installing controls). This analysis builds upon the VCU-CES study – Fish Consumption and Human Health Risks – that used DEQ's fish tissue data and reference dose recommendations set forth by EPA (and used by VDH) to compute potential changes in human health effects (IQ level being the endpoint[3]), given existing fish consumption patterns and current levels of methylmercury bio-accumulation.

A fuller understanding of DEQ's monetization of human health risks associated with freshwater fish consumption is incomplete without a contextual appreciation of the U.S. EPA's Clean Air

[3] Economic endpoints are well-defined, economically meaningful effects associated with a contaminant- U.S. EPA National Center for Environmental Economics (NCEE).

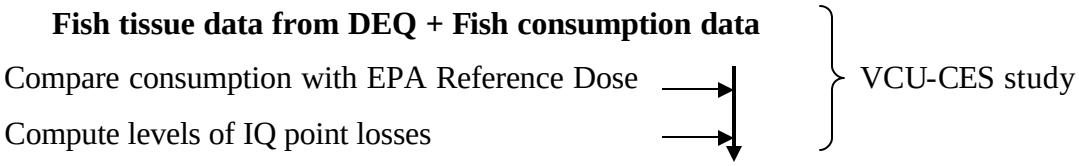
Mercury Rule-based Regulatory Impact Analysis (US EPA 2005b) and follow-up update assessment done by Griffiths, et al. (2007). EPA narrowed its focus of human health risk assessment due to methylmercury based fish contamination to recreationally-caught freshwater fish only. Target populations of interest were narrowed to women of childbearing age (as also cited in the VCU-CES study) but also focused on only freshwater exposures in the eastern half of the United States and measured the changes in IQ levels as economic endpoints.

DEQ's estimation of the monetary benefits (or impacts) of mercury emissions (of implementing emission controls) replicates the U.S. EPA approach and specifically the updated Griffiths et al. (2007) study but narrowed its focus to freshwater-based recreational anglers across select counties of the Commonwealth. The chart below provides a visual understanding of this section of the report in terms of the various components and related "data inputs" and the "outputs." Following the visual representation of the study, a summary is provided of the economic benefit assessment approach, data used and related results.

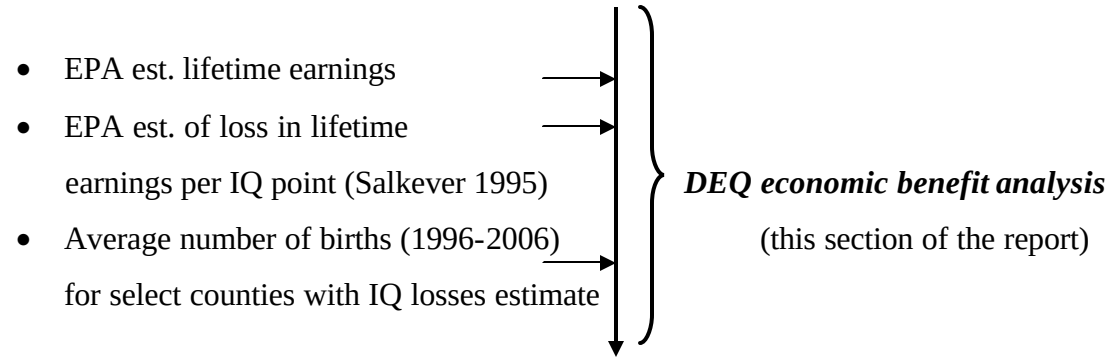
Summary of methodology, assumptions and data used

A visual interpretation of the procedure below depicts the process by which monetization of human health risk effects is undertaken using the findings from the human health risk study.

Overview of DEQ approach to monetized impacts of mercury emissions



Net IQ points lost (prenatal methylmercury exposed children in select VA counties only)



Estimate of net future earnings loss per child[4]

The above graphic interpretation is also explained in detail in the following sub-sections.

- ***Procedure for monetizing IQ losses (gains) and assumptions used***

The methods used for this section of the study are primarily based upon the approach adopted by EPA and utilized EPA estimates on the relationship between IQ points lost and related net loss in future earnings potential and average lifetime earnings data (US $2000). EPA estimated average present value of future earnings using the total average annual earnings for the population, also in five-year intervals, broken out by sex and education. The EPA also summed the earnings across age intervals, assuming a 3 percent discount rate and a 1 percent annual gain in productivity and used the Gross Domestic Product (GDP) deflator to convert $366,021 (1992 dollars) into $472,465 (2000 dollars). Furthermore, expected value of foregone future earnings associated with IQ decrements was adopted by U.S. EPA from assessment by Salkever (1995) that used data from the National Longitudinal Study of Youth (NLSY) and a statistical model to estimate the linkage between IQ levels, educational attainment and future earnings potential.

DEQ used that estimate as well, to capture the loss in future lifetime earnings for children born to the susceptible sub-population of women of childbearing age from the sampled counties in the Commonwealth. Summarized below are the equation and related steps that were used to quantify the monetary impact of potential IQ losses associated with mercury emissions.

Net change in future lifetime earnings for total targeted population (children) =

*Lifetime earnings * % change in lifetime earnings / IQ point * IQ points lost due to mercury emissions * # of births (for select counties of interest)*

where:

Lifetime earnings estimate: $472,465 (U.S. EPA estimate in 2000 dollars)

% change in lifetime earnings per IQ point: 2.379 percent decrease in future earnings or 0.0238

[4] Estimate of net future lifetime earnings loss per child is specific to the child only and limited to the select counties where fish consumption surveys were undertaken. It does not translate into any economic impacts to the counties.

IQ points lost due to mercury emissions: VCU-CES study-based estimates of change in IQ points lost

 # births: Annual average for the last 10 years (1996-2006) for the select counties (VDH).

Numerically, this can be interpreted as:

Loss per child in lifetime earnings = $472,465 * 0.0238* 0.03 * # of children born in select Virginia counties between 1996-2006.

Steps used to implement this procedure are:

1. Lifetime earnings estimate was multiplied with percent change in earnings per IQ point.
2. Product of Step 1 was then multiplied with VCU-CES study-based net change in IQ points lost
3. Finally, this combined value from Steps 1 and 2 was multiplied with total average number of births across the select counties of Virginia where fish consumption surveys were conducted, to obtain monetized estimates of potential future loss in lifetime earnings per child in the select counties of the Commonwealth.

- ***Key supporting assumptions:***

It must be noted that this study makes some key assumptions, and any interpretation of the results without consideration of the assumptions would lead to misinterpretation of the results:

1. **Monetary impact to children only and not a fiscal impact:**

The monetary impact to the children due to prenatal exposure to methylmercury is the monetary impact to the individuals (in this case, children of the select counties) alone. This estimate should not be reflected as costs to the family, county or city, or the Commonwealth at large, as this is an individualistic economic endpoint measurement and not a fiscal and/or welfare impact assessment of a region due to mercury emissions. Furthermore, this estimate is on the higher end or more of an "upper bound" estimate and assumes that 100 percent of all children in the select counties experienced pre-natal exposure to methylmercury. Research indicates that susceptible sub-populations are usually responsive to fish advisories and thus, actual estimates of exposures and thus, monetized impacts of IQ losses would be lower than what is summarized in the following section.

2. **Site-specific economic impact only:**

This measure is specific to the select counties as identified earlier in the Fish Consumption and Human Health Risk assessment study by VCU-CES. Estimates of monetary impacts of IQ losses from this study cannot be generalized for all the children across the Commonwealth. If such an assessment is to be considered, a careful extrapolation has to take into account likely areas of freshwater fishing by anglers, locations of fishing and deposition-induced, mercury-contaminated waters and, more

specifically, good information is needed on the consumption rates by women of childbearing age in other non-select study sites.

3. Comparing costs and benefits simultaneously is not feasible:

The economic costs of control technologies (for coal-fired power plants) as identified in the earlier chapter of this report, is very dependent on market availability of inputs for coal, dynamics of electricity supply and demand and, more importantly, the size and efficiency of various coal-fired power plants across Virginia, in terms of performance of mercury control technologies (co-benefit and individual controls). The cost assessment across each plant varies by the timeline by which each plant seeks to break even on their capital costs of installation of new control technologies or upgrading the retrofits. Economic benefits (through reductions in mercury emissions and related IQ gains) are an individualistic measure of pre-natal exposure-based potential IQ deficits in children. The economic estimates of forgone lifetime earnings are based on EPA estimates and updated using the latest GDP deflator. Comparing the costs of control technologies by electric generating units which are added to the costs of energy generation and distribution is different from the net economic benefits of reduced mercury exposure through lower levels of methylmercury contamination, which is a more individualistic measure and has no implications for the economic health of a workforce of a specific industry, or a city or county as a whole. Lastly, mercury depositions in streams of interest are from all sources, not just from electric generating units; thus, any determination of control technologies for coal-fired power plants using the economic impact to children due to methylmercury would be difficult and complex.

4. Recreationally-caught freshwater fish assessment only:

This assessment was undertaken on recreationally-caught freshwater fish consumption only. Commercial fish consumption and related health effects were not feasible and, therefore, not the focus of this effort. However, Shimshack et al. (2007) have evaluated the role of responses to U.S. Food and Drug Administration (FDA) advisory that informed citizens of the potential sub-populations at risk from consuming store-bought fish that is contaminated by methylmercury. The study did find that generally, targeted populations across the United States did respond to informational advisories by significantly reducing the consumption of appropriate fish species.

- ***Results:***

Adopting the above mentioned steps and modeling equation, we get the following results in terms of monetary impact of IQ losses associated with methylmercury exposure to women of childbearing age.

Table 8-1 Monetary impact of IQ losses (select counties) due to mercury emissions

Lifetime earnings est. (Year 2000 dollars) **(A)**	EPA's dose-response slope (B)	Net IQ points lost (C)	Net impacts per child (D= A*B*C)
$ 472,465	0.0238	0.03	$ 337.34

Table 8-1 indicates that the economic impact in terms of future forgone lifetime earnings per child in the select counties alone would be approximately $337.34, which is a relatively very marginal economic impact per child. Two likely scenarios of economic impact were assessed using this IQ loss estimate per child of 0.03.

- **Most likely scenario:** According to the VCU-CES report, from a total sample size of 150 respondents, only 42 percent of the target population of interest - women of childbearing age - (16 to 49) ate the fish they caught. Assuming this rate of consumption reflects the consumption rate across the select counties, 42 percent of the total births over the past 10 years were computed, and the economic impact for that specific sub-population of pre-natal exposed children was assessed.

  Economic impact to select counties alone due to 42% methyl-mercury exposure:

  = Net economic impact per child * Number of births (42% exposure rate)

  OR

  = $ 337 * 6104 = $ 2.05 million (across an annual average of 6,104 children)

- **Worst-case scenario:** The worst-case scenario reflects the assumption that all children across the select counties of assessment were exposed over the last 10 years to methyl-mercury exposure. If such an assumption is considered, the economic impact is summarized below:

  Economic impact to select counties alone due to 100% exposure to methyl-mercury exposure:

  = Net economic impact per child * 10 year average of annual number of births

  OR

  = $ 337 * 14,364 = $ 4.8 million

Conclusions

The above section indicates the net economic impact for the select counties across the Commonwealth to be approximately $337.00 per child with a most-likely economic impact estimate of $ 2.05 million and a worst-case scenario of $ 4.8 million. This assessment uses the EPA based CAMR impact analysis procedure and updated Griffiths et al. (2007) estimates on lifetime earnings potential, the dose-response slope (Salkever, 1995) and annual average 10-year birth data for the select counties across Virginia (VDH). It must also be noted that this economic benefit assessment is a very simplistic version of benefit-transfer assessment and generalizing the economic estimates across the entire Commonwealth to all potential pre-natal exposed children may not be realistic and appropriate.

Chapter 8 References

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Chapter 9- Conclusions

Virginia would benefit from reduced mercury deposition as a result of implementation of pollution controls required by CAIR and CAMR. The following are the findings of this report.

Mercury Deposition Modeling

- Mercury sources located outside of Virginia contribute to the mercury deposition occurring within the state. Global sources are responsible for the largest amount of mercury being deposited within the state.

- Mercury deposition would be predicted to decrease statewide in future years as a result of implementation of emission controls in use to meet requirements of the CAIR and the CAMR. Virginia benefits from mercury reductions occurring in surrounding states, particularly emissions reductions from EGUs.

- Emission sources located in Virginia contribute to mercury deposition within the state, and the greatest impacts from the in-state sources are simulated near the source locations. This includes EGU sources and non-EGU sources.

- Examining deposition patterns for EGU and non-EGU sources indicates that, in general, EGU sources tend to impact a larger area compared to non-EGU sources. This is likely due to non-EGU sources having shorter stack heights and lower exit velocities, which result in less dispersion of mercury.

- The modeling results were calculated by using requirements that must be met under the CAIR and the CAMR. The Washington, D.C. Circuit Court of Appeals has recently issued opinions vacating both of these rules.

Potential Changes to Mercury Fish Tissue Concentrations

- Based on available information from multiple experiments and field experiences, mercury that is air-deposited into aquatic ecosystems can be expected to contaminate fish.

- Lakes and wetlands are especially sensitive to even small amounts of added mercury because these environments are very efficient in transforming the mercury into a form that is readily accumulated by fish.

- Reduction in mercury inputs into a waterbody is expected to result in lowered concentrations of mercury in the fish after the ecosystem readjusts to the lower mercury levels in the environment.

- It is reasonable to expect a proportional lowering of fish mercury concentrations over time in response to decreases in mercury deposition rates from the air.

- The time frame needed before these lowered fish concentrations could occur depends on how efficiently mercury is processed by the aquatic ecosystem and picked up by the fish.

- Each individual waterbody is expected to react slightly differently due to natural variances in the chemical and physical conditions and differences in food-web structure.

- Lakes are expected to respond quickest (within a few years to decades) to reduced mercury deposition, with wetlands requiring more time to equilibrate to the lowered mercury inputs.

- The projected reductions in mercury-air-deposition rates after 2010 and 2018 estimated by the ICF model (based on CAIR and CAMR) suggests that fish mercury levels may become lower in the future such that some species may no longer warrant a fish consumption advisory.

- The VDH issues fish consumption advisories when average concentrations of mercury in fish exceed 0.50 ppm.

- The DEQ has recently proposed the adoption of a fish tissue criterion for mercury of 0.30 ppm, which is lower than the current threshold concentration used by the VDH to issue fish consumption advisories. If the State Water Control Board adopts this fish tissue criterion for mercury, in the future DEQ may classify some waterbodies as impaired due to elevated mercury contamination in fish before the VDH would find it necessary to issue a fish consumption advisory.

- Of the thirteen mercury-sensitive waterbodies in Virginia with current fish consumption advisories due to mercury contamination in fish, the fish mercury levels may be lowered enough in the future (to below 0.5 ppm mercury level currently used by the VDH) such that three or four of these advisories may no longer be warranted.

- In all but two of the advisory areas, at least one species of fish may have reduced mercury levels in the future that could allow for its removal from the fish consumption advisory and, in one case (Dismal Swamp Canal), the advisory area may be reduced.

- Under the projected reduced air deposition rates for the future (based on CAIR and CAMR), nine to ten of the current fish consumption advisories will likely remain in place for at least one species of fish.

- Average mercury concentrations for at least one species of fish could remain higher than 0.30 ppm, so all of these waterbodies could remain classified as impaired by DEQ.

Pollution Control Technology Costs

- The costs of mercury control at coal-fired power plants are affected by a number of parameters, including what technologies are chosen, what regulations are in place, and the market-based determination of demand versus supply of energy.

- A number of options for reducing mercury emissions from coal-fired power plants are commercially available, and others are being developed. A number of control technologies for the reduction of mercury are available to coal-fired power plants, allowing each facility to choose the best fit in terms of cost-effectiveness.

- The DEQ cost assessment was based on a thorough review of existing and future projected mercury controls by Virginia-based electric generating units. Specifically, best available information on control technologies (performance, constraints, market prices of inputs and by-product disposal estimates) was used in this analysis. The results support the view, which is widely held by U.S. EPA, U.S. DOE, industry research and other state agencies, that mercury control is more cost-effective if coal-fired power plants adopt a multi-pollutant post-combustion control technology sequence. Specifically, a combination of SCR, FGD, Fabric Filter and ACI was found to have the most cost-effective configuration.

Fish Consumption Trends in Virginia's Waterways and Monetization of Human Health Risk Effects (IQ level)

- Based upon the estimated maternal exposure to current fish mercury concentrations, the VCU-CES study estimated future levels of IQ changes due to 2010 and 2018 levels of controls to result in average (mean) avoided IQ deficits of 0.03 IQ points.

- Under the worst-case scenario, the estimated net per capita income earning loss to children is $337.00, or $4.8 million across all 14,364 children born in the select counties. Under the "most likely" scenario, it was estimated that 6,104 pre-natal children (i.e., less than half of the 14,364 children born in the select counties) would be exposed to methylmercury and would thus have net income losses totaling $2.05 million. The two monetized scenarios are estimates of impacts for areas where risk assessment of methylmercury exposure due to fish consumption was undertaken.

Appendix A- Final ICF report

VDEQ Mercury Study

Mercury Deposition Modeling for the Virginia Mercury Study

Final Report

September 4, 2008

08-007

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VDEQ Mercury Study

Mercury Deposition Modeling for the Virginia Mercury Study

Final Report

September 4, 2008

Prepared for
Michael Kiss and Patricia Buonviri
Virginia Department of Environmental Quality
629 East Main Street
Richmond, VA 23219
(804) 698-4000

Prepared by:
Sharon Douglas, Jay Haney, YiHua Wei,
Thomas Myers and Belle Hudischewskyj
ICF International
101 Lucas Valley Road, Suite 260
San Rafael, CA 94903
(415) 507-7164

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List of Acronyms and Abbreviations

AEP = American Electric Power

AERMET = AERMOD Meteorological Preprocessor

AERMOD = AMS/ EPA Regulatory Model

AMS = American Meteorological Society

AQS = Air Quality System

ARL = Air Resources Laboratory

CAIR = Clean Air Interstate Rule

CAMR = Clean Air Mercury Rule

CART = Classification and Regression Tree

CASTNet = Clean Air Status and Trends Network

CB = Carbon bond

CMAQ = Community Multiscale Air Quality

CO = Carbon monoxide

CTM = Chemical Transport Model

Dep = Deposition

EGU = Electric Generating Unit

EC = Elemental carbon

EPA = Environmental Protection Agency

FF = Fabric filter

FGD = Flue gas desulfurization

HB1055 = Virginia House Bill 1055

Hg = Mercury

HG0 = Elemental mercury

HG2 = Reactive gaseous mercury (also divalent gaseous mercury)

HGP = Particle bound mercury

IC/BC = Initial and boundary conditions

IMPROVE = Interagency Monitoring of Protected Visual Environments

MACT = Maximum Available Control Technology

Max = Maximum

MCIP = Meteorology-Chemistry Interface Processor

MDN = Mercury Deposition Network

Min = Minimum

MM5 = Fifth Generation Mesoscale Model

NADP= National Acid Deposition Program

NAMMIS = North American Mercury Model Inter-comparison Study

NEI = National Emissions Inventory

NH_3 = Ammonia

NH_4 = Ammonium

NO_3 = Nitrate

NOAA = National Oceanographic and Air Administration

NO_x = Nitrogen oxides

NRV = Natural, recycled and volcanic

NWS = National Weather Service

OC = Organic carbon

$PM_{2.5}$ = Fine particular matter (with a diameter of less than or equal to 2.5 microns)

PM_{10} = Particulate matter (with a diameter of less than or equal to 10 microns)

PMF = Positive Matrix Factorization

PPTM = Particle and Precursor Tagging Methodology

PSU/NCAR = Pennsylvania State University/National Center for Atmospheric Research

REMSAD = REgional Modeling System for Aerosols and Deposition

SMOKE = Sparse-Matrix Operator Kernel Emissions

SO_2 = Sulfur dioxide

SO4 = Sulfate

TRI = Toxics Release Inventory

VA08 = Site identifier for the Culpeper, Virginia MDN monitoring site

VA28 = Site identifier for the Shenandoah National Park, Virginia MDN monitoring site

VA98 = Site identifier for the Harcum, Virginia MDN monitoring site

VDEQ = Virginia Department of Environmental Quality

VOC = Volatile organic compound

WBAN = Weather Bureau Army Navy

List of Units

g km^{-2} = grams per square kilometer (Note: g km^{-2} = $\mu g m^{-2}$)

in = inches

km = kilometer

lb/yr = pounds per year

m = meter

ppb = parts per billion

$\mu g\ m^{-2}$ = micrograms per square meter (Note: $\mu g\ m^{-2}$ = g km^{-2})

$\mu g\ m^{-3}$ = micrograms per cubic meter

ng m^{-2} = nanograms per square meter

tpy = tons per year

Executive Summary

The key objectives of the Virginia atmospheric mercury deposition modeling analysis were to

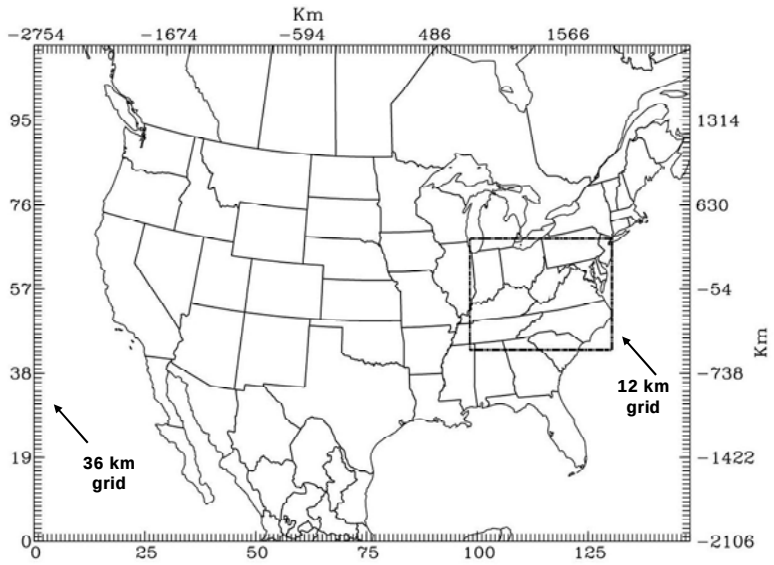
- Examine and quantify the contribution of global, regional and local emissions sources to mercury deposition throughout the Commonwealth;,
- Examine the effects of future-year emissions changes on airborne mercury deposition; and
- Provide information to support the further analysis of the impact of mercury deposition on the environment.

The modeling analysis was designed to account for the different scales and chemical interactions important to mercury deposition. The Community Multiscale Air Quality (CMAQ) modeling system was applied to simulate and quantify the effects of national and regional emissions on mercury deposition. The CMAQ model is a state-of-the-science, regional air quality modeling system that is designed to simulate the physical and chemical processes that govern the formation, transport, and deposition of gaseous and particulate species in the atmosphere. The CMAQ modeling system supports the detailed simulation of mercury (Hg), including the emission, chemical transformation, transport, and wet and dry deposition of elemental, divalent, and particulate forms of mercury. The CMAQ Particle and Precursor Tagging Methodology (PPTM) for mercury was used in this study to provide detailed, quantitative information about the contribution of selected sources, source categories, and/or source regions to simulated mercury concentrations and (wet and dry) deposition.

The EPA Gaussian model AERMOD was applied for 15 of the highest-emitting point sources in the Virginia emissions inventory to further assess the local contributions of these sources.

Both CMAQ and AERMOD were applied for an annual simulation period corresponding to a base year of 2001. This base year was selected based on meteorology. However, mercury emissions for 2002 were used for the Virginia sources since the 2002 emissions data represent the most recent, complete and quality assured emission inventory for Virginia. The base year for this study is therefore referred to as 2001/2002. The CMAQ modeling used both 36- and 12-km horizontal resolution, as shown in Figure ES-1.

Figure ES-1. CMAQ 36- and 12-km Resolution Nested-Grid Modeling Domain.



The evaluation of model performance for CMAQ considered concentration and deposition of both mercury and non-mercury species. Good model performance is achieved for ozone and $PM_{2.5}$ species. For mercury, simulated annual wet deposition amounts on average are within 10 percent of the observed values for both the 36- and 12-km domains.

The models were also applied for three future years: 2010, 2015 and 2018, using projected emissions data. Projection to the future years has provided information on the potential effects of future emissions changes and the effectiveness of potential emissions controls on mercury deposition. Analysis of the mercury deposition modeling results focused on Virginia and the major water basins.

Table ES-1 displays the base- and future-year emissions for Virginia. Emissions totals are given in Table ES-1a and percent reductions are given in Table ES-1b. Emissions are provided for Electric Generating Unit (EGU) sources, non-EGU sources, non-point (area) sources, and all sources (total). The non-point source category includes such sources as residential/industrial fuel combustion, fluorescent lamp breakage, health services, agricultural production, waste disposal, landfills, and other combustion sources.

Table ES-1a. Mercury Emissions Totals (lbs/year) for the Commonwealth of Virginia.

Region	EGU				Non-EGU				Non-Point				Total Emissions			
	2002	2010	2015	2018	2001/ 2002	2010	2015	2018	2002	2010	2015	2018	2002	2010	2015	2018
Virginia	1380	860	840	780	980	660	600	620	380	280	300	300	2740	1800	1740	1700

Table ES-1b. Percent Change in Mercury Emissions Totals Compared to the 2002 Base Year for the Commonwealth of Virginia.

Region	EGU			Non-EGU			Non-Point			Total Emissions		
	2010	2015	2018	2010	2015	2018	2010	2015	2018	2010	2015	2018
Virginia	-37.7	-39.1	-43.5	-32.6	-38.8	-36.7	-26.3	-21.1	-21.1	-34.3	-36.5	-37.9

The majority of the emissions reductions are expected by 2010. For Virginia, mercury emissions from EGUs are expected to be reduced by ~40 percent by 2010, mainly from controls mandated by the EPA Clean Air Interstate Rule (CAIR)[1], with additional reductions in 2015 and 2018 from the Clean Air Mercury Rule (CAMR)[2] and other state-specific rules. For the non-EGU sector in Virginia, mercury emissions are expected to be reduced by about 32 percent in 2010, decrease further in 2015, but slightly increase in 2018. The increases are due to future-year growth projections. For the non-point sector in Virginia, mercury emissions are expected to decrease by about 24 percent in 2010 (due to new MACT standards, etc.) and basically stay the same beyond that. For Virginia, total mercury emissions are expected to decrease by about 34 percent in 2010, and slightly more than that by 2015 and 2018.

[1] Although CAIR was vacated by the U.S. Court of Appeals on 11 July 2008, the modeling analysis included the provisions of the original rule.

[2] Although the United States Court of Appeals for the D.C. District ruled on 8 February 2008 that EPA's CAMR was illegal, the original provisions of CAMR compliance were simulated in the future-year modeling analysis for this study.

Table ES-2 summarizes CMAQ-simulated base and future-year mercury deposition (per unit area) for Virginia.

Table ES-2. Mercury Deposition Totals (g km^{-2}) for Virginia.

Region	2001/2002	2010	2015	2018
Virginia	22.7	18.6	18.2	18.1

Compared to the base year, the percent reduction in simulated mercury deposition is 18 percent for 2010, 19.9 percent for 2015, and 20.5 percent for 2018.

In this study, AERMOD was used to examine the effects of emissions changes on local deposition. Table ES-3 displays the average emissions for each year examined for the AERMOD sources (the fifteen facilities in Virginia with the most mercury emissions in 2002).

Table ES-3. Average Mercury Emissions (lbs/yr) for the Top 15 Mercury Emitters in the Commonwealth of Virginia, Based on Emissions for 2002.

	2001/2002	2010	2015	2018
All 15 Sources	130.7	75.4	69.1	65.5

Compared to the base year, the mercury emissions from the top 15 emitting sources are reduced by 40.7 percent for 2010, 44.2 percent for 2015, and 47.5 percent for 2018. These 15 sources include both EGU and non-EGU sources and emissions from both sectors are substantially reduced in all three future years. The corresponding percent reduction in mercury deposition from these sources (averaged over all 15 sources) is 38.3, 41.7 and 43.9 percent, respectively, for 2010, 2015 and 2018. For this subset of sources, the local reduction in mercury deposition from non-EGU sources is, on average, greater than that for EGU sources. This reduction in local deposition is consistent with a greater reduction in emissions for the non-EGU sources.

Source apportionment (CMAQ/PPTM) was applied for selected sources and source regions for the base year and 2018. The first CMAQ/PPTM scenario examined the contributions from mercury air emissions sources in 1) Virginia, 2) surrounding states (in the remainder of the 12-km modeling domain), 3) all other U.S. states (outside of the 12-km domain), 4) Canada and Mexico, 5) global emissions sources, and 6) natural emissions to mercury deposition in Virginia. The second CMAQ/PPTM scenario quantified the contributions from EGU and non-EGU facilities in Virginia and the surrounding states.

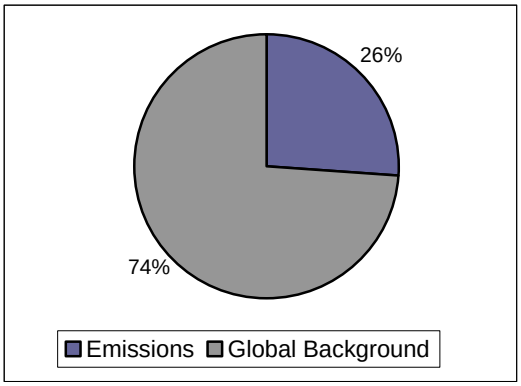
CMAQ/PPTM results for the entire state are presented in Figure ES-2. In this figure, the total deposition for the grid cell is given at the top of the page. The pie chart in the upper left-hand corner of the display summarizes the percent contribution to total deposition from emissions versus global background concentrations (represented in the modeling by the initial and boundary conditions (IC/BCs)). Global background refers to mercury that is circulated around the earth, and sources both within and outside of the modeling domain may contribute to the global background concentrations. The bar chart in the upper right-hand corner attributes total (overall) and emissions-based deposition to wet and dry deposition. Note that the total or overall deposition is the sum of the deposition from both emissions and global background sources. In the next two pie charts, the contributions from emissions sources are broken out in detail. The middle pie chart includes all tags. The lower pie chart does not include the global background and natural emissions source tags. Without the global background and natural emissions contributions, the

lower pie chart allows a more detailed comparison of the local and regional anthropogenic source contributions. Deposition is given in terms of the deposition per square kilometer.

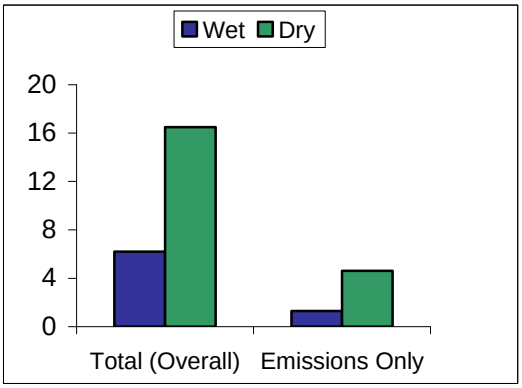
Figure ES-2. Summary of CMAQ/PPTM Mercury Tagging Results for Virginia.

Simulated Annual Hg Deposition for 2001 for Virginia: 22.69 g/km²

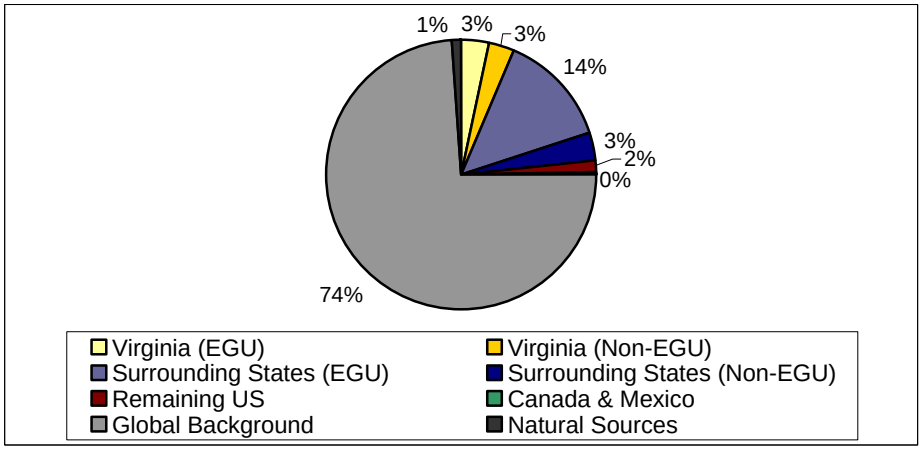
Emissions vs. Global Background Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

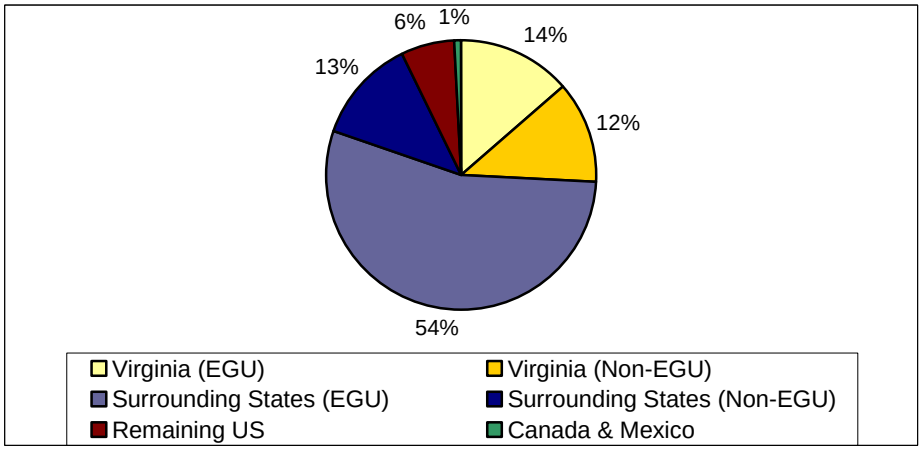
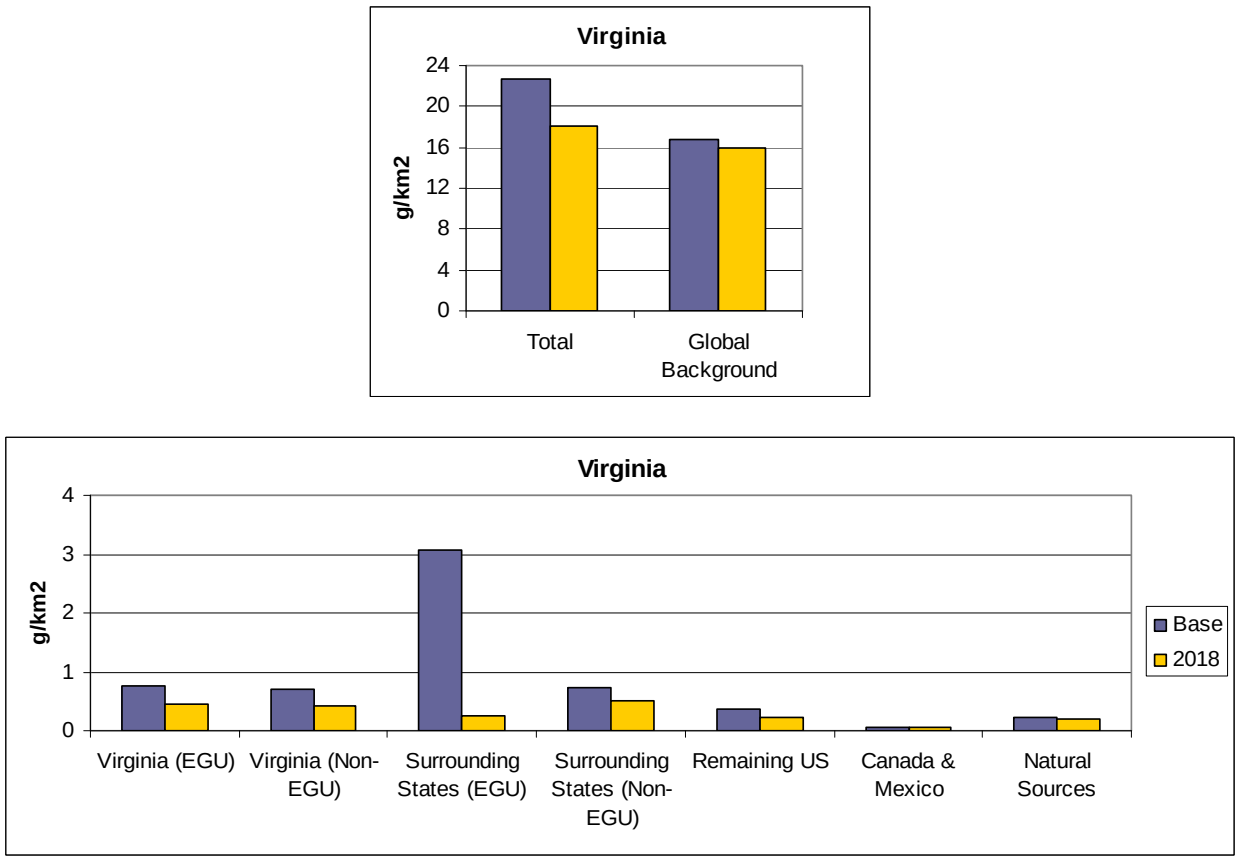


Figure ES-3 displays the relative contribution from each of the tagged source regions and source categories to mercury deposition for Virginia for both 2001/2002 and 2018. Global background (represented in the modeling by the initial and boundary condition (IC/BC) tag) is a primary contributor to simulated mercury deposition. The second largest contribution is from EGU sources in the surrounding states. This is followed by EGU sources in Virginia, non-EGU sources in Virginia, non-EGU sources in the surrounding states, sources in the remainder of the U.S., and natural sources.

Figure ES-3. CMAQ/PPTM 12-km Mercury Tagging Results for Virginia for 2001/2002 and 2018.



The contributions from all sources are lower for 2018. Although the IC/BC and natural emissions inputs are the same for both years, their contributions are lower for 2018 due to lower regional-scale ozone concentrations in the future year. Ozone and other oxidants influence mercury chemistry and lower ozone concentrations lead to less oxidation of certain forms of mercury and less mercury deposition. Of primary interest for this analysis is the change in contribution from the non-background/anthropogenic sources.

Overall mercury deposition for Virginia is lower by 20.4 percent for 2018, compared to the base year. The change in deposition is the result of changes in emissions from the various source categories and regions and the tagging results can be used to attribute the changes in deposition to the tagged source categories and regions. The greatest reduction comes from EGU sources located outside of Virginia (in the 12-km modeling domain that encompasses several nearby states), and 61 percent of the reduction in mercury deposition for Virginia is attributable to reductions in emissions from EGU sources in these nearby states. In addition, 7.2

percent of the overall simulated mercury reduction for Virginia is attributable to reductions in the emissions from EGU sources located within the state, 5.7 percent is attributable to reductions in the emissions from non-EGU sources in the state, 4.6 percent is attributable to reductions in non-EGU sources in nearby states, and 2.8 percent is attributable to emissions reductions in the remainder of the U.S. While the global background and natural emissions estimates, as input to the model, are the same for both years, there is also a reduction in the contribution from these tags. This is due to lower regional-scale concentrations of ozone and other species in the future year, which results in less mercury deposition. About 18 percent of the overall reduction in deposition for Virginia is attributed to a lower contribution from the boundary conditions and less than one percent of the overall reduction is attributed to a lower contribution from natural emissions. Since the emissions changes are similar for all three future-years, it is expected that the attribution of the changes for 2018 can be also applied for 2010 and 2015.

When compared in a relative sense, the CMAQ and AERMOD modeling results agree very well. The AERMOD results indicate that mercury reductions from a given facility within the state will reduce local mercury deposition by a percentage that is similar to the emissions reductions. On a statewide basis, the CMAQ results indicate that the average reduction in mercury deposition from facilities within the state is comparable, on a percentage basis, to the average emissions reduction. Both models indicate that in-state controls are effective in reducing the in-state contribution to mercury deposition.

1. Introduction

This report summarizes the methods and results of a mercury deposition modeling study for the Commonwealth of Virginia. In this study, the Community Multiscale Air Quality (CMAQ) modeling system was used to estimate the regional, national, and global contributions to airborne mercury deposition for Virginia and to examine the effects of expected future-year emissions changes on the modeled deposition amounts. The American Meteorological Society (AMS)/Environmental Protection Agency (EPA) Regulatory Model (AERMOD) was used to simulate the effects of local emissions and emissions changes for selected areas and sources.

The modeling results provide a basis for quantifying the contribution of emissions sources to mercury deposition and evaluating the effectiveness of control measures in reducing mercury deposition. By quantifying deposition, the modeling results also provide a link between the analysis of mercury emissions and the assessment of the impacts of airborne mercury on the environment.

1.1. Background and Discussion of the Mercury Deposition Problem for Virginia

Human exposure to mercury is most commonly associated with the consumption of contaminated fish. Due to measured high levels of mercury in fish, at least 44 U.S. states have, in recent years, issued fish consumption advisories. These advisories typically suggest limits on the consumption of certain types of fish or not eating fish from certain bodies of water because of unsafe levels of mercury contamination. States have identified more than 6,000 individual bodies of water as mercury impaired and have issued mercury fish advisories for more than 2,000 individual bodies of water.

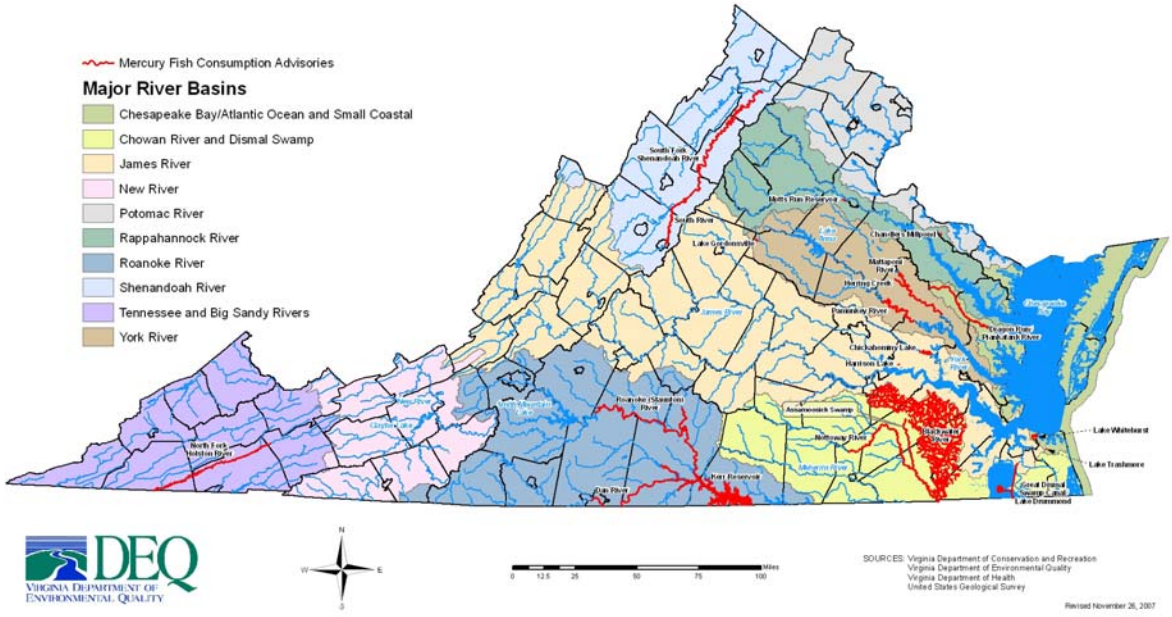
Until 2002, significant mercury contamination in Virginia surface waters was known only in three rivers (the North Fork of the Holston River, the South River, and the South Fork of the Shenandoah River) and was associated with historical industrial releases. Since then, however, state monitoring efforts have identified mercury contamination in a number of surface waters without readily identifiable sources.

The Virginia Department of Environmental Quality (VDEQ) expanded its mercury monitoring in 2002 based on an increasing scientific understanding of mercury's environmental chemistry and discoveries in other states (e.g., Florida, Maryland) of mercury pollution in water bodies without direct sources. The 2002 monitoring effort focused mostly on river basins in eastern Virginia. As a result of this effort, Virginia found elevated mercury levels in some fish in the Blackwater River, the Great Dismal Swamp Canal, the Dragon Run Swamp, and the Piankatank River. Consistent with findings from Florida and elsewhere, these water bodies in Virginia possess characteristics favorable for the formation of the highly bio-accumulative form of mercury, methyl mercury. These characteristics include low dissolved oxygen, high organic matter, and low pH, and are most prevalent in "backwaters" of the southeastern portion of the state.

Since that time, monitoring efforts have continued and fish consumption advisories have been issued for several bodies of water in Virginia. VDEQ has compiled a list of "mercury sensitive waters," the characteristics of which are consistent with mercury methylation and bioaccumulation of mercury in fish. These are primarily located along the coastal plain and include: Lake Gordonsville (in Louisa Co.), Lake Whitehurst (in Norfolk), Lake Trashmore (in Virginia Beach), a portion of the Mattaponi River, a portion of Herring Creek, a portion of the Pamunkey River, Chickahominy Lake (in Charles City Co.), Harrison Lake (in Charles City Co.), portions of the Blackwater River, a portion of the Dismal Swamp Canal, and Dragon Run

Swamp. Other areas suspected of being “mercury sensitive waters” for which monitoring was conducted in 2006-2007 include additional portions of the Blackwater River, the Nottoway River, and the Meherrin River. Figure 1-1 displays the waterways with fish consumption advisories.

Figure 1-1. Major River Basins and Waters under Fish Consumption Advisories for Mercury in Virginia.



The primary source of mercury to these water bodies is suspected to be atmospheric deposition. There are currently two Mercury Deposition Network (MDN) sites located in Virginia, in Shenandoah National Park and Harcum. A third site, located near Culpeper, was operational between late 2002 and 2006. Wet deposition data from these sites have contributed to the regional characterization of mercury transport and deposition throughout the state. Supplemental monitoring of dry deposition at the Harcum site in 2005 revealed that dry deposition of reactive gaseous (divalent) mercury along the Piankatank River (near the Chesapeake Bay) and in upstream areas is an important contributor to the high mercury levels observed in the water and fish in the area.

Global, regional, and local sources of air mercury emissions contribute to the deposition, and understanding these contributions is an important step toward identifying measures that will effectively reduce mercury deposition and environmental mercury levels.

The key objectives of the mercury deposition modeling analysis were to examine and quantify the contribution of global, regional and local emissions sources to mercury deposition throughout the Commonwealth, to examine the effects of future-year emissions changes on airborne mercury deposition, and to provide information to support the further analysis of the impact of mercury deposition on the environment.

The results of this study are currently being used by VDEQ to assess the effectiveness of planned emissions controls, evaluate the need for additional measures to reduce mercury emissions in Virginia, and develop a long-term management strategy for meeting water quality criteria and protecting human health.

1.2. Overview of Mercury Deposition Modeling

Several different types of modeling and analysis tools have been developed and applied to the study of mercury deposition. Modeling tools differ primarily in terms of overall numerical formulation (e.g. grid based (Eulerian), trajectory (Lagrangian), plume (Gaussian) formulations), treatment of mercury chemistry and other processes (such as deposition and the effects of meteorology), and applicable scales (e.g. global, regional, local). In addition, data analysis techniques such as receptor modeling have also been used to study mercury deposition. A portion of the literature review contained in Appendix C of this report summarizes the ongoing development of mercury capabilities in air quality modeling and some recent national- and regional-scale applications.

Grid-based models are designed to simulate the physical and chemical processes that govern the formation, transport, and deposition of gaseous and particulate species in the atmosphere. Two state-of-the-science, regional air quality modeling systems for mercury deposition are CMAQ and the REgional Modeling System for Aerosols and Deposition (REMSAD), both of which were developed under funding from EPA and both of which have been used for national- and regional-scale regulatory assessments. The CMAQ model was designed as a "one-atmosphere" model and can be used to simulate ozone, particulate matter, and mercury. CMAQ supports the detailed simulation of the emission, chemical transformation, transport, and wet and dry deposition of elemental, divalent, and particulate forms of mercury.

According to Bullock et al. (2008), the CMAQ model reflects the current state-of-the-science in simulating the atmospheric processes that influence the dispersion, advection, chemical transformation, and deposition of mercury. The CMAQ model includes three mercury (Hg) species: elemental mercury (Hg^0 or HG0), reactive gaseous mercury (RGM or HG2), and particulate mercury (PHg or HGP). Throughout the remainder of this report, these three forms of mercury are referred to as HG0, HG2, and HGP. Reactive gaseous mercury is known to be comprised almost entirely of divalent mercury (Hg^{2+}), since Hg compounds at other valence states tend to be chemically unstable in the atmosphere. Particle-bound mercury is also primarily comprised of divalent mercury, but may also include elemental mercury.

In addition to the state-of-the-science chemical mechanism for mercury, other key features of the CMAQ model in simulating mercury deposition include state-of-the-science advection, dispersion and deposition algorithms, the latest version of the Carbon Bond chemical mechanism (CB05), and the CMAQ Particle and Precursor Tagging Methodology (PPTM).

PPTM for mercury (Douglas et al., 2006) provides detailed, quantitative information about the contribution of selected sources, source categories, and/or source regions to simulated mercury concentrations and (wet and dry) deposition. Mercury emissions from selected sources, source categories, or source regions are (numerically) tagged and then tracked throughout a simulation, and the contribution from each tag to the resulting simulated concentration or deposition for any given location can be quantified.

Several areas of potential uncertainty that affect grid-based models such as CMAQ include: representation of emissions (including natural emissions), boundary conditions (global emissions) and meteorology; uncertainties in the chemical reaction rates; representing the dispersion and chemistry in plumes; and accounting for the deposition of elemental mercury and re-emission of mercury.

Trajectory models are an alternative to grid-based modeling. In these models, the transport of emissions from specific sources (or to specific receptor locations) is estimated using forward (or backward) trajectories. The movement of air parcels along the trajectories is guided by

meteorological parameters (such as wind and stability) and the contents of each air parcel may be subject to dispersion and chemical transformation (depending upon the complexity of the model). Examples of trajectory based models include CALPUFF and HYSPLIT. Use of the HYSPLIT model for mercury deposition modeling is discussed in Cohen et al. (2004) and in Cohen (2004). The authors estimate contributors to mercury deposition to the Great Lakes and the Chesapeake Bay. The results tend to differ from grid-based modeling estimates in that very distant sources are estimated to contribute to deposition loading. Trajectory modeling is not well suited for simulating contributions from distant sources since the uncertainty of any given trajectory increases with the time (and thus distance between the source and receptor).

Gaussian dispersion (or plume) models are designed to simulate the local-scale dispersion and deposition of pollutants. Currently, the most widely used model of this type is AERMOD (EPA, 2004). AERMOD is a steady-state Gaussian dispersion model designed to simulate the local-scale dispersion of pollutants from low-level or elevated sources in simple or complex terrain. It is an EPA "preferred" model (40 CFR Part 51, Appendix W, *Guideline on Air Quality Models*). Recent versions of AERMOD (EPA, 2006a) include algorithms for simulating deposition of gaseous and particulate pollutants. AERMOD can also be used to simulate the effects of local emission changes for selected areas and sources. Typical applications of AERMOD limit the analysis of results to within approximately 10 kilometers (km) of the source location.

AERMOD does not include a chemical mechanism for mercury. That is, AERMOD can be used to simulate the dispersion and deposition of mercury, but not the chemical transformation of mercury. However, this may not be an important limiting factor for near-source assessments. Wet and dry deposition can be estimated using AERMOD. The wet deposition algorithms use a washout ratio that is dependent on precipitation rate and the properties of the pollutant being simulated. Dry deposition is based on aerodynamic resistance calculations and the deposition velocities are calculated based on surface type and local meteorological conditions. An important limitation of Gaussian models such as AERMOD is the simple representation of the meteorological conditions (important but complex meteorological features cannot be represented). Representing the effects of complex terrain (such as that found in western Virginia) and land-use are also sources of uncertainty.

Receptor modeling, as applied to mercury deposition, uses a combination of observed wet deposition data, air quality data, meteorological data, and information about emissions source characteristics (e.g., location, emissions process, speciation) to identify potential sources or source categories that may be contributing to observed deposition. Examples of statistical-based receptor modeling approaches include the Positive Matrix Factorization (PMF) and UNMIX tools. One limitation of receptor modeling is that meteorological conditions are generally not considered or are represented by a few simple parameters. In some cases, receptor modeling has been combined with trajectory modeling as a way to better incorporate the effects of meteorology and narrow down the source-receptor relationships. However, as noted earlier, the uncertainties associated with trajectory modeling, which increase with distance from the receptor location, may also add to the uncertainties in the hybrid source-receptor modeling results. Other limitations of source-receptor modeling include the need for very high resolution, comprehensive data to establish the contributing source profiles and reliance on statistical rather than physical and chemical relationships to infer source attribution.

1.3. Summary of the Mercury Deposition Modeling Approach for Virginia

The Virginia mercury deposition modeling includes the use of several different types of air quality and deposition models. These include a state-of-the-science regional modeling system with source-contribution-assessment capabilities to simulate and quantify the effects of national and regional emissions on mercury deposition, and a Gaussian model for the detailed assessment of local contributions. In addition, boundary conditions for the regional model are based on the output from a global model. The approach was designed to account for the different scales and chemical interactions important to mercury deposition. Model selection is discussed in detail in the modeling protocol, which is included as Appendix A.

At the regional scale, the latest version (version 4.6) of the Community Multiscale Air Quality (CMAQ) modeling system was applied. The CMAQ model is a state-of-the-science, regional air quality modeling system that is designed to simulate the physical and chemical processes that govern the formation, transport, and deposition of gaseous and particulate species in the atmosphere. The CMAQ modeling system supports the detailed simulation of mercury (Hg), including the emission, chemical transformation, transport, and wet and dry deposition of elemental, divalent, and particulate forms of mercury.

The CMAQ Particle and Precursor Tagging Methodology (PPTM) for mercury was used in this study to provide detailed, quantitative information about the contribution of selected sources, source categories, and/or source regions to simulated mercury concentrations and (wet and dry) deposition. Using this methodology, mercury emissions from selected sources, source categories, or source regions are (numerically) tagged and then tracked throughout a simulation, and the contribution from each tag to the resulting simulated concentration or deposition for any given location can be quantified. By tracking the emissions from selected sources or source locations, the methodology also provides information on the fate of the emissions from these sources.

The CMAQ modeling domain for this study includes an outer grid that encompasses the entire contiguous U.S. as well as portions of Canada and Mexico and, therefore, all or nearly all mercury emissions sources in North America. The horizontal resolution of the outer, coarse grid is 36 kilometers (km). The domain also includes a higher-resolution inner grid that encompasses Virginia and several surrounding states. Boundary concentrations for the regional-scale modeling (applied to the outermost grid) were estimated based on global model simulation results.

At the local scale, the EPA Gaussian model AERMOD was applied for selected point sources in the Virginia emissions inventory. Initially, AERMOD was used to screen the mercury emissions sources to determine the potential for impacts outside the vicinity of the source. AERMOD was also used to simulate the effects of local emission changes for selected areas and sources.

Both CMAQ and AERMOD were applied for an annual simulation period corresponding to a base year which, as detailed later in this report, is primarily 2001 but some of the emissions inputs are for 2002. Throughout the report, the base-year scenario is referred to as either the “base year” or the “2001/2002 base year.” The models were also applied for three future years: 2010, 2015 and 2018. PPTM was applied for selected sources and source regions for the 2001/2002 base year and 2018. Emissions inputs for the application of CMAQ and AERMOD were prepared using the latest available emissions data and projections, as obtained from VDEQ and EPA. Model-ready meteorological input files for 2001 and other requisite input files for CMAQ were provided by EPA. Meteorological inputs for AERMOD were prepared using available meteorological data for this same period.

The components of the base- and future-year modeling analyses are summarized in Figure 1-2. Figure 1-2a displays the components of the base-year modeling analysis. This includes the evaluation of model performance as well as diagnostic and sensitivity tests to examine the response of each modeling system to changes and/or uncertainties in the inputs. Figure 1-2b displays the components of the future-year modeling. The combination of modeling tools selected for this study has allowed us to address the variety of factors influencing mercury deposition in Virginia. Projection to the future years has provided information on the potential effects of future emissions changes and the effectiveness of potential emissions controls on mercury deposition.

Figure 1-2a. Schematic Diagram of the Virginia Mercury Deposition Modeling Analysis: Base-Year Modeling.

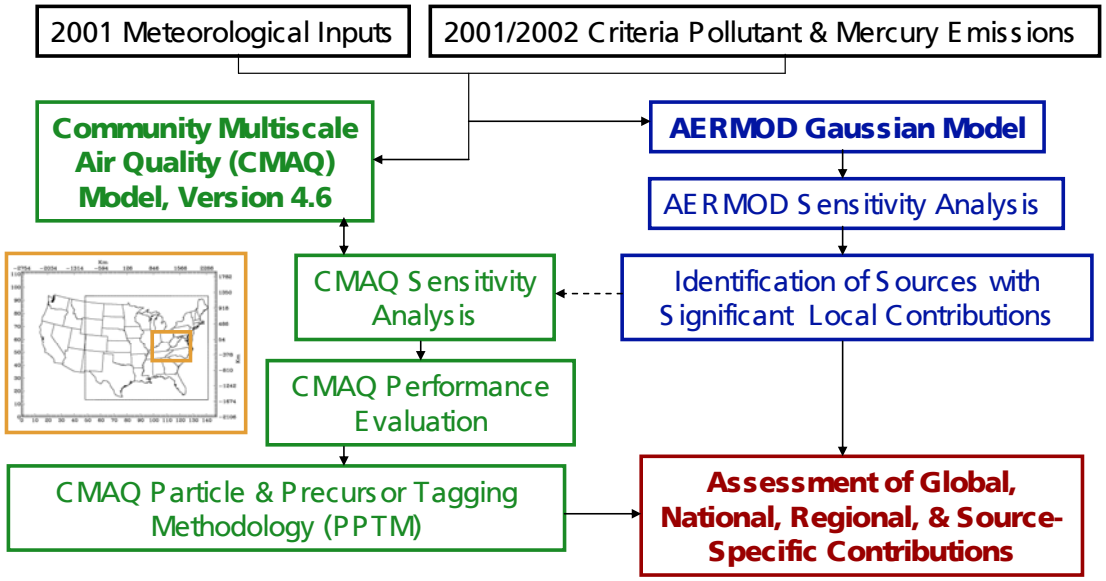
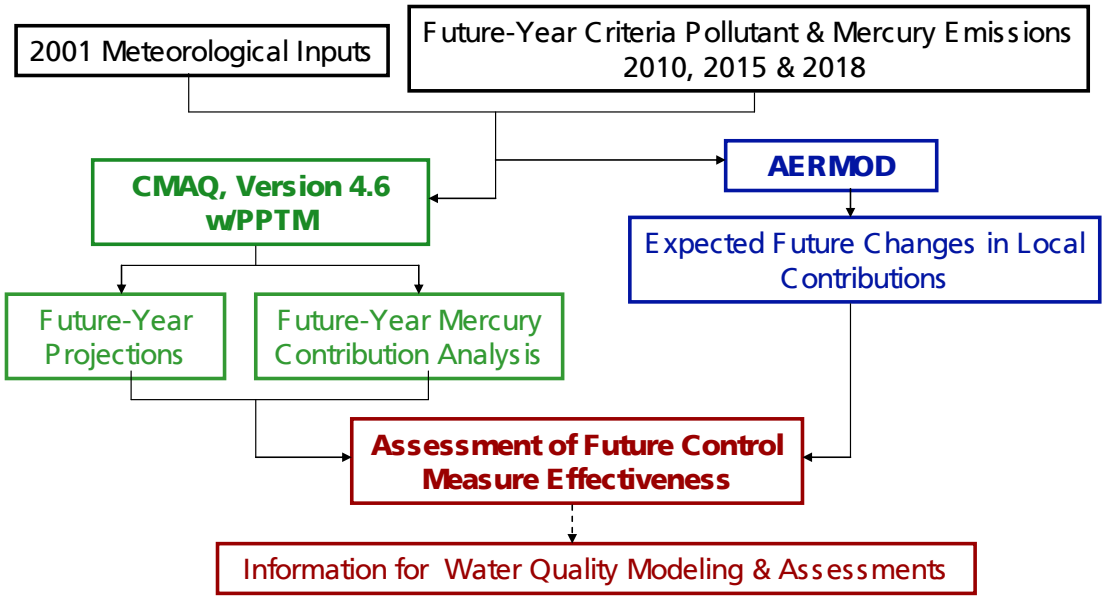


Figure 1-2b. Schematic Diagram of the Virginia Mercury Deposition Modeling Analysis: Future-Year Modeling.



1.4. Report Contents

The methods and results of the mercury deposition modeling are presented in the remainder of this report. Section 2 provides a conceptual description of mercury deposition for Virginia. Sections 3 and 4 provide details of the grid-based (CMAQ) and source-specific (AERMOD) modeling methodologies, respectively. Section 5 presents the CMAQ modeling results. Section 6 presents the AERMOD modeling results. Section 7 summarizes the results and findings from the mercury deposition assessment. The report also contains three appendixes. The modeling protocol is included as Appendix A. The conceptual model report, prepared earlier in the study, is provided as Appendix B. Finally, the emissions data analysis report, summarizing a review of the mercury emissions data that were used in the modeling, is provided in Appendix C.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2. Conceptual Description of Mercury Deposition for Virginia

A conceptual description for mercury deposition for Virginia was developed at the beginning of this study and is presented in Appendix B. This conceptual description is based on observed mercury deposition data, meteorological data, and emissions inventory information. It also draws on mercury deposition modeling results from prior studies. The key elements of the conceptual description are summarized and updated in this section of the report, based on the latest data and mercury deposition modeling results (which are presented later in this report).

Mercury wet deposition data are available for three Mercury Deposition Network (MDN) sites in Virginia: Culpeper, Shenandoah National Park, and Harcum (NADP, 2008). The period of record for the MDN data is late 2002 through 2006 for Culpeper, late 2002 to the present for Shenandoah, and approximately 2005 to the present for the Harcum site. The Culpeper site was located in north central Virginia. The Shenandoah site is a high elevation monitoring site located within the national park (in northwestern Virginia), and the Harcum site is located along the southern portion of the inner coast of the Chesapeake Bay. The locations of the sites are shown in Figure 2-1, along with the locations of MDN sites in several neighboring states (which will be referenced later in this section). Each measurement of wet deposition represents an approximate seven-day period. Annual mercury wet deposition for these sites is summarized in Table 2-1. The units are nanograms per square meter (ng m^{-2}).

Figure 2-1. Locations of MDN Monitoring Sites in Virginia and Neighboring States.

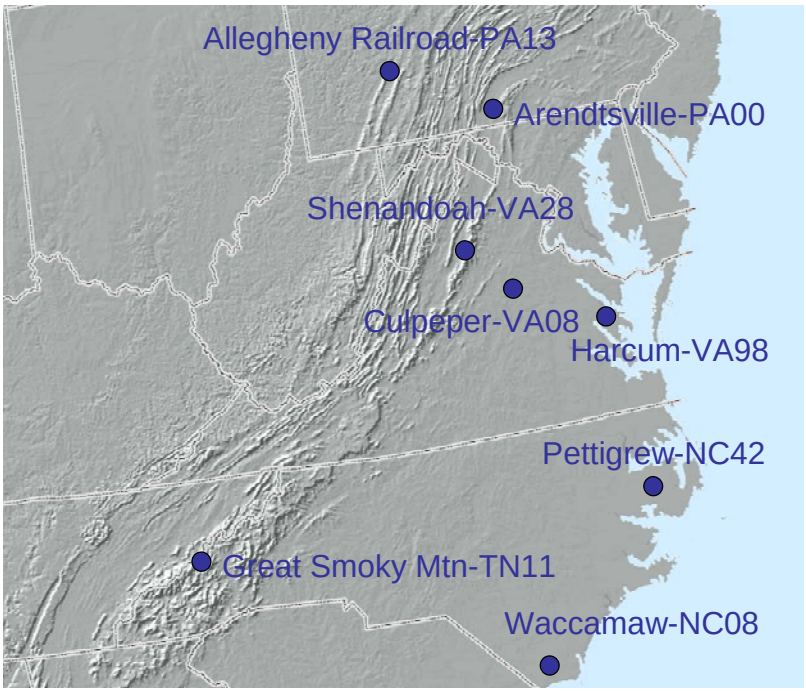
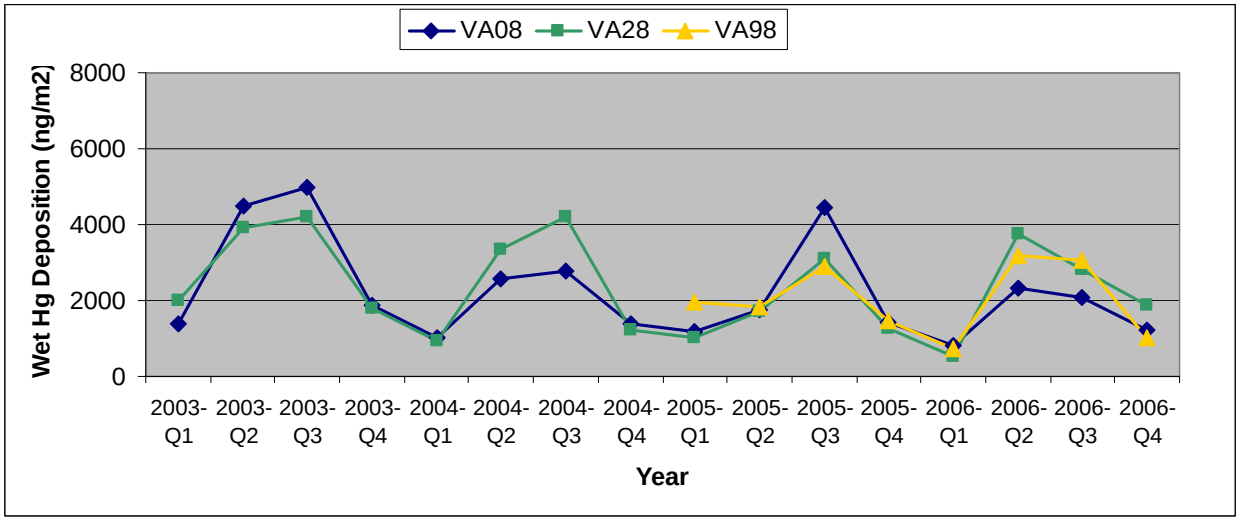


Table 2-1. Summary of Annual Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia.

Site Name (MDN ID)	Annual Observed Mercury Wet Deposition (ng m^{-2})			
	2003	2004	2005	2006
Culpeper (VA08)	13,097	7,784	8,811	6,463
Shenandoah National Park (VA28)	11,922	9,727	7,074	8,986
Harcum (VA98)	—	—	8,218	8,029

Within each calendar year, there are variations in deposition by week, month, and quarter, primarily in accordance with variations in rainfall amount. Figure 2-2, which displays quarterly deposition amounts, indicates that, like rainfall, mercury deposition has an annual cycle, with higher deposition amounts during the second and third quarters (April through June and July through September, respectively). The deposition amounts are generally similar among the three sites.

Figure 2-2. Quarterly Observed Mercury Wet Deposition (ng m^{-2}) for the Three MDN Monitoring Sites in Virginia.



Analysis of both the data and recent modeling results has provided insight into some key questions regarding the nature of mercury deposition. Key questions and issues addressed in the conceptual description are summarized in the remainder of this section.

- **Is mercury deposition primarily a local issue, or are regional, national, and global factors important?**

  Based on a review of the available data and prior modeling results, it is expected that global, national, regional, and local factors contribute to mercury deposition in Virginia. The primary source of mercury to impaired water bodies is believed to be atmospheric deposition, which is comprised of both natural and anthropogenic emissions. These emissions can be directly emitted or they can be re-emitted to the atmosphere after being deposited at another location.

Various atmospheric processes influence the transport and deposition of mercury and these involve a variety of scales ranging from global to local. Specifically:

- Mercury may be transported globally by atmospheric circulation systems and prior (Myers et al., 2006) and current mercury deposition modeling results (from the Virginia mercury study) indicate that global background may comprise 60 to 75 percent of the contribution to mercury deposition at the Virginia MDN sites.
- Mercury may also be subject to regional-scale transport. Modeling also indicates that emissions contributing to the simulated deposition are from Virginia, the neighboring states, and other states within the U.S. Similarities in observed mercury wet deposition among monitoring sites in Virginia and several neighboring states also support the conclusion that mercury deposition is a regional-scale issue.
- Finally, prior and current modeling also reveals local source-specific contributions to mercury deposition at the three monitoring sites.

- **Does mercury deposition vary with time?**

  Annual mercury wet deposition amounts vary by year for monitoring sites in Virginia and the surrounding states.

  In addition, within each calendar year, there are variations in deposition by week, month, and quarter, primarily in accordance with variations in rainfall amount.

  Mercury deposition (and rainfall amount) appears to have an annual cycle, with higher deposition amounts during the second and third quarters (April through June and July through September, respectively). As illustrated later in this section, this annual cycle is consistent with that for precipitation.

- **Does mercury deposition vary from location to location?**

  Measurements of wet mercury deposition data indicate that deposition varies from location to location. For the period 2003-2005, annual mercury deposition for the Virginia MDN sites is about the same as that for nearby sites in southern Pennsylvania, and lower than that for nearby sites in North Carolina and Tennessee. In some cases, deposition characteristics are similar for geographically similar sites within the mid-Atlantic region. For each of the Virginia MDN sites, it is possible to identify a monitoring site (from a neighboring state) that has similar deposition characteristics.

  Prior modeling performed by EPA (EPA, 2005a) and the current regional modeling results for the Virginia mercury study also indicate that mercury deposition varies from location to location and more specifically that annual mercury deposition is related to the distribution of emission sources, especially within the eastern U.S.

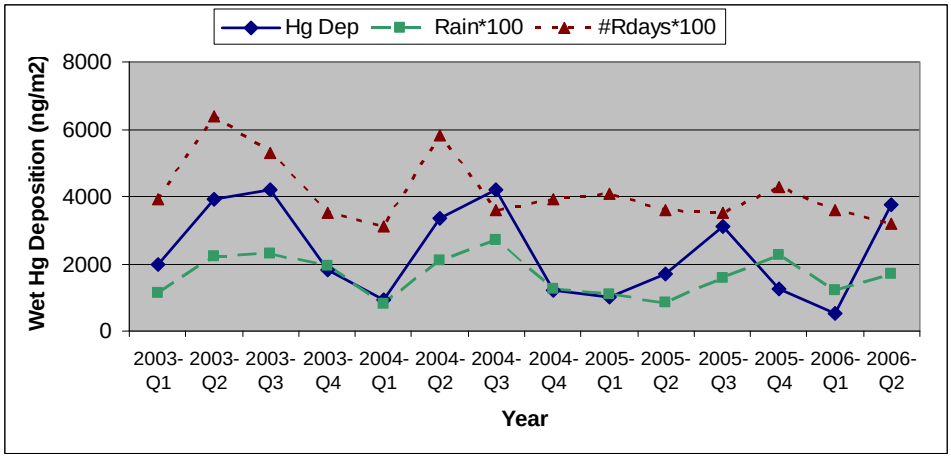
  At the local level, the source-specific modeling indicates that there may be areas of high deposition close to mercury emitting sources.

- **How does meteorology influence mercury deposition in Virginia?**

  A number of different meteorological factors influence mercury deposition in Virginia. Key factors include precipitation, temperature, wind speed, and the potential for recirculation. The relative importance of each of these factors varies among the three monitoring sites. In addition, there are different types of meteorological conditions and combinations of parameters that lead to high deposition.

Precipitation is an important mechanism for wet mercury deposition. Mercury wet deposition is correlated with rainfall, but rainfall amount does not fully explain the observed variations in deposition. As an example, Figure 2-3 compares quarterly mercury wet deposition with rainfall amount and number of days with measurable rainfall for the Shenandoah MDN site (VA28). For plotting purposes, rainfall amount has been multiplied by 100, such that a value of 2000 corresponds to 20 inches of rainfall in a given quarter. The number of rain days has also been multiplied by 100, such that a value of 2000 corresponds to 20 days with rain in a given quarter. Both mercury wet deposition and precipitation are measured at the MDN site. This comparison indicates that mercury deposition is affected by the amount and frequency of precipitation, but that there are also other factors that influence mercury deposition.

Figure 2-3. Quarterly Observed Mercury Wet Deposition (ng m^{-2}), Total Rainfall (Scaled to Inches x 100), and Number of Days with Rainfall (Scaled by 100): Shenandoah National Park (VA28).



For all three MDN sites, there is a positive correlation between rainfall, temperature, and relative humidity such that the greater the values of these parameters, the greater the deposition. Higher deposition is associated with lower wind speeds and a well mixed (or unstable) atmosphere. The conditions are representative of summertime conditions and consistent with the timing of the higher observed deposition amounts.

Wind directions, both near the surface and at upper levels, may influence the regional and local transport of mercury emissions from source regions or individual sources for subsequent deposition at the monitoring sites (and to bodies of water) in Virginia. For all three MDN sites, wind directions are slightly different during high deposition periods compared to all periods and indicate possible regional or local transport of mercury emissions from the east or northeast for Culpeper and Shenandoah, and from the south or southwest for Harcum.

Finally, dry deposition of mercury is influenced by several meteorological factors including the temperature characteristics of the atmosphere and the wind speed.

- **Are there discernable trends in mercury deposition and have recent changes in deposition been accompanied by changes in emissions or primarily driven by meteorological variability?**

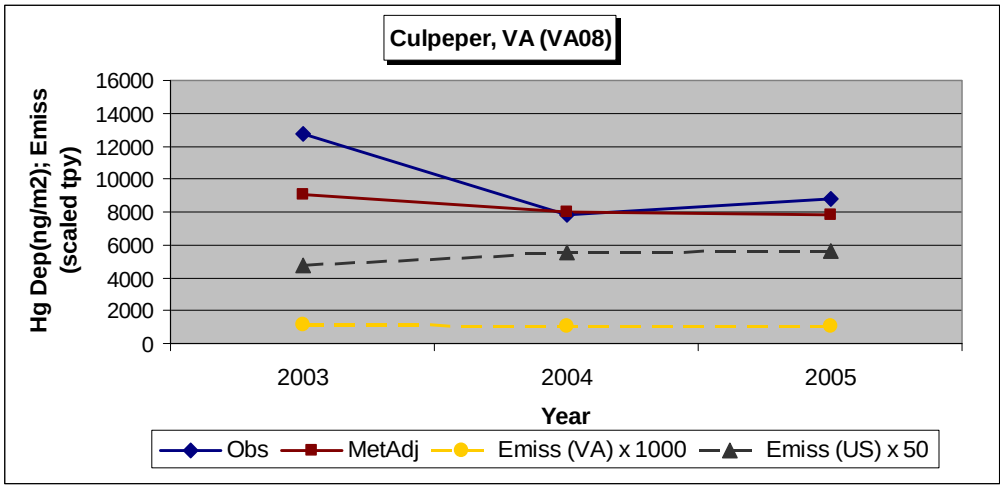
  Variations in meteorology contribute to observed variations in quarterly and annual mercury wet deposition.

  Annual deposition amounts that have been adjusted to account for these variations in meteorology exhibit much less variation among the years. Figure 2-4 shows observed and meteorologically adjusted deposition values along with the EPA Toxics Release Inventory (TRI) emissions (EPA, 2007a) for Virginia and the entire U.S. Note that for plotting purposes, the emissions totals for Virginia (tons per year (tpy)) have been multiplied by 1000 and the emissions totals (tpy) for the U.S. have been multiplied by 50.

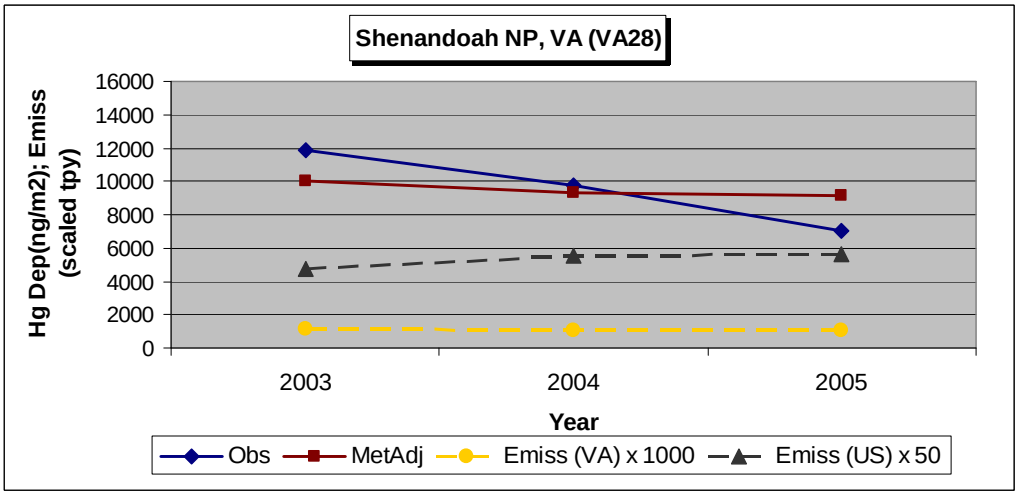
Figure 2-4. Actual and Meteorologically-Adjusted Annual Mercury Wet Deposition (ng m-2) for MDN Monitoring Sites in Virginia Plotted Together with TRI Annual Mercury Emissions Totals (scaled tpy) for Virginia and the Entire U.S.

Note that the Emissions are Scaled to Enable Display of the Different Datasets and Comparison of the Tendencies.

(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



For both sites, the meteorologically adjusted deposition values for 2003-2005 are consistent with changes in the emissions for Virginia. The adjusted deposition values indicate a slight downward trend.

Similarly, for sites in Pennsylvania and North Carolina, the meteorologically adjusted deposition trends for 2000-2005 are consistent with changes in the U.S. emissions. For 2003 to 2005 the trend is slightly upward, in contrast to that for the Virginia sites.

- **What is the relative importance of wet versus dry deposition, and the various forms of mercury?**

  Prior and current regional modeling results suggest that for all three Virginia sites, dry deposition is a significant contributing factor to total mercury deposition. Overall, for these studies, the simulated dry deposition represents about 45 percent or more of the total deposition. Prior modeling also indicates that both wet and dry deposition are predominantly reactive gaseous mercury, and that dry deposition includes about 10 percent particulate mercury.

  The implications regarding dry deposition are consistent with monitoring data. The National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) conducted a monitoring study during the summer of 2005 at the Harcum site (NOAA, 2007) and found that dry deposition was significant and was dominated by reactive gaseous mercury.

  Source-specific modeling results also indicate a predominance of dry deposition. Wet deposition is modeled to occur near the source, while dry deposition occurs both near the source and downwind. This type of modeling suggests that, near the source locations, particulate-bound mercury deposition is greatest followed by reactive gaseous mercury deposition.

3. Grid-Based Mercury Deposition Modeling Methodology

The Community Multiscale Air Quality (CMAQ) model was used to simulate mercury deposition at the regional scale. This section of the report describes the methodology for the application of CMAQ.

3.1. Selection and Overview of CMAQ Version 4.6 with PPTM

The selection of CMAQ as the primary modeling tool for the Virginia mercury study was based on the technical formulation, capabilities, and features of the model. In accordance with EPA guidance (EPA, 2006b), its peer-review status and use in previous applications was also considered.

The CMAQ model is a state-of-the-science, regional air quality modeling system that is designed to simulate the physical and chemical processes that govern the formation, transport, and deposition of gaseous and particulate species in the atmosphere (Byun and Ching, 1999). The CMAQ model was designed as a "one-atmosphere" model and can be used to simulate ozone, particulate matter, and mercury. For mercury, CMAQ supports the detailed simulation of the emission, chemical transformation, transport, and wet and dry deposition of elemental, divalent, and particulate forms of mercury. The latest version of CMAQ, version 4.6, was used for this study.

According to Bullock et al. (2007), the CMAQ model reflects the current state-of-the-science in simulating the atmospheric processes that influence the dispersion, advection, chemical transformation and deposition of mercury. The CMAQ model includes three mercury (Hg) species: elemental mercury (HG0), reactive gaseous mercury (HG2), and particulate-bound mercury (HGP). Reactive gaseous mercury is known to be comprised almost entirely of divalent mercury (Hg^{2+}), since Hg compounds at other valence states tend to be chemically unstable in the atmosphere. Particulate-bound mercury is also primarily comprised of divalent mercury, but may also include elemental mercury.

Mercury simulation capabilities were first incorporated into the CMAQ model by adding gaseous and aqueous chemical reactions involving mercury to the CMAQ chemical mechanism (Bullock and Brehme, 2002). Since that time, the chemical mechanism has been further updated to include additional reactions and updated information on reaction rates. The most recent changes to CMAQ for mercury include an improved dry deposition algorithm and the incorporation of natural mercury emissions. The CMAQ modeling system, including the mercury modeling component, has been peer reviewed (e.g., Amar et al., 2005).

In addition to the state-of-the science chemical mechanism for mercury, other key features of the CMAQ model in simulating mercury deposition include state-of-the-science advection, dispersion and deposition algorithms, the latest version of the Carbon Bond chemical mechanism (CB05), and the CMAQ Particle and Precursor Tagging Methodology (PPTM).

PPTM for mercury (Douglas et al., 2006) provides detailed, quantitative information about the contribution of selected sources, source categories, and/or source regions to simulated mercury concentrations and (wet and dry) deposition. Mercury emissions from selected sources, source categories, or source regions are (numerically) tagged and then tracked throughout a simulation, and the contribution from each tag to the resulting simulated concentration or deposition for any given location can be quantified. By tracking the emissions from selected sources or source locations, the methodology also provides information on the fate of the emissions from these sources.

The CMAQ model has been used by EPA to support the development of the Clean Air Mercury Rule (CAMR) (EPA, 2005a). This study included the evaluation of global modeling results to prescribe boundary conditions for CMAQ, evaluation of mercury deposition using MDN data, and assessment of the contribution of mercury emissions from coal-fired power plants on mercury deposition in the U.S.

CMAQ was also included in the North American Mercury Model Intercomparison Study (NAMMIS) (Bullock et al., 2008) and the performance and response of CMAQ was found to be reasonable and also consistent with that for the REgional Modeling System for Aerosols and Deposition (REMSAD), which has been widely applied and tested for mercury (e.g., Myers et al., 2006).

Additional detail regarding the selection of the CMAQ model is provided in the modeling protocol document (Appendix A).

3.2. CMAQ Application Procedures for the Virginia Mercury Deposition Modeling Study

The application of CMAQ, including the simulation period, modeling domain, input preparation, performance evaluation, and base-case and future-year modeling, are discussed in this section.

As noted throughout this section, many of the components of the modeling analysis were based on the CAMR modeling, including the outer modeling domain, simulation period, meteorological inputs, and national-scale emission inventories. Key differences between this analysis and the CAMR modeling analysis include the use of a high-resolution modeling domain over Virginia and the surrounding states, updated emissions estimates, in particular for Virginia, and the use of CMAQ version 4.6 with PPTM.

3.2.1. Simulation Period

The simulation period for the application of CMAQ is calendar year 2001. All of the inputs, with the exception of the mercury emissions for Virginia, represent 2001. In running the model, the simulation period was divided into two parts covering January through June and July through December, respectively. Each part of the simulation also includes an additional five start-up simulation days, which are intended to reduce the influence of uncertainties in the initial conditions on the simulation results.

In selecting this simulation period, meteorological and emissions database availability and meteorological representativeness were considered. Additional detail regarding the selection of the simulation period is provided in the modeling protocol document (Appendix A).

The 2001 simulation period is characterized by normal precipitation amounts during the summer months for Virginia and most of the surrounding areas, but less than normal precipitation during the fall period. Temperatures during the summer months were normal for 2001.

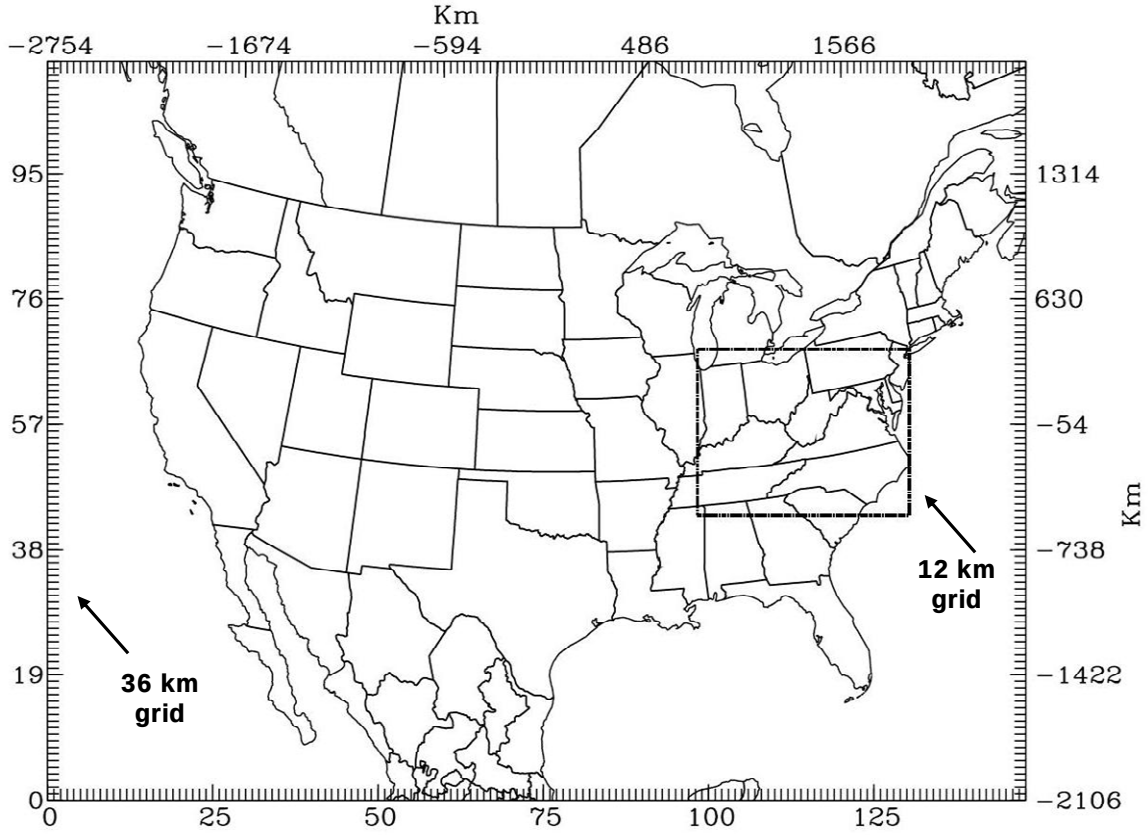
While 2001 was selected as the simulation period, sensitivity testing was conducted using 2002 meteorological inputs to examine the differences in the CMAQ results due to the use of alternative meteorological conditions.

3.2.2. CMAQ Modeling Domain

Horizontal Extent and Grid Spacing

The CMAQ modeling domain is illustrated in Figure 3-1. The outermost domain is based on the regional-scale modeling domain that has been established by EPA for regulatory applications (e.g. CAMR modeling). The outer grid encompasses the entire contiguous U.S. as well as portions of Canada and Mexico and, therefore, all or nearly all mercury emissions sources in North America. The horizontal resolution of the outer, coarse grid is 36 km. The inner grid focuses on Virginia and the surrounding states and has a horizontal grid resolution of 12 km.

Figure 3-1. CMAQ 36- and 12-km Resolution Nested-Grid Modeling Domain.



Vertical Structure

The CMAQ domain includes 14 vertical layers. CMAQ uses a sigma vertical coordinate system, which is a terrain-following vertical coordinate system with numerous numerical advantages. The vertical structure of the modeling domain is such that the highest resolution is achieved near the surface. The top of the modeling domain is approximately 10,000 m. The sigma layers and their approximate heights (under standard pressure conditions) are provided in Table 3-1.

Table 3-1. Vertical Levels that Define the CMAQ Modeling Domain.

Layer Number	Sigma	Height (m)
1	0.995	0
2	0.99	36
3	0.98	72
4	0.96	145
5	0.94	293
6	0.91	444
7	0.86	674
8	0.8	1074
9	0.74	1579
10	0.65	2115
11	0.55	2989
12	0.4	4078
13	0.2	6037
14	0	9733

3.2.3. Input Preparation

The mercury emission inventories used in the CMAQ modeling were prepared specifically for this study. Most of the other inputs were obtained from EPA and were used in prior EPA modeling studies.

Emission inventories

CMAQ requires hourly, gridded emissions for a number of different species, including criteria pollutants, related precursor species and mercury. The criteria pollutant portion of the inventory includes emissions for nitrogen oxides (NO_x), volatile organic compounds (VOC), sulfur dioxide (SO_2), ammonia (NH_3), primary particulates, and numerous other precursor species. These emissions are primarily used to simulate ozone and particulate matter, and certain species are also involved in reactions concerning mercury. The mercury portion of the emission inventory includes emissions for the three forms of mercury elemental (HG0), reactive gaseous (HG2), and particulate (HGP). The criteria pollutant and mercury emissions are typically prepared separately, and then merged to create a model-ready emission inventory.

For this study, CMAQ model-ready emission inventories were prepared for the base year using a combination of data for 2001 and 2002, and for the three future years 2010, 2015 and 2018 using projected emissions for these years.

BASE-YEAR EMISSION INVENTORIES

The 36- and 12-km model-ready criteria-pollutant emission inventories prepared by EPA for the 2001 annual simulation period were used to represent the criteria pollutants. The 36-km criteria pollutant emission inventory was used directly, since the VDEQ 36-km domain is the same as that used by EPA. The 12-km emissions for the VDEQ subdomain were extracted from a larger 12-km domain used by EPA. In both cases, the emissions were re-speciated for use with the CB05 chemical mechanism.

The mercury emissions inventory incorporates the latest mercury emissions data for point sources in Virginia for 2002. These emissions (along with emissions for 2005) were reviewed and updated

as part of this study to ensure that the methods used to calculate the emissions are valid, the data are complete, and that the emissions totals, locations, and stack parameters are correct. (Additional detail regarding the review of Virginia mercury sources is contained in Appendix C).

Baseline mercury emissions for all other areas and source categories were based on the latest version (version 3) of the 2002 National Emissions Inventory (NEI). Currently the NEI inventory does not include mercury emissions for motor vehicle or non-road sources. EPA estimates (EPA, 2007b) that emissions from these source categories represent less than five percent of the overall mercury emissions. In processing the base year emissions, ICF worked with EPA to correct a couple of errors for emissions sources in Pennsylvania where the emissions were unrealistically high. Natural, recycled, and volcanic (NRV) mercury emissions for all areas were extracted from the corresponding EPA 2001 emissions files.

The Sparse-Matrix Operator Kernel Emissions (SMOKE) processing system was used to process the mercury emissions for input to the CMAQ model. Following application of SMOKE, the quality assurance procedures outlined in the quality assurance plan for the project were applied to the emissions processing. SMOKE was then used to merge the criteria pollutant and mercury emissions into a model-ready emissions inventory for CMAQ.

FUTURE-YEAR EMISSION INVENTORIES

Future-year emission inventories were prepared for 2010, 2015, and 2018. Emissions projections were based on information available from EPA (e.g., CAMR (EPA, 2005b)) and from VDEQ (primarily through surveys; see Appendix C for addition information on the surveys).

The future-year criteria pollutant emissions inventories were based on future-year emission inventories prepared by EPA as part of the Clear Skies modeling analyses (EPA, 2003) as updated in 2005. For 2010 and 2015, the criteria pollutant emissions were extracted from EPA's 2010 and 2015 Clear Skies emissions inventory, respectively, and for 2018, the criteria pollutant emissions were extracted from EPA's 2020 Clear Skies emissions inventory. These inventories were projected from an earlier version of the NEI and prepared by EPA for the same 36-km domain used the Virginia mercury study. The emissions were re-speciated for use with the CB05 chemical mechanism and then used to represent the criteria pollutant emissions for the 36-km outer domain for the Virginia modeling study.

For the 12-km domain, the future-year criteria pollutant emissions from the 36-km resolution inventories were allocated to the 12-km grid using spatial allocation factors. The factors were developed using the base-year (2001)12-km emission inventory, as follows. The emissions for each set of nine 12-km grid cells corresponding to each 36-km grid cell were first combined. The percent of the combined emissions contained within each 12-km grid cell was calculated. The future-year emissions for each 36-km grid cell were then allocated to the 12-km grid cells according to this percentage. Using this approach, the spatial distribution of emissions within each 36-km grid cell is the same for the base and future years but the amount of emissions reflects the future year. For all three future-years, the criteria pollutant emissions were re-speciated for use with the CB05 chemical mechanism.

The mercury emission inventories were processed specifically for this study. For all areas of the domain, with the exception of Virginia, the future-year inventories were based on the EPA Clear Skies inventories. For 2010 and 2015, the mercury emissions were extracted from EPA's 2010 and 2015 Clear Skies emissions inventories, respectively, and for 2018, the emissions were extracted from EPA's 2020 Clear Skies emissions inventory. To reflect anticipated future growth in demand for electricity throughout the U.S., the Clear Skies inventories include a number of

generic Electric Generating Units (EGUs). The emissions for these units are small compared to the other sources (less than 50 pounds per year (lbs/yr)).

For Virginia, point source emissions estimates for each future year were provided by VDEQ (and are described in more detail in Appendix C of this report). Emissions for small landfill sources included in the 2002 NEI Version 3, but not in the VDEQ inventory, were incorporated and kept at 2002 levels for the future years. No generic EGUs were included for Virginia, since any new sources are expected to have low emissions and, to date, the locations and/or emissions of potential new sources have not been determined.

For all states, the future-year emissions estimates for mercury take into account the provisions of CAMR. The CAMR, promulgated on May 18, 2005, includes two mechanisms to reduce mercury emissions from electric power plants. First, it sets standards of performance for new and existing coal-fired power plants. Second, it establishes a two-phase, national cap-and-trade program. In the initial phase of the cap-and-trade program, the national mercury emissions will be capped at 38 tons and emissions reductions will occur as a "co-benefit" of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions under the Clean Air Interstate Rule (CAIR) issued on March 10, 2005. In the second phase, due in 2018, coal-fired power plants will be subject to a second cap, which will reduce emissions to 15 tons upon full implementation. Although the United States Court of Appeals for the D.C. District ruled on 8 February 2008 that EPA's CAMR was illegal, the original provisions of CAMR compliance, as estimated by VDEQ for Virginia sources and by EPA in their Clear Skies modeling inventories for all other states, were simulated in the future-year modeling analysis for this study. The future-year modeling conducted for this project was well underway by the time of the ruling.

In addition to CAMR, Virginia-specific laws were also accounted for in the future emissions projections. To participate in the federal cap-and-trade program, states must submit to EPA a State Implementation Plan revision that describes how the state will meet its mercury reduction budget under CAMR. States may adopt a "model rule" or a rule(s) with comparable provisions. Legislation enacted by Virginia in April 2006 (HB1055) authorized the Air Pollution Control Board to adopt and submit to EPA the model rule. As described below, the Virginia legislation also provided authority for state-specific rules to further control mercury emissions from sources regulated under CAMR. These are summarized by the following amendments to the Code of Virginia:

- § 10.1-1328 C—This section directs the Air Pollution Control Board to adopt and submit to EPA the CAMR "model rule" for participation in the federal mercury cap-and-trade trading program. The rule will include a set-aside of mercury allowances for new sources not to exceed 5 percent of the total state budget during the first five years and 2 percent thereafter.
- § 10.1-1328 D—This section is a state-specific (i.e., that exceeds the requirements of CAMR) rule. Its requirements are similar to the CAMR cap-and-trade program, but it applies to additional (smaller) sources and includes additional restrictions on compliance options.
- § 10.1-1328 E—This section directs the Air Pollution Control Board to adopt regulations governing mercury emissions that meet, but do not exceed, the requirements and implementation timetables for (i) any coke oven batteries for which the EPA has promulgated standards under § 112(d) of the Clean Air Act, and (ii) facilities subject to review under § 112(k) of the Clean Air Act and that receive scrap metal from persons subject to § 46.2-635 of the Code of Virginia.
- § 10.1-1328 F—This section is a state-specific rule that prohibits electric generating facilities in nonattainment areas from meeting mercury compliance obligations by purchasing credits from other facilities. An exception applies when the facility owner can demonstrate compliance using allowances at another of its facilities within 200 kilometers of the Virginia border.

These rules and provisions have been incorporated into the emissions estimates and the future-year emission inventories. The future-year emissions estimates also reflect the implementation timing and effects of the CAIR and CAMR emission reduction provisions (using the best available information at the time the work was conducted).

For quality assurance purposes, preparation of the future-year emissions included an analysis of expected emissions reductions, future-year trends for all source categories, and a comparison of Virginia emissions with neighboring states, regions, and national sources affecting Virginia.

As for the base-year, SMOKE was used to process the mercury emissions for each future year and to merge the criteria pollutant and mercury emissions into a model-ready emissions inventory for CMAQ.

EMISSIONS SUMMARIES

Table 3-2 summarizes the criteria pollutant emissions by state and by source category for the base and future year scenarios. The tables include totals for Virginia and the surrounding states of Kentucky, Maryland, North Carolina, Pennsylvania, Tennessee, Washington, D.C., and West Virginia. The sectors include area sources (sources that do no have elevated or well-defined stacks such waste incinerators, medical waste incinerators, gold mines etc.), point sources (sources with elevated, well defined stacks or plumes such as power plants, steel mills, etc.), on-road mobile sources, and non-road mobile sources (such as construction equipment, farm equipment, etc.).

Table 3-2a. 2001 Criteria Pollutant Emissions Totals (tons/yr) by Source Category for the Commonwealth of Virginia and Selected Surrounding States.

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO_2 (tpy)	PM_{10} (tpy)	PM_{25} (tpy)	NH_3 (tpy)
Kentucky	Area	80,863	166,716	247,445	58,064	308,441	251,438	45,107
Kentucky	Point	284,354	117,482	110,445	580,121	74,939	52,708	618
Kentucky	Onroad	140,239	81,926	1,078,638	4,558	3,884	2,922	4,625
Kentucky	Nonroad	91,843	34,166	291,250	12,119	5,655	5,178	37
Kentucky	*Total*	*597,298*	*400,290*	*1,727,779*	*654,862*	*392,919*	*312,246*	*50,387*
Maryland	Area	18,922	109,517	135,388	41,889	136,820	108,108	16,863
Maryland	Point	100,586	33,779	126,434	293,667	30,567	23,138	470
Maryland	Onroad	140,278	80,157	1,113,751	3,598	3,836	2,805	5,265
Maryland	Nonroad	45,474	45,349	460,610	5,165	4,032	3,701	42
Maryland	*Total*	*305,260*	*268,801*	*1,836,182*	*344,318*	*175,256*	*137,752*	*22,640*
North Carolina	Area	36,074	390,264	785,754	34,693	387,396	294,325	46,787
North Carolina	Point	212,450	122,904	84,210	525,481	60,277	38,811	1,917
North Carolina	Onroad	266,950	177,024	2,178,291	10,236	7,538	5,660	9,196
North Carolina	Nonroad	78,211	70,921	734,017	7,891	6,900	6,324	87
North Carolina	*Total*	*593,686*	*761,113*	*3,782,271*	*578,301*	*462,110*	*345,120*	*57,987*

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO_2 (tpy)	PM_{10} (tpy)	PM_{25} (tpy)	NH_3 (tpy)
Pennsylvania	Area	56,932	341,963	300,048	99,081	473,707	421,835	34,378
Pennsylvania	Point	328,499	134,489	129,342	1,093,503	109,222	79,557	1,519
Pennsylvania	Onroad	302,656	181,634	2,614,202	9,946	8,207	6,116	10,368
Pennsylvania	Nonroad	126,257	87,784	955,139	13,959	8,993	8,243	101
Pennsylvania	*Total*	*814,343*	*745,870*	*3,998,732*	*1,216,490*	*600,129*	*515,751*	*46,367*
Tennessee	Area	27,268	244,652	202,999	42,729	318,413	270,359	40,426
Tennessee	Point	243,510	154,351	133,451	457,127	80,975	57,406	2,415
Tennessee	Onroad	199,670	129,223	1,654,713	7,457	5,497	4,119	6,799
Tennessee	Nonroad	91,499	49,447	452,304	10,624	6,199	5,677	57
Tennessee	*Total*	*561,946*	*577,672*	*2,443,468*	*517,937*	*411,084*	*337,561*	*49,696*
Washington DC	Area	2,341	10,890	2,440	6,197	7,960	7,376	982
Washington DC	Point	969	412	158	1,715	525	201	14
Washington DC	Onroad	8,814	6,187	73,920	219	234	164	386
Washington DC	Nonroad	2,700	1,295	15,475	325	239	220	3
Washington DC	*Total*	*14,824*	*18,783*	*91,992*	*8,456*	*8,958*	*7,961*	*1,384*
West Virginia	Area	15,071	73,430	119,094	13,577	153,602	136,022	7,868
West Virginia	Point	259,566	74,274	120,816	562,935	61,965	45,436	533
West Virginia	Onroad	63,790	36,615	509,776	2,190	1,771	1,349	1,956
West Virginia	Nonroad	56,267	15,531	120,691	7,466	2,884	2,642	13
West Virginia	*Total*	*394,693*	*199,849*	*870,378*	*586,168*	*220,221*	*185,449*	*10,370*
Virginia	Area	49,038	226,091	242,778	15,667	306,474	237,512	28,410
Virginia	Point	161,377	78,184	78,531	298,851	39,759	26,477	845
Virginia	Onroad	215,356	127,508	1,738,543	6,409	5,804	4,309	7,423
Virginia	Nonroad	91,845	57,828	598,852	9,280	6,497	5,937	61
Virginia	*Total*	*517,617*	*489,611*	*2,658,704*	*330,207*	*358,533*	*274,235*	*36,739*

Data Source: EPA 2001 Tier 3 criteria emissions summary

Table 3-2b. 2010 Criteria Pollutant Emissions Totals (tons/yr) by Source Category, for the Commonwealth of Virginia and Selected Surrounding States.

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM25 (tpy)	NH3 (tpy)
Kentucky	Area	82,996	115,489	181,661	55,375	137,123	43,770	53,612
Kentucky	Point	141,084	68,696	126,928	412,980	52,452	40,009	636
Kentucky	Onroad	83,213	44,449	664,670	536	2,766	1,746	5,757
Kentucky	Nonroad	75,948	27,166	309,567	10,075	5,129	4,924	27
Kentucky	*Total*	*383,240*	*255,799*	*1,282,827*	*478,967*	*197,470*	*90,450*	*60,031*
Maryland	Area	21,720	66,161	122,762	51,438	67,799	30,644	25,852
Maryland	Point	35,079	7,165	136,717	96,451	15,029	10,914	447
Maryland	Onroad	89,989	42,727	660,593	580	2,788	1,713	6,348
Maryland	Nonroad	37,759	28,348	468,771	2,506	3,409	3,238	29
Maryland	*Total*	*184,545*	*144,400*	*1,388,843*	*150,975*	*89,025*	*46,509*	*32,677*
North Carolina	Area	30,937	298,148	755,017	33,288	156,422	70,272	174,184
North Carolina	Point	114,612	69,863	98,222	337,188	49,727	37,982	2,208
North Carolina	Onroad	150,713	94,532	1,229,513	1,018	5,148	3,226	10,998
North Carolina	Nonroad	58,590	50,980	785,545	1,639	5,790	5,509	56
North Carolina	*Total*	*354,852*	*513,524*	*2,868,298*	*373,133*	*217,086*	*116,989*	*187,446*
Pennsylvania	Area	62,115	244,661	263,780	104,895	180,074	69,608	77,644
Pennsylvania	Point	191,761	41,294	134,998	365,698	63,226	50,403	1,402
Pennsylvania	Onroad	193,428	95,632	1,494,397	1,160	5,793	3,612	12,580
Pennsylvania	Nonroad	100,897	66,418	1,023,691	7,860	8,019	7,656	65
Pennsylvania	*Total*	*548,201*	*448,006*	*2,916,865*	*479,613*	*257,112*	*131,279*	*91,692*
Tennessee	Area	30,251	204,378	167,511	44,891	140,596	46,253	43,973
Tennessee	Point	105,744	95,554	153,220	315,452	57,675	47,621	2,673
Tennessee	Onroad	110,406	66,297	924,624	738	3,708	2,316	8,020
Tennessee	Nonroad	72,462	38,041	490,821	6,566	5,448	5,210	38
Tennessee	*Total*	*318,863*	*404,270*	*1,736,176*	*367,647*	*207,427*	*101,400*	*54,705*
Washington DC	Area	2,880	10,059	2,257	7,101	3,376	1,473	1,054
Washington DC	Point	563	5	139	875	262	144	11
Washington DC	Onroad	5,834	3,207	43,633	41	178	105	457
Washington DC	Nonroad	2,060	800	15,342	24	174	167	2
Washington DC	*Total*	*11,336*	*14,071*	*61,371*	*8,042*	*3,990*	*1,889*	*1,525*

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM25 (tpy)	NH3 (tpy)
West Virginia	Area	16,531	52,655	111,783	14,020	31,642	17,442	11,239
West Virginia	Point	107,084	17,877	140,526	267,319	46,041	35,580	535
West Virginia	Onroad	25,446	14,280	229,499	165	877	544	1,936
West Virginia	Nonroad	48,100	14,830	139,182	7,060	2,821	2,712	10
West Virginia	*Total*	*197,162*	*99,643*	*620,989*	*288,564*	*81,380*	*56,279*	*13,720*
Virginia	Area	51,055	152,710	226,435	18,280	99,538	43,065	47,036
Virginia	Point	116,452	46,965	89,346	223,803	29,280	23,840	725
Virginia	Onroad	117,831	68,430	1,014,190	803	3,499	2,038	9,229
Virginia	Nonroad	71,890	37,973	572,677	3,661	5,424	5,176	43
Virginia	*Total*	*357,228*	*306,077*	*1,902,648*	*246,547*	*137,740*	*74,119*	*57,034*

Data Source: SMOKE input files for EPA 2010 Clear Skies

Table 3-2c. 2015 Criteria Pollutant Emissions Totals (tons/yr) by Source Category for the Commonwealth of Virginia and Selected Surrounding States.

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM25 (tpy)	NH3 (tpy)
Kentucky	Area	86,737	118,613	178,135	57,037	140,843	44,206	54,466
Kentucky	Point	119,509	76,259	136,994	309,021	53,360	40,343	677
Kentucky	Onroad	51,705	33,987	587,044	594	2,335	1,279	6,293
Kentucky	Nonroad	70,723	22,742	320,697	11,310	4,723	4,536	29
Kentucky	*Total*	*328,673*	*251,602*	*1,222,870*	*377,962*	*201,261*	*90,364*	*61,466*
Maryland	Area	22,630	68,291	118,312	54,886	70,262	30,836	27,493
Maryland	Point	36,612	7,991	161,990	84,609	14,339	9,833	516
Maryland	Onroad	73,128	35,380	625,121	662	2,495	1,341	7,140
Maryland	Nonroad	33,804	25,893	498,732	2,652	3,078	2,917	32
Maryland	*Total*	*166,174*	*137,555*	*1,404,155*	*142,810*	*90,174*	*44,927*	*35,182*
North Carolina	Area	31,658	312,232	749,577	34,395	161,045	71,037	184,705
North Carolina	Point	109,442	81,892	110,228	207,069	49,737	36,966	2,482
North Carolina	Onroad	93,967	72,588	1,086,449	1,140	4,427	2,413	12,140
North Carolina	Nonroad	47,408	43,984	815,102	1,374	4,815	4,569	61
North Carolina	*Total*	*282,474*	*510,696*	*2,761,356*	*243,977*	*220,024*	*114,984*	*199,388*
Pennsylvania	Area	63,134	255,255	250,978	105,197	184,330	69,349	78,772
Pennsylvania	Point	185,948	46,770	149,289	265,251	57,667	44,017	1,536
Pennsylvania	Onroad	153,638	78,421	1,403,706	1,294	4,990	2,710	13,832
Pennsylvania	Nonroad	89,284	57,293	1,069,881	8,480	7,054	6,727	71
Pennsylvania	*Total*	*492,005*	*437,739*	*2,873,854*	*380,222*	*254,041*	*122,802*	*94,211*
Tennessee	Area	31,754	219,627	164,797	46,727	145,615	47,163	44,435
Tennessee	Point	101,939	111,197	173,664	298,076	64,647	53,321	2,958
Tennessee	Onroad	69,026	50,812	817,379	826	3,200	1,740	8,845
Tennessee	Nonroad	64,785	32,126	508,528	7,157	4,800	4,587	42
Tennessee	*Total*	*267,504*	*413,762*	*1,664,369*	*352,785*	*218,261*	*106,811*	*56,279*
Washington DC	Area	3,079	10,689	2,150	7,450	3,586	1,540	1,133
Washington DC	Point	600	7	205	904	272	154	12
Washington DC	Onroad	4,925	2,664	41,975	47	167	88	517
Washington DC	Nonroad	1,548	706	15,872	4	130	126	2
Washington DC	*Total*	*10,152*	*14,065*	*60,202*	*8,405*	*4,156*	*1,907*	*1,664*

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM25 (tpy)	NH3 (tpy)
West Virginia	Area	17,278	53,639	109,396	14,834	31,981	17,303	11,573
West Virginia	Point	88,160	19,978	156,249	178,345	42,924	31,832	600
West Virginia	Onroad	15,185	10,240	196,680	175	725	394	2,011
West Virginia	Nonroad	46,281	12,086	146,386	8,014	2,702	2,600	11
West Virginia	*Total*	*166,903*	*95,943*	*608,710*	*201,367*	*78,332*	*52,128*	*14,195*
Virginia	Area	53,166	156,772	222,764	18,598	102,437	43,372	48,435
Virginia	Point	121,479	55,055	99,165	183,246	30,440	24,461	793
Virginia	Onroad	100,587	56,674	975,905	898	3,223	1,670	10,161
Virginia	Nonroad	64,211	33,983	602,616	3,732	4,787	4,560	47
Virginia	*Total*	*339,442*	*302,484*	*1,900,450*	*206,474*	*140,887*	*74,063*	*59,437*

Data Source: SMOKE input files for EPA 2015 Clear Skies

Table 3-2d. 2020 Criteria Pollutant Emissions Totals (tons/yr) by Source Category for the Commonwealth of Virginia and Selected Surrounding States.

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM25 (tpy)	NH3 (tpy)
Kentucky	Area	91,929	117,064	175,225	58,588	138,317	43,793	55,439
Kentucky	Point	112,256	84,578	149,195	272,636	52,185	38,451	726
Kentucky	Onroad	36,425	28,950	572,119	653	2,273	1,146	6,819
Kentucky	Nonroad	68,163	20,642	338,836	13,621	4,537	4,359	32
Kentucky	*Total*	*308,773*	*251,234*	*1,235,375*	*345,499*	*197,312*	*87,748*	*63,016*
Maryland	Area	23,703	69,174	114,208	56,995	66,608	30,393	28,702
Maryland	Point	41,377	8,980	189,610	71,464	18,652	13,607	585
Maryland	Onroad	67,957	32,189	639,970	745	2,518	1,255	7,917
Maryland	Nonroad	31,434	25,361	534,327	3,180	2,838	2,682	35
Maryland	*Total*	*164,471*	*135,705*	*1,478,114*	*132,383*	*90,616*	*47,938*	*37,238*
North Carolina	Area	32,749	313,241	744,973	35,223	153,549	70,098	191,673
North Carolina	Point	118,220	93,256	122,923	177,489	61,778	47,911	2,775
North Carolina	Onroad	65,948	61,657	1,062,447	1,263	4,358	2,191	13,256
North Carolina	Nonroad	40,447	41,299	866,518	1,616	4,057	3,834	66
North Carolina	*Total*	*257,364*	*509,453*	*2,796,861*	*215,592*	*223,742*	*124,034*	*207,769*
Pennsylvania	Area	63,868	262,341	238,780	103,800	176,760	67,356	79,494
Pennsylvania	Point	196,733	52,510	162,991	249,522	59,811	45,465	1,702
Pennsylvania	Onroad	140,686	71,937	1,427,330	1,429	4,908	2,463	15,054
Pennsylvania	Nonroad	83,360	53,304	1,139,122	10,181	6,387	6,082	78
Pennsylvania	*Total*	*484,646*	*440,092*	*2,968,223*	*364,932*	*247,865*	*121,366*	*96,328*
Tennessee	Area	33,135	226,549	162,220	48,399	140,943	46,600	45,461
Tennessee	Point	108,714	127,886	197,795	208,450	66,544	53,876	3,273
Tennessee	Onroad	48,696	43,211	799,580	915	3,155	1,585	9,652
Tennessee	Nonroad	60,367	29,464	538,760	8,600	4,362	4,165	46
Tennessee	*Total*	*250,911*	*427,111*	*1,698,355*	*266,363*	*215,004*	*106,225*	*58,431*
Washington DC	Area	3,330	11,344	2,073	7,771	3,529	1,587	1,279
Washington DC	Point	743	15	288	1,164	524	396	14
Washington DC	Onroad	4,718	2,435	43,448	53	173	85	576
Washington DC	Nonroad	1,170	684	16,776	4	90	86	2
Washington DC	*Total*	*9,961*	*14,478*	*62,585*	*8,992*	*4,317*	*2,154*	*1,871*

State	Sector	NOx (tpy)	VOC (tpy)	CO (tpy)	SO2 (tpy)	PM10 (tpy)	PM25 (tpy)	NH3 (tpy)
West Virginia	Area	18,515	54,453	107,414	15,421	32,162	17,227	11,895
West Virginia	Point	93,866	22,567	174,325	175,279	46,449	34,842	682
West Virginia	Onroad	10,450	8,489	187,203	185	689	346	2,086
West Virginia	Nonroad	46,111	10,606	154,623	9,664	2,717	2,617	13
West Virginia	*Total*	*168,941*	*96,114*	*623,565*	*200,548*	*82,016*	*55,032*	*14,676*
Virginia	Area	55,793	160,118	219,532	18,464	100,396	43,151	49,754
Virginia	Point	126,542	62,519	107,744	163,561	38,406	31,722	871
Virginia	Onroad	97,572	52,436	1,009,305	995	3,279	1,602	11,076
Virginia	Nonroad	59,359	32,773	643,226	4,464	4,305	4,092	52
Virginia	*Total*	*339,266*	*307,846*	*1,979,807*	*187,484*	*146,386*	*80,567*	*61,753*

Data Source: SMOKE input files for EPA 2020 Clear Skies

Table 3-3 summarizes the mercury emissions by state and source category for the base and future-year scenarios. The tables include totals for Virginia and the surrounding states of Kentucky, Maryland, North Carolina, Pennsylvania, Tennessee, Washington, D.C., and West Virginia. Point-source, non-point source, and total emissions are provided. The non-point source category includes such sources as residential/industrial fuel combustion, fluorescent lamp breakage, health services, agricultural production, waste disposal, landfills, and other combustion sources.

For 2002 base-year mercury emissions, the State of Pennsylvania has the highest totals, followed by West Virginia and North Carolina. In EPA's estimates (in their Clear Skies modeling analysis) for the future years, mercury emissions drop significantly for some states, reflecting expected reductions due to CAIR controls and the original CAMR control provisions.

Table 3-3a. 2002 Mercury Emissions Totals (tpy) for Virginia and Surrounding States.

State	Point				Non-Point				Total			
	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)
Kentucky	1.39	0.90	0.15	2.45	0.04	0.03	0.02	0.09	1.44	0.93	0.17	2.54
Maryland	0.47	0.80	0.15	1.42	0.08	0.05	0.03	0.17	0.55	0.85	0.19	1.59
North Carolina	1.17	1.29	0.24	2.69	0.08	0.05	0.03	0.15	1.24	1.34	0.27	2.85
Pennsylvania	3.25	3.30	0.62	7.18	0.19	0.11	0.08	0.38	3.44	3.42	0.69	7.55
Tennessee	1.73	0.87	0.18	2.77	0.03	0.02	0.01	0.05	1.76	0.88	0.19	2.83
Washington DC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01
West Virginia	2.03	1.92	0.37	4.32	0.05	0.03	0.02	0.09	2.08	1.95	0.39	4.42
Virginia	0.63	0.39	0.17	1.18	0.09	0.06	0.04	0.19	0.72	0.44	0.20	1.37

Notes: Point Source: Emissions for Virginia are based on VDEQ 2002 data and the emissions for other states are based on the EPA 2002 NEI Version 3.

Non-Point Source: Emissions are based on 2002 NEI Version 3

Table 3-3b. 2010 Mercury Emissions Totals (tpy) for Virginia and Surrounding States.

State	Point				Non-Point				Total			
	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)
Kentucky	1.07	0.49	0.19	1.74	0.05	0.01	0.00	0.06	1.12	0.49	0.19	1.81
Maryland	0.55	0.39	0.20	1.14	0.08	0.02	0.01	0.11	0.63	0.41	0.21	1.25
North Carolina	1.11	0.50	0.18	1.79	0.09	0.02	0.01	0.12	1.21	0.51	0.19	1.91
Pennsylvania	1.93	0.98	0.39	3.29	0.22	0.08	0.05	0.34	2.15	1.05	0.43	3.64
Tennessee	1.02	0.36	0.13	1.50	0.07	0.01	0.00	0.08	1.09	0.36	0.13	1.59
Washington DC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
West Virginia	1.02	0.26	0.05	1.33	0.03	0.00	0.00	0.03	1.05	0.26	0.05	1.36
Virginia	0.39	0.26	0.11	0.76	0.11	0.02	0.01	0.14	0.50	0.28	0.12	0.90

Notes: Point Source: Emissions for Virginia are based on VDEQ 2010 estimates and the emissions for other states are based on the EPA 2010 Clear Skies estimates

Non-Point Source: Emissions based on the EPA 2010 Clear Skies estimates

Table 3-3c. 2015 Mercury Emissions Totals (tpy) for Virginia and Surrounding States.

State	Point				Non-Point				Total			
	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)
Kentucky	0.84	0.44	0.19	1.47	0.06	0.01	0.00	0.07	0.90	0.45	0.20	1.54
Maryland	0.57	0.37	0.18	1.12	0.08	0.02	0.01	0.11	0.65	0.39	0.20	1.24
North Carolina	0.94	0.36	0.12	1.43	0.10	0.01	0.01	0.12	1.04	0.38	0.13	1.56
Pennsylvania	2.06	0.82	0.38	3.27	0.22	0.07	0.05	0.35	2.29	0.90	0.43	3.61
Tennessee	1.08	0.33	0.15	1.57	0.08	0.01	0.00	0.09	1.16	0.34	0.16	1.66
Washington DC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
West Virginia	1.07	0.10	0.02	1.19	0.03	0.00	0.00	0.03	1.09	0.11	0.02	1.22
Virginia	0.36	0.26	0.10	0.72	0.11	0.02	0.01	0.15	0.48	0.28	0.12	0.87

Notes: Point Source: Emissions for Virginia are based on VDEQ 2015 estimates and the emissions for other states are based on the EPA 2015 Clear Skies estimates

Non-Point Source: Emissions based on the EPA 2015 Clear Skies estimates

Table 3-3d. 2018/2020 Mercury Emissions Totals (tpy) for Virginia and Surrounding States.

State	Point				Non-Point				Total			
	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)	HG0 (tpy)	HG2 (tpy)	HGP (tpy)	Total (tpy)
Kentucky	0.90	0.41	0.21	1.52	0.06	0.01	0.00	0.07	0.96	0.42	0.21	1.59
Maryland	0.62	0.40	0.19	1.21	0.09	0.02	0.01	0.12	0.71	0.42	0.20	1.32
North Carolina	0.89	0.39	0.14	1.42	0.11	0.01	0.01	0.13	0.99	0.41	0.15	1.55
Pennsylvania	2.06	0.83	0.41	3.30	0.23	0.07	0.05	0.35	2.29	0.90	0.46	3.65
Tennessee	1.06	0.21	0.10	1.37	0.09	0.01	0.01	0.10	1.15	0.22	0.11	1.47
Washington DC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01
West Virginia	1.10	0.11	0.02	1.23	0.03	0.00	0.00	0.04	1.13	0.11	0.03	1.26
Virginia	0.36	0.24	0.10	0.70	0.12	0.02	0.01	0.15	0.48	0.26	0.12	0.85

Notes: Point Source: Emissions for Virginia are based on VDEQ 2018 estimates and the emissions for other states are based on the EPA 2020 Clear Skies estimates

Non-Point Source: Emissions based on the EPA 2020 Clear Skies estimates

Meteorological Inputs

As noted earlier, existing meteorological input files were used for this study. These were prepared by EPA for use in CMAQ modeling for the selected modeling domain using the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Fifth Generation Mesoscale Model (MM5) (EPA, 2005a). The MM5 outputs were postprocessed by EPA for input to CMAQ using the Meteorology-Chemistry Interface Processor (MCIP) program. The meteorological input preparation methodology and some information on MM5 model performance are provided by McNally (2003). The 2001 MM5-derived meteorological fields are available for both 36- and 12-km resolution. The 36-km meteorological fields were used directly, since the VDEQ 36-km domain is the same as that used by EPA. The 12-km meteorological fields for the VDEQ subdomain were extracted from a larger 12-km domain used by EPA.

The 2002 meteorological inputs used for sensitivity testing were also prepared by EPA (using MM5 and MCIP), for both 36- and 12-km resolution (Dolwick et al., 2007).

Initial and Boundary Conditions and Other Geophysical Data

For this study, existing initial condition, boundary condition, land-use and photolysis rate input files prepared by EPA for use in CMAQ modeling for the selected modeling domain and simulation period (EPA, 2005a) were used. For mercury, the boundary conditions were extracted from the output of a global model—the Chemical Transport Model (CTM) (Shia et al., 1999; Seigneur et al., 2001). This set of boundary conditions was selected based on a comparison of three sets of boundary conditions available for use in this study. Boundary values from three global models (the CTM, Geos-Chem, and GRAHM models) were compared (Myers et al., 2006) and the CTM values were found to be in the middle of the range of the three models.

3.2.4. Model Performance Evaluation

The evaluation of model performance for CMAQ considered concentration and deposition of both mercury and non-mercury species. The non-mercury species include ozone, fine particulate matter ($PM_{2.5}$), and related species. For mercury, simulated total wet deposition was compared with actual and "estimated" data for the MDN monitoring sites. The simulated and observed values of concentration and/or deposition for each site and the average over all sites were compared for 1) the full domain, 2) the 12-km inner grid of the modeling domain, and 3) Virginia (mercury only).

A variety of statistical measures were used to quantify model performance. These include:

- Mean observed concentration or deposition = $\sum O_i / N$
- Mean simulated concentration or deposition = $\sum S_i / N$
- Ratio of means = $(\sum S_i / N)/(\sum O_i / N)$
- Mean bias = $\sum (S_i - O_i) / N$
- Mean fractional bias (expressed as percent) = $200 \cdot (\sum (S_i - O_i)/ (S_i + O_i)) /N$
- Mean error = $\sum |S_i - O_i| /N$
- Mean fractional error (expressed as percent) = $200 \cdot (\sum |S_i - O_i|/ (S_i + O_i)) /N$
- Coefficient of determination (R^2) =
  $(\sum S_i O_i - \sum S_i \sum O_i/N)^2 /[(\sum O_i^2 - (\sum O_i)^2/N) \cdot (\sum S_i^2 - (\sum S_i)^2/N)]$

Where S is the simulated value, O is the observed value, and N is the number of simulation-observation pairs used in the calculation. The subscript i is an index and is used here to indicate that each sum is from i =1 to N. Statistical measures were calculated on a monthly, seasonal and annual basis, based on data availability.

Plots and graphics were also used to assess the reasonableness of the results. Spatial plots of the simulated and observed values were used to qualitatively assess the ability of the model to emulate the spatial deposition patterns. Monthly time-series plots comparing these same values at the monitoring sites were used to determine whether the timing and magnitude of the simulated values matches the observations. Scatter plots were used to graphically compare the simulated and observed deposition values.

As part of the performance evaluation, potential weaknesses in the model input fields were identified and some limited sensitivity analysis was conducted to examine the effects of these weaknesses or uncertainties. This focused on the mercury boundary conditions and the meteorological representativeness of the simulation period. In addition, PPTM was also used as a probing tool and examined the PPTM results to verify that the contributions from selected emission sources are commensurate with the locations and emissions of the sources as well as the prescribed meteorological conditions.

Model performance is summarized in Section 5.

3.2.5. Base- and Future-year Modeling and Analysis

CMAQ version 4.6 with PPTM was applied for the 2001/2002 base year and three future years: 2010, 2015, and 2018.

Several CMAQ/PPTM simulations were conducted using the baseline 2001/2002 emissions inventory. These simulations were designed to assess the contributions of various source sectors to mercury deposition to water bodies in Virginia.

The first scenario examined and quantified the contributions from all mercury air emissions sources in 1) Virginia, 2) surrounding states (defined here as the remainder of the 12-km grid), 3) all other U.S. states (outside of the 12-km grid), 4) Canada and Mexico, 5) global emissions sources, and 6) natural emissions. Tags were assigned to each of the six regions/categories listed above. An initial/boundary condition tag was used to represent the global impact on deposition. In this tag, the boundary conditions are those for the outer, 36-km domain. Natural emissions include those from soils, rocks, volcanoes, and the oceans. This set of tags provides estimates of Virginia, regional, national, and global impacts on deposition for any location (grid cell or group of grid cells) within the state or the modeling domain.

The second scenario quantified the contributions from Electric Generating Unit (EGU) and non-EGU facilities in Virginia and the surrounding states. The tags were assigned to 1) all of Virginia's EGU sources and separately, 2) all of the non-EGU sources in the state, 3) all EGU sources in the surrounding states (remainder of the 12-km grid), and 4) all non-EGU sources in the surrounding states (remainder of the 12-km grid). The results allow us to quantify and compare the contributions from the EGU and non-EGU source sectors to mercury deposition for any location (grid cell or group of grid cells) within the state or the modeling domain.

CMAQ was then applied for 2010, 2015 and 2018, using emissions projected to these years. For 2010 and 2015, PPTM was not employed. For 2018, the same CMAQ/PPTM scenarios that were done for the baseline were also done for the future year.

For each future year, the simulated change in mercury deposition, overall and from each tagged or modeled source or source category, was examined. The PPTM results were used to attribute the future-year reductions in mercury deposition for 2018 for each area of interest to the specific tagged sources or source categories.

Graphical and tabular summaries of the results were prepared. Plots of the CMAQ results were prepared for each CMAQ modeling domain and for each of the major water basins in the Commonwealth of Virginia. Tabular summaries of the overall and PPTM results were also assembled. Analysis of the results focused on the effectiveness of the various measures and emissions changes in reducing future-year mercury deposition both statewide and within the key areas of interest. Given the uncertainties associated with mercury deposition modeling, analysis of the results emphasizes the relative changes in deposition associated with the emissions changes for each source and source category.

The CMAQ modeling results are presented in Section 5.

4. Source-Specific Mercury Deposition Modeling Methodology

The EPA Gaussian model AERMOD (EPA, 2004) was used to examine mercury deposition at the local scale for selected areas and sources. The methodology for the application of AERMOD is presented in this section of the report.

4.1. Selection and Overview of AERMOD

The selection of AERMOD for the Virginia mercury study was based on the technical formulation and capabilities of the model as well as its extensive use for other source-specific model applications.

AERMOD is a steady-state Gaussian dispersion model designed to simulate the local-scale dispersion of pollutants from low-level or elevated sources in simple or complex terrain. It is an EPA "preferred" model (40 CFR Part 51, Appendix W, *Guideline on Air Quality Models*). Recent versions of AERMOD (EPA, 2006a) include algorithms for simulating deposition of gaseous and particulate pollutants. In this study, AERMOD (version 07026) was applied for selected point sources in the Virginia emissions inventory and was used to screen the mercury emissions sources and to determine whether they have the potential to impact areas outside the vicinity of the source. AERMOD was also used to simulate the effects of local emission changes for selected areas and sources.

The dispersion algorithms are based on the fundamental concepts of planetary boundary layer meteorology. The airflow and stability characteristics (e.g., convective versus stable) as well as the vertical structure of the boundary layer are accounted for in simulating dispersion. Numerous features and options accommodate a variety of source types, pollutants, and land-use and topographical features.

Wet and dry deposition can be estimated using AERMOD. The wet deposition algorithms use a washout ratio that is dependent on precipitation rate and the properties of the pollutant being simulated. Dry deposition is based on aerodynamic resistance calculations, and the deposition velocities are calculated based on surface type and local meteorological conditions. The ability to simulate mercury deposition is a relatively new feature of AERMOD and has not been widely tested.

Additional detail regarding the selection of the AERMOD model is provided in the modeling protocol document (Appendix A).

4.2. AERMOD Application Procedures for the Virginia Mercury Deposition Modeling Study

The application of AERMOD, including the simulation period, sources and receptor areas, input preparation, performance evaluation, and base-case and future-year modeling, is discussed in this section. AERMOD was applied separately for each selected source and for elemental, reactive gaseous, and particulate-bound mercury.

4.2.1. Simulation Period

The simulation period for the application of AERMOD is calendar year 2001.

4.2.2. AERMOD Spatial Configuration

Selection of Sources for Application of AERMOD

AERMOD was applied for the 15 sources in Virginia with the greatest mercury emissions based on the VDEQ 2002 emissions inventory data. The sources reflect several different types of facilities and a variety of species distributions, stack parameters, locations relative to sensitive watershed areas, and designated potentials for future control. The top 15 sources and their emissions rates are listed in Table 4-1.

Table 4-1. AERMOD Facilities and Emissions Rates for Elemental (HG0), Reactive Gaseous (HG2), Particulate (HGP), and Total Mercury. Electric Generating Units (EGUs) are also Identified.

Facility Name	Rank	HG0 (lbs/yr)	HG2 (lbs/yr)	HGP (lbs/yr)	Total (lbs/yr)	EGU?
Dominion—Chesterfield Power Station	1	179.42	107.65	71.77	358.83	EGU
Chaparral Steel	2	233.84	29.23	29.23	292.30	non-EGU
Dominion—Bremo	3	83.86	50.32	33.55	167.73	EGU
American Electric Power- Clinch River	4	38.21	121.00	0.00	159.21	EGU
Dominion - Chesapeake Energy Center	5	78.69	47.22	31.48	157.38	EGU
Potomac River Generating Station	6	11.83	106.43	0.00	118.26	EGU
Dominion - Yorktown Power Station	7	53.82	32.29	21.53	107.64	EGU
Jewel Coke Company LLP	8	84.50	10.56	10.56	105.62	non-EGU
Dominion-Possum Point Power Station	9	50.09	30.06	20.04	100.19	EGU
Stone Container Enterprises (Smurfit)	10	38.88	23.33	15.55	77.76	non-EGU
Stone Container Corporation -Hopewell	11	34.84	20.91	13.94	69.69	non-EGU
American Electric Power (Glen Lyn)	12	26.06	39.08	0.00	65.14	EGU
Intermet Foundry Archer Creek	13	32.50	19.50	13.00	65.01	non-EGU
RES dba Steel Dynamics	14	48.64	6.08	6.08	60.80	non-EGU
Spruance Genco LLC	15	27.75	16.65	11.10	55.50	EGU

For most facilities, the speciation is based on EPA default speciation profiles. For the two American Electric Power (AEP) facilities and the Potomac River Generating Station, the speciation is based on (limited) stack testing. Use of the alternative speciation results in no HGP emissions for these facilities. This is important to keep in mind when reviewing the AERMOD results, since the AERMOD results indicate that HGP is an important component of mercury deposition near the source locations.

Specification of Receptor Grids

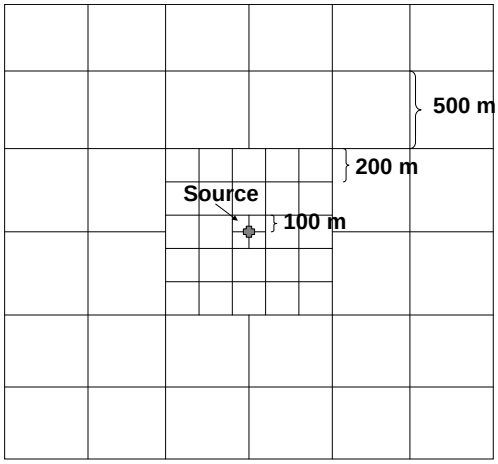
The receptor area for each source was defined following EPA guidance and consists of a 10 by 10 grid with grid cells of 100 x 100 meters (m) near the source that increase to 200 x 200 m and then to 500 x 500 m. The receptor area covers a 3000 x 3000 m (3 x 3 km) area surrounding the source. Note that while the location of the maximum deposition varied within each receptor area, the specified 3-km square receptor area appeared to capture the maximum deposition in all cases.

In the AERMOD input file, this receptor configuration is defined as follows:

GRIDCART 3KMVAR XPNTS -1500. -1000. -500. -300. -100. 100. 300. 500. 1000. 1500.

GRIDCART 3KMVAR YPNTS -1500. -1000. -500. -300. -100. 100. 300. 500. 1000. 1500.

Where GRIDCART refers to a Cartesian grid and the location of each grid point in the west-east (x) and south-north (y) directions (XPNTS and YPNTS, respectively) are given in meters. The source is at location (0,0). This basic grid configuration is depicted below.



4.2.3. Input Preparation

AERMOD requires several input files:

The simulation control file specifies which options and features of AERMOD are to be applied, and contains information about the emissions sources (location, emissions rate, stack parameters, etc.) as well as the receptor locations (essentially the gridded geographical area over which the estimated concentrations and deposition amounts are calculated). This file also specifies several deposition-related parameters. Separate simulation control files were prepared for elemental, reactive gaseous, and particulate-bound mercury.

Two meteorological input files provide detailed information about 1) the characteristics of the boundary layer (wind, temperature, stability parameters) and 2) the vertical structure of temperature and wind near the source location. For deposition analyses, the boundary layer meteorological file includes information about pressure, relative humidity, cloud cover and precipitation.

Emissions Inputs

Source-specific emissions estimates for input to AERMOD for both the baseline year and each future year are the same as those used for the CMAQ modeling and are based on the 2002 emissions data for Virginia. Stack parameter, exit velocity, and stack diameter information for use by AERMOD was also extracted from the CMAQ emissions inventory. The emissions rates were converted to g/s for use by AERMOD. Separate simulation control files were prepared for elemental, reactive gaseous, and particulate emissions.

Deposition Parameters

There are four parameters that AERMOD uses to calculate wet deposition of elemental and reactive gaseous mercury. These are 1) diffusivity in air, 2) diffusivity in water, 3) cuticular resistance, and 4) Henry's Law coefficient. These were set in accordance with EPA guidance (EPA, 2005c) and are based on Wesely et al. (2002). Where possible, information from CMAQ was used to adjust the AERMOD values. These are summarized in Table 4-2.

Table 4-2. AERMOD Gaseous Wet Deposition Parameter Specifications for the Virginia Mercury Study.

Form of Mercury	Diffusivity in Air ($cm^2\ s^{-1}$)	Diffusivity in Water ($cm^2\ s^{-1}$)	Cuticular Resistance ($s\ cm^{-1}$)	Henry's Law Coefficient ($Pa\ m^{-3}\ mol^{-1}$)
Elemental	7.23×10^{-6}	6.30×10^{-6}	1.0×10^{7}	150
Reactive gaseous	6.0×10^{-6}	3.256×10^{-4}	1.0×10^{7}	6.0×10^{-6}

AERMOD relies on several other parameters to calculate dry deposition of mercury, including seasonal definitions, deposition land-use category, reactivity factor, and fractional maximum leaf area index. For this application, each month was assigned to a season as follows:

- **Seasonal Category 1** *(midsummer with lush vegetation):* May–August
- **Seasonal Category 2** (autumn with un-harvested cropland): September, October
- **Seasonal Category 3** *(late autumn or winter with no snow):* January, February, November, December
- **Seasonal Category 5** *(transitional spring):* March, April.

The land-use category for dry deposition was set to Category 4 (forest). Following EPA guidance, the reactivity factor was set to 0 for HG0 and to 1 for HG2, reflecting the higher reactivity for HG2. The fraction of maximum leaf area index was set to 0.5.

For particle-bound mercury, Method 2 of AERMOD was applied. This method is applicable when particle size distribution is not well known or when particles represent a small portion of the mass. Method 2 requires the specification of the fine mass fraction and the mean particle diameter. For this study, a fine mass fraction of 0.8 and a mean particle diameter of 0.4 microns were used, based on Wesely et al. (2002).

Meteorological and Land-Use Inputs

Corresponding meteorological inputs for AERMOD for 2001 were developed using observed data. For each source included in the AERMOD analysis, meteorological inputs were prepared using available surface and upper-air meteorological data from nearby, geographically representative monitoring sites. The meteorological monitoring sites were paired with the source locations based on proximity, and similarities in geographical and land-use characteristics. Table 4-3 lists the AERMOD sources along with the matched surface and upper-air meteorological monitoring sites. The elevation of each location is given in the table. The distance between the facility and each of the paired meteorological monitoring sites is also listed.

Table 4-3. AERMOD Facilities and Paired Meteorological Monitoring Sites. Locations are in Virginia, Except Where Noted.

Facility Name	Facility Elevation (m)	Met Site Type	WBAN or CASTNet #	WBAN or CASTNet Name	Met Site Elevation (m)	Distance (km)
Dominion—Chesterfield Power Station	10.1	SFC	13740	Richmond	50	16.0
		UPR	93734	Sterling (Washington Dulles)	85	177.9
Chaparral Steel	50.3	SFC	13740	Richmond	50	38.7
		UPR	93734	Sterling (Washington Dulles)	85	199.9
Dominion—Bremo	67.1	SFC	93736	Charlottesville	190	49.2
		UPR	93734	Sterling (Washington Dulles)	85	158.0
American Electric Power—Clinch River	452.5	SFC	13877	Bristol-Johnson City-Kingsport, TN	465	53.4
		UPR	53829	Roanoke/Blacksburg	648	161.4
Dominion—Chesapeake Energy Center	4.0	SFC	13737	Norfolk	7	17.8
		UPR	93739	Wallops Island	13	147.8
Potomac River Generating Station	10.4	SFC	13743	Washington, DC	3	5.2
		UPR	93734	Sterling (Washington Dulles)	85	41.1
Dominion—Yorktown Power Station	4.0	SFC	93741	Newport News	13	9.7
		UPR	93739	Wallops Island	13	117.3
Jewel Coke Company LLP	365.9	SFC	13877	Bristol-Johnson City-Kingsport, TN	457	89.5
		UPR	53829	Roanoke/Blacksburg	648	144.6
Dominion-Possum Point Power Station	11.0	SFC	13773	Quantico	4	5.2
		UPR	93734	Sterling (Washington Dulles)	85	41.1
Stone Container Enterprises (Smurfit)	3.0	SFC	13740	Richmond	50	45.3
		UPR	93734	Sterling (Washington Dulles)	85	170.5
Stone Container Corporation—Hopewell	14.3	SFC	13740	Richmond	50	24.6
		UPR	93734	Sterling (Washington Dulles)	85	187.9
American Electric Power (Glen Lyn)	464.5	SFC	VPI120	Horton Station	920	27.4
		UPR	53829	Roanoke/Blacksburg	648	44.4
Intermet Foundry Archer Creek	167.6	SFC	13733	Lynchburg	287	16.2
		UPR	53829	Roanoke/Blacksburg	648	122.0
RES dba Steel Dynamics	301.8	SFC	13741	Roanoke	350	5.7
		UPR	53829	Roanoke/Blacksburg	648	37.3
Spruance Genco LLC	16.5	SFC	13740	Richmond	50	12.2
		UPR	93734	Sterling (Washington Dulles)	85	169.8

The meteorological inputs for AERMOD were generated using the AERMOD Meteorological Processor (AERMET) program (version 06341) (EPA, 1998 and 2006c). For each location/site pair, one needs to specify the roughness length, albedo and Bowen ratio based on the land-use characteristics of the area in which the surface meteorological monitoring site is located. This was accomplished by first assessing the land-use for each 100 by 100 m grid cell in a 3-km area surrounding the site. The land-use was plotted and divided into sectors of similar land use based on visual inspection. For each sector the fractional land use was calculated. Each land-use value was assigned a value of roughness length, albedo and Bowen ratio based on tables provided in EPA (2007c). Then a weighted value for each parameter was calculated for each sector based on the fractional land use.

The remaining steps included extraction of hourly surface and twice-daily upper-air data from the National Weather Service (NWS) database, quality assurance of the data, merging of the surface and upper-air data, and application of AERMET to calculate the planetary boundary layer parameters required by AERMOD. In applying AERMET, the methods and reference levels for standard NWS data were employed (EPA, 1998).

The meteorological inputs are contained in two files. The first file includes surface wind, temperature, pressure, relative humidity, and stability information as well as cloud cover and precipitation values. The second file contains information on the vertical structure of temperature and wind near the source location.

It is difficult to review the AERMET-derived meteorological files from a physical meteorological perspective. AERMET and AERMOD, however, both provide report files that contain error and warning messages that can be used to identify problems with data completeness or questionable values in the observed data or calculated parameters. Each of the report files was carefully reviewed. On average less than 8 percent of the hourly data values were reported as missing, and about 20 percent of the hourly wind speeds were reported as calm.

4.2.4. Model Performance Evaluation

The first step in evaluating AERMOD performance was to check the results for reasonableness. The annual deposition output from AERMOD was plotted for each facility and corresponding receptor area. Plots of wet, dry, and total deposition were reviewed to confirm that the magnitude and spatial distribution was reasonable. The deposition of HG0, HG2 and HGP was compared to the speciation of the emissions and checks were made to ensure that these were consistent. Three key findings emerged from this review: 1) dry deposition is greater than wet deposition for all facilities, 2) maximum wet deposition tends to occur in the receptor cells closest to the facility, and 3) maximum dry deposition within the 3-km receptor area tends to occur further away from the facility location. As noted earlier, the 3-km square receptor area appeared to capture the maximum deposition in all cases.

The finding related to wet deposition is consistent with wash out of the emissions near the facility when precipitation is occurring. The finding related to dry deposition is consistent with expected plume behavior under a variety of meteorological conditions and transport of the emissions to a downwind location before deposition occurs.

To further explore the reasonableness of the AERMOD results, several sensitivity tests were conducted in which selected AERMOD input parameters were varied. According to Wesely et al. (2002), the deposition parameters for the three forms of mercury are not all well established. Thus, possible uncertainties in the values for air diffusivity, water diffusivity, and particle size distribution were explored by making small changes to these parameters. In addition, the effects of using homogeneous versus more detailed surface characteristics and the sensitivity of the model to changes in the emissions rates and stack parameter information were examined. The sensitivity results for AERMOD are presented in Section 6 of this report.

It was not possible to evaluate the AERMOD results using observed data. However, the AERMOD results were compared with the CMAQ results, in terms of the overall deposition amount and the relative deposition of HG0, HG2 and HGP and wet versus dry deposition. This comparison is also presented in Section 6.

4.2.5. Base- and Future-year Modeling and Analysis

AERMOD was applied for the base simulation period using 2002 emissions and for 2010, 2015 and 2018 using projected emissions for those years. Total emissions for the base and future years are summarized in Table 4-4.

Table 4-4. AERMOD Emissions Rates for Total Mercury (lbs/yr) for 2002, 2010, 2015 and 2018 for the Top 15 Emitting Facilities for the Base Year.

Facility Name	Rank	2002 Total Hg (lbs/yr)	2010 Total Hg (lbs/yr)	2015 Total Hg (lbs/yr)	2018 Total Hg (lbs/yr)
Dominion—Chesterfield Power Station	1	358.83	183.15	151.47	159.39
Chaparral Steel	2	292.30	100.50	50.50	50.50
Dominion—Bremo	3	167.73	172.74	189.88	200.38
American Electric Power- Clinch River	4	159.21	80.00	81.00	81.00
Dominion—Chesapeake Energy Center	5	157.38	81.05	89.09	94.01
Potomac River Generating Station	6	118.26	72.37	72.37	29.77
Dominion—Yorktown Power Station	7	107.64	105.85	73.46	31.19
Jewel Coke Company LLP	8	105.62	106.91	106.91	106.91
Dominion-Possum Point Power Station	9	100.19	1.99	1.49	1.25
Stone Container Enterprises (Smurfit)	10	77.76	80.57	82.36	83.41
Stone Container Corporation -Hopewell	11	69.69	9.66	9.79	9.87
American Electric Power (Glen Lyn)	12	65.14	67.09	73.74	77.82
Intermet Foundry Archer Creek	13	65.01	21.77	12.87	13.89
RES dba Steel Dynamics	14	60.80	21.57	12.65	13.65
Spruance Genco LLC	15	55.50	25.95	28.53	30.11

There are both increases and decreases in the emissions between the base and future years, depending on the facility and the year. Compared to the base year, overall total mercury emissions for these fifteen facilities are 42 percent lower for 2010, 47 percent lower for 2015, and 50 percent lower for 2018. Additional detailed summaries of the AERMOD emissions are provided in Section 6 of this report.

Tabular and graphical summaries of the AERMOD results for the base and future years were prepared and analyzed. The results are presented in Section 6.

In this study, AERMOD was intended to be used primarily as a screening tool - to identify facilities that may have large local impacts on mercury deposition that may not be resolved by CMAQ due to the grid resolution and other factors. To complete this goal, the reductions simulated by AERMOD for each future year were compared in a relative sense (e.g., using percent change) with those simulated by CMAQ and used to quantify the possible uncertainty in the CMAQ results that are attributable to the effects of grid resolution. The combined CMAQ/AERMOD results are presented in Section 7 of this report.

5. CMAQ Modeling Results

The CMAQ modeling results are presented in this section of the report. The base-year modeling exercises included the initial simulation for the 2001/2002 base year, a meteorological sensitivity simulation, an update to the emissions inventory, and an evaluation of model performance. The CMAQ/PPTM feature was used to assess baseline contributions from tagged sources and source regions to mercury deposition.

The future-year modeling exercise included the application of CMAQ for 2010 and 2015, and the application of CMAQ/PPTM for 2018. For 2018, PPTM was applied for the same sources and source regions that were tagged and examined for base-year simulation. All future-year modeling results were assessed relative to the base year results, with emphasis on the relative, rather than absolute, changes in mercury deposition.

The spatial plots of mercury deposition presented in this section use a variety of different scales in order to display the spatial patterns of deposition and deposition differences. Note that the color scheme is not tied to specific ranges of deposition, but is used instead to highlight the patterns of deposition corresponding to each individual plot. For example, in a given a plot of total annual mercury deposition from all sources the scale may range from 0 to 64 grams per square kilometer (g km^{-2}) and the color red may be used to designate deposition values greater than 56 g km^{-2}, in another plot of mercury deposition from selected sources the scale may range from 0 to 20 g km^{-2} and the color red may be used to designate deposition values greater than 17.5 g km^{-2}, and in another a plot of mercury deposition from natural sources the scale may range from 0 to 2 g km^{-2} and the color red may be used to designate deposition values greater than 1.8 g km^{-2}. The spatial plots are intended to display the spatial patterns. For detailed comparisons of the deposition amounts the reader should refer to the pie charts, bar charts and tables that are also presented in this section.

In addition to the results presented in this section, a full of set CMAQ-derived, gridded output files of mercury deposition for each simulation year have been prepared and provided to VDEQ for use in water quality analysis.

5.1. Base-year Modeling

The results of the meteorological sensitivity simulation, the evaluation of model performance, and the CMAQ/PPTM baseline contribution analysis are presented in this section of the report.

5.1.1. Meteorological Sensitivity Simulation

While 2001 was selected as the annual simulation period, sensitivity testing was conducted using 2002 meteorological inputs. CMAQ-ready meteorological inputs for 2002 were obtained from EPA. These alternate meteorological inputs were prepared using the same tools and methods used for 2001, namely MM5 and MCIP (as discussed in Section 4). In particular, assessing the sensitivity of the model to the meteorological inputs (and thus potentially the use of a different base year for the modeling analysis) was of interest.

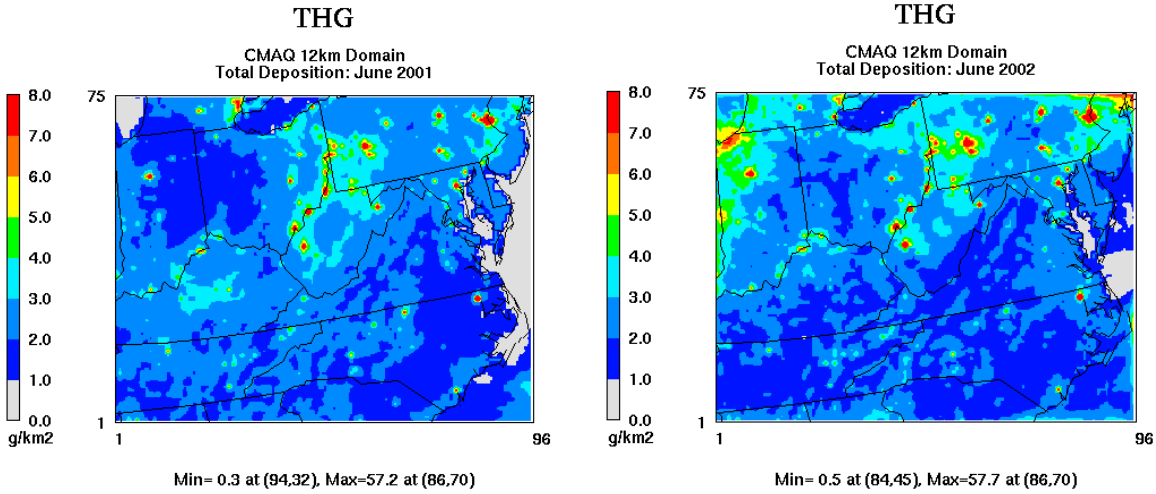
It is widely understood that changes in the meteorological conditions input to a simulation have the potential to affect simulated mercury deposition in a variety of complex ways. Wet deposition is directly related to the location, amount and timing of rainfall and other forms of precipitation. Dry deposition is affected by atmospheric stability and wind speed. The sources contributing to both wet and dry deposition are determined in part by the source-receptor relationships defined by wind speed and wind direction. Thus changes in any of these parameters have the potential

to affect deposition. This study did not include a detailed assessment of the differences between the meteorological inputs and their effects on simulation deposition. Instead, the assessment focused on whether use of a different simulation period (and its associated meteorological conditions) would produce very different CMAQ results.

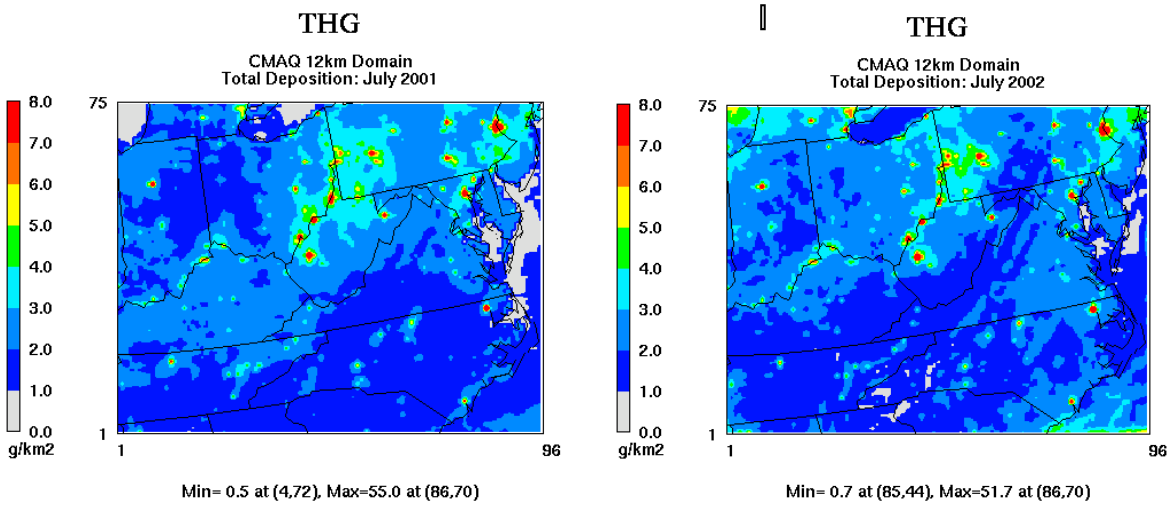
For Virginia, both precipitation and wet deposition tend to be highest during the summer months. The data presented in Section 2 indicate that wet deposition tends to be greatest for the third quarter of the year. Thus the sensitivity simulations focused on July, August and September. The CMAQ base year simulation for July, August, and September was rerun using the complete set of meteorological inputs for these months for 2002. The monthly deposition totals are compared in Figure 5-1, which displays total deposition for each of the three months for 2001 and 2002.

Figure 5-1. Monthly CMAQ-Simulated Total Mercury Deposition (g km^{-1}) for June, July, August 2001 and 2002.

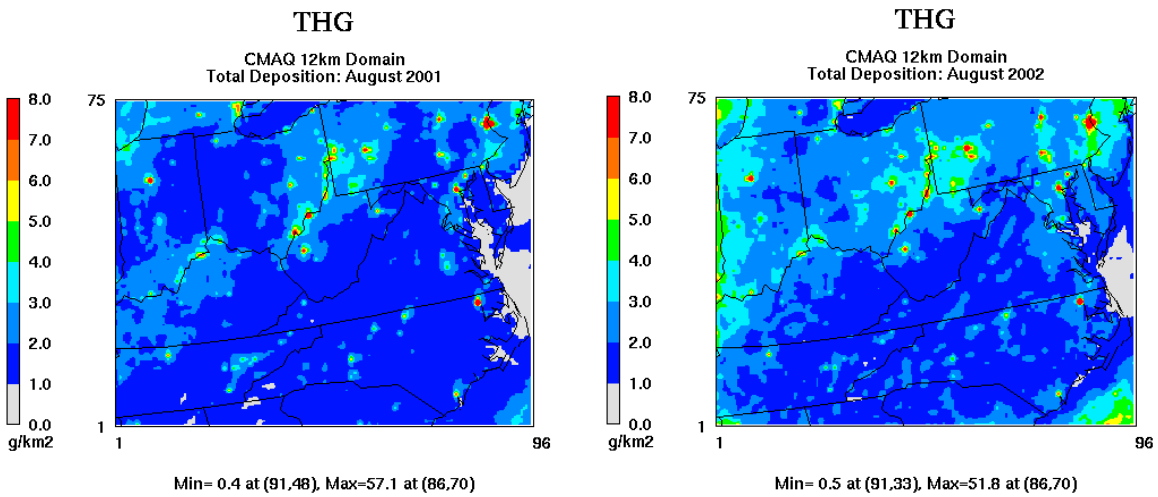
(a) June 2001 (left) and June 2002 (right)



(b) July 2001 (left) and July 2001 (right)



(c) August 2001 (left) and August 2002 (right)



When comparing the simulated deposition within the 12-km domain, there are similarities in the deposition patterns that are related to the distribution of emissions sources. Overall deposition amounts for 2002 are greater for June, less for July, and greater for August compared to those for 2001. A similar comparison of the wet and dry deposition amounts (not shown) indicates that the differences in total deposition are due to differences in both wet and dry deposition, but that some of the larger differences are for wet deposition.

Wet deposition is, of course, correlated with rainfall. So it is important to examine how the rainfall compares between the two years. The reliability of the deposition results also depends on how well the observed rainfall is represented by the meteorological inputs. Thus another important factor to consider in assessing the quality of the results for the two different years is the ability of MM5 to simulate the observed rainfall amounts for each year. Table 5-1 summarizes and compares the observed and simulated rainfall amounts for three locations in Virginia (Shenandoah National Park, Charlottesville, and Norfolk) for each of the three months and each year. These sites were selected to represent different geographical areas in the state (namely the mountains, mid-section and coastal regions). In addition to total rainfall amount, the number of days with measurable precipitation is also given.

Table 5-1a. Observed and Simulated Monthly Rainfall Amount (in) and Number of Rain Days for June, July, and August 2001 and 2002: Shenandoah National Park.

Month	2001				2002			
	Observed Rainfall (in)	Simulated Rainfall (in)	# of Observed Rain Days	# of Simulated Rain Days	Observed Rainfall (in)	Simulated Rainfall (in)	# of Observed Rain Days	# of Simulated Rain Days
June	5.44	9.78	15	17	3.47	7.79	9	15
July	2.82	4.79	5	14	3.21	9.51	10	19
August	6.63	7.39	17	16	3.48	8.51	13	21
Total	14.89	21.96	37	47	10.16	25.81	32	55

Table 5-1b. Observed and Simulated Monthly Rainfall Amount (in) and Number of Rain Days for June, July, and August 2001 and 2002: Charlottesville.

Month	2001				2002			
	Observed Rainfall (in)	Simulated Rainfall (in)	# of Observed Rain Days	# of Simulated Rain Days	Observed Rainfall (in)	Simulated Rainfall (in)	# of Observed Rain Days	# of Simulated Rain Days
June	5.12	4.51	17	12	3.18	3.80	11	10
July	2.04	2.29	10	8	4.55	5.18	14	12
August	2.68	2.44	15	9	2.16	2.46	9	9
Total	9.84	9.24	42	29	9.89	11.44	34	31

Table 5-1c. Observed and Simulated Monthly Rainfall Amount (in) and Number of Rain Days for June, July, and August 2001 and 2002: Norfolk.

Month	2001				2002			
	Observed Rainfall (in)	Simulated Rainfall (in)	# of Observed Rain Days	# of Simulated Rain Days	Observed Rainfall (in)	Simulated Rainfall (in)	# of Observed Rain Days	# of Simulated Rain Days
June	6.96	3.02	12	8	4.29	5.02	10	9
July	2.43	1.81	11	6	3.10	6.22	11	15
August	5.97	9.12	14	11	2.77	6.67	11	13
Total	15.36	13.95	37	25	10.16	17.91	32	37

The observed values for the two years show that 2001 was characterized by a greater amount of precipitation than 2002 for Shenandoah and Norfolk and about the same amount as for 2002 for Charlottesville. The number of days with measurable precipitation is greater for 2001 for all three areas. The distribution of rain throughout the summer months is different for the two years.

For Shenandoah (Table 5-1a), the MM5-derived rainfall amounts are higher than observed for both 2001 and 2002. The overestimation is much greater for 2002. The average rainfall bias for this site is 2.4 in for 2001 and 5.2 in for 2002.

For Charlottesville (Table 5-1b), the MM5-derived rainfall amounts are slightly lower than observed for 2001 and slightly higher than observed for 2002. The average bias for this site is -0.2 in for 2001 and 0.5 in for 2002.

For Norfolk (Table 5-1c), the MM5-derived rainfall amounts are slightly lower than observed for 2001 and higher than observed for 2002. The average bias for this site is -0.5 in for 2001 and 2.6 in for 2002.

Figure 5-2 provides a visual comparison of the simulated and observed rainfall amount by month for each year and each site.

Figure 5-2a. Observed and Simulated Monthly Rainfall Amount (in) for June, July, and August 2001 and 2002: Shenandoah National Park.

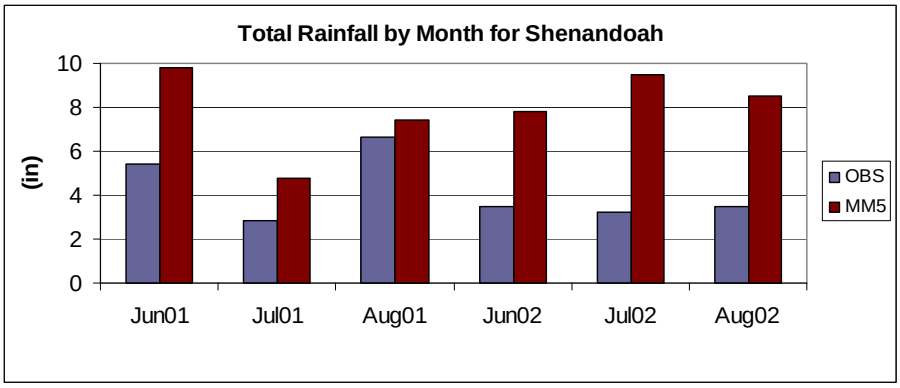


Figure 5-2b. Observed and Simulated Monthly Rainfall Amount (in) for June, July, and August 2001 and 2002: Charlottesville.

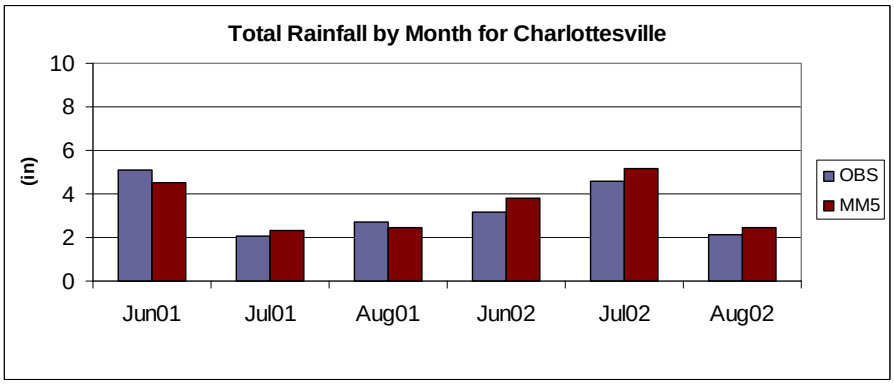
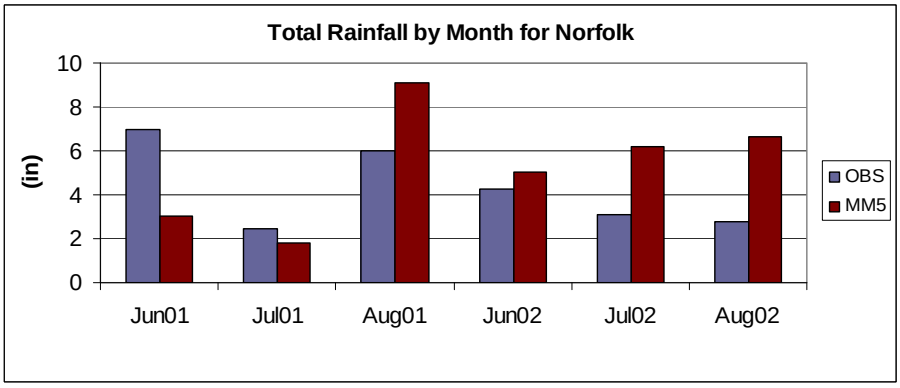


Figure 5-2c. Observed and Simulated Monthly Rainfall Amount (in) for June, July, and August 2001 and 2002: Norfolk.



In summary, this comparison with observed precipitation data indicates that the MM5 model does a better job of simulating the observed precipitation amounts for the selected sites for 2001 for the subset simulation period. However, model performance does vary by month. The overall better representation of summertime precipitation amounts by MM5 provides some additional confirmation that 2001 is a more suitable simulation period than 2002 (for the critical summer months). Note that the selection of the simulation period was discussed in more detail in Section 3. The results of the sensitivity simulation indicate that the model is sensitive to rainfall and possibly other of the meteorological conditions. One conclusion from this analysis is that the ability of CMAQ to simulate deposition is dependent on the ability of the meteorological inputs to represent key meteorological conditions, such as rainfall.

5.1.2. Model Performance Evaluation

The CMAQ model is a multi-pollutant model and certain of the non-mercury species, especially ozone and other oxidants, may influence the simulation of mercury. In addition, examining model performance for a variety different species and for both air concentrations and deposition may aid the overall evaluation of the model results and specifically the identification of biases or deficiencies for certain regions, time periods and/or meteorological (or other) conditions. Thus, the evaluation of model performance for CMAQ considered concentration and deposition of both mercury and non-mercury species.

The simulated and observed values of concentration and deposition for each monitoring site and the average over all sites within 1) the full domain, 2) the 12-km inner grid of the modeling domain, and 3) Virginia were compared. The emphasis of the model performance evaluation was mercury deposition for Virginia and the 12-km grid. Following EPA guidance (EPA, 2006b), the evaluation of model performance examined 1) whether the CMAQ model is able to replicate observed (and estimated) mercury deposition data, and 2) whether the response of the model to changes in mercury emissions is reasonable.

Model Evaluation Datasets

NON-MERCURY SPECIES CONCENTRATIONS AND DEPOSITION DATA

Model performance for ozone was evaluated against observations available from the EPA Air Quality System (AQS) network. For the national-scale modeling domain, the number of sites ranges from approximately 500 to several thousand, depending on the time of year. The sites are primarily located in urban areas. The daily average simulated ozone concentration for each monitor for each day of the annual simulation period was compared to the corresponding observed concentration.

Measurements of $PM_{2.5}$ were obtained from the AQS network, which includes several thousand sites, and the Interagency Monitoring of Protected Visual Environments (IMPROVE) network, which samples approximately 150 Class I national parks and wilderness areas throughout the U.S. For $PM_{2.5}$ and its component species, daily, monthly and annual average values were compared.

Observed wet deposition amounts of sulfate, nitrate, and ammonia from the National Acid Deposition Program (NADP) were used to assess the model's ability to simulate the deposition for each of these species. The NADP network includes more than 200, typically rural, sites. Monthly average values were compared.

MERCURY DEPOSITION DATA

For mercury, the CMAQ wet deposition values were compared to data from the Mercury Deposition Network (MDN), as available from the National Acid Deposition Program (NADP). There are a total of 53 MDN monitors with complete data for 2001 in the full modeling domain.

Emphasis was given to the evaluation of model performance for the 12-km grid. There are a total of 9 MDN monitors with complete data for 2001 in the 12-km modeling domain, and these include several sites in Pennsylvania and North Carolina. Sites at the Allegheny Portage Railroad National Historic Site, Pennsylvania; Arendtsville, Pennsylvania; and Pettigrew State Park, North Carolina all have data for 2001 and are likely most representative, based on proximity and/or similar geographical features, to the areas of interest in Virginia. In particular, Pettigrew State Park, near the Albemarle Sound, may be representative of coastal Virginia.

Mercury wet deposition data for Virginia are available for three MDN monitoring sites, Shenandoah National Park (beginning in October 2002), Culpeper (beginning in November 2002) and Harcum (beginning in December 2004). The Culpeper site is located in north-central Virginia and the Harcum site is located in coastal Virginia. Although there are no actual data for these sites for the 2001 simulation period, the data for 2003-2005 for sites in Virginia and throughout region were used to estimate deposition for 2001 at the Virginia monitoring sites. The methodology used to estimate deposition is discussed in the next section. The estimated deposition values were used in the evaluation of CMAQ model performance.

ESTIMATED MERCURY DEPOSITION "DATA"

The results from the Classification and Regression Tree (CART) analysis (which was conducted to support the development of the conceptual model) were used to estimate deposition for 2001 for the Virginia monitoring sites. CART is a statistical analysis tool developed by Brieman, et al. (1984) and enhanced by Steinberg, et al. (1997) and Salford Systems (2007). Specifically, each seven-day period in 2001 was classified according to the observed meteorological conditions and determined the corresponding CART-based classification group. The daily average mercury deposition for the grouping (the daily average for all other periods in the classification group) was assigned to the 2001 weekly period (multiplying by 7 to get the weekly deposition amount). This was done for each period for the entire year of 2001 and then the weekly mercury deposition values were used to estimate seasonal and annual deposition amounts. The key assumption here is that by matching the meteorological conditions for 2001 on a weekly basis to those for later years, observed mercury deposition for the later years can be used to estimate deposition for 2001. Applying this assumption on a weekly basis accounted for the variable effects of meteorology throughout the year.

As a second approach to estimating the data, each of the Virginia sites was paired with a nearby site with a longer period of record. Various ratios of the observed data were used to estimate wet deposition for the Virginia sites for 2001. The ratios were based on year-to-year differences in wet deposition at the longer-term sites and, alternatively, site-to-site differences in deposition between the paired sites for each year with available data at both sites. The Culpeper site was paired with Arendtsville, PA; the Shenandoah site was paired with the Allegheny Portage Railroad National Historic Site, PA; and Harcum was paired with Pettigrew State Park, NC. Refer to Figure 2-1 for a map showing the locations of these sites.

The results of both the CART and ratio methods are presented in Table 5-2.

Table 5-2a. Observed and Estimated Annual Mercury Wet Deposition (g km^{-2}) for Selected MDN Sites in Virginia: Culpeper.

Year	Culpeper (VA08)			
	Observed	Estimated Based on Year-to-Year Ratio	Estimated Based on Site-to-Site Ratio	Estimated Using CART Analysis
2001		6.85	6.78	5.88
2003	12.73			
2004	7.78			
2005	8.81			

Table 5-2b. Observed and Estimated Annual Mercury Wet Deposition (g km^{-2}) for Selected MDN Sites in Virginia: Shenandoah.

Year	Shenandoah (VA28)			
	Observed	Estimated Based on Year-to-Year Ratio	Estimated Based on Site-to-Site Ratio	Estimated Using CART Analysis
2001		11.53	10.99	8.18
2003	11.87			
2004	9.73			
2005	7.07			

Table 5-2c. Observed and Estimated Annual Mercury Wet Deposition (g km^{-2}) for Selected MDN Sites in Virginia: Harcum.

Year	Harcum (VA98)			
	Observed	Estimated Based on Year-to-Year Ratio	Estimated Based on Site-to-Site Ratio	Estimated Using CART Analysis
2001		4.50	4.50	7.05
2003				
2004				
2005	8.15			

The more detailed CART-based estimation technique gives a result that is different from one obtained from ratios of the observed data. The differences among the estimates highlight that there is uncertainty in the estimated data. Because the CART-based estimation technique relies only on data for the Virginia sites and accounts for year-to-year difference in meteorology at these sites, the CART-based estimates were used in calculating statistical performance evaluation. Nevertheless, the other values may provide perspective to the reader in reviewing the statistical results.

Statistical Performance Metrics

A variety of statistical measures were used to quantify model performance. These were listed and described in Section 3. Statistical measures were calculated on a monthly, seasonal and annual basis, based on data availability.

Currently, EPA modeling guidance does not provide benchmarks for the evaluation of CMAQ model performance for any species. For ozone modeling, early EPA modeling guidance (EPA, 1991) suggested ranges for the normalized bias (within ±15 percent) and normalized gross error (less than or equal to 35 percent). Although originally developed for urban-scale ozone modeling, these ranges have continued to be referenced for regional-scale modeling. More recently, model performance criteria based on a mean fractional bias of within ±15 percent and a mean fractional error of less than 35 percent have been applied or recommended (e.g., Boylan et al., 2005). Compared to the normalized bias and error, the fractional bias and error are better suited for regional modeling since the measures can be meaningfully calculated for a broader range of concentrations. For $PM_{2.5}$, typical and recommended ranges for mean fractional bias and error are considerably wider. Boylan and Russell (2006) recommend the following criteria for acceptable model performance: mean fractional bias within ±60 percent and mean fractional error less than 75 percent, with corresponding goals of ±30 and 50 percent, respectively. These values are based on the results of selected modeling studies. There are currently no such criteria for deposition, including for mercury deposition (Bullock et al., 2008), so we have also adopted these same values for deposition. In the remainder of this section, the qualitative assessments of model performance are referenced to these criteria.

Results

OZONE

Model performance for ozone is summarized in Table 5-3. Table 5-3a presents the statistical performance measures for the 36-km domain, and Table 5-3b presents this same information for the 12-km subdomain. Statistical measures for ozone are summarized for each month of the typical ozone season (April through October). Daily average ozone values were used to calculate the statistical measures. Only days with daily averaged observed values greater than 40 ppb were used in the calculations.

Table 5-3a. Summary of CMAQ Model Performance for Ozone for the 2001 Simulation Period: 36-km Domain.

Metric Descriptor	Units	Metric ID	Apr	May	Jun	Jul	Aug	Sep	Oct
No. of obs/sim pairs		N	26515	29982	27067	27928	28759	23521	17608
Mean observed	ppb	OBS	55.8	62.1	66.2	64.5	66.2	59.2	54.9
Mean simulated	ppb	SIM	64.5	70.1	73.3	67.2	69.5	60.8	54.6
Ratio of means		RATIO	1.2	1.1	1.1	1.0	1.0	1.0	1.0
Mean bias	ppb	MB	8.7	8.0	7.1	2.8	3.2	1.6	-0.3
Mean fractional bias	%	MFB	14.2	12.6	10.8	4.5	5.4	3.2	-0.1
Mean error	ppb	ME	10.8	11.8	12.7	11.5	12.3	9.7	8.1
Mean fractional error	%	MFE	18.0	17.9	18.5	17.2	18.0	16.0	14.6
Correlation		R	0.559	0.602	0.625	0.527	0.525	0.528	0.513
Correlation coefficient		R2	0.312	0.362	0.391	0.278	0.276	0.279	0.263

Table 5-3b. Summary of CMAQ Model Performance for Ozone for the 2001 Simulation Period: VDEQ 12-km Subdomain.

Metric Descriptor	Units	Metric ID	Apr	May	Jun	Jul	Aug	Sep	Oct
No. of obs/sim pairs		N	9033	9535	9247	9453	9966	7426	4914
Mean observed	ppb	OBS	56.6	63.9	68.8	65.1	67.3	58.6	54.8
Mean simulated	ppb	SIM	63.1	68.1	73.1	66.9	69.5	56.7	51.2
Ratio of means		RATIO	1.1	1.1	1.1	1.0	1.0	1.0	0.9
Mean bias	ppb	MB	6.5	4.2	4.3	1.8	2.2	-1.9	-3.6
Mean fractional bias	%	MFB	11.0	7.5	7.2	3.1	4.1	-2.9	-6.4
Mean error	ppb	ME	9.1	8.7	10.3	9.6	10.1	8.5	7.7
Mean fractional error	%	MFE	15.4	13.7	15.0	14.6	14.8	14.8	14.6
Correlation		R	0.558	0.738	0.729	0.619	0.613	0.546	0.587
Correlation coefficient		R2	0.311	0.545	0.531	0.383	0.376	0.298	0.345

For the 36-km grid (Table 5-3a), the ratio of mean simulated to mean observed ozone is close to one for each month. The mean fractional bias is within 15 percent and is positive for all months, with the exception of October. Note that a positive value indicates an overestimation of ozone. The mean fractional error is within 20 percent. These values are indicative of reasonable model performance for ozone on the national scale.

For the 12-km grid (Table 5-3b), the ratio of mean simulated to mean observed ozone is also close to one for all months. The mean fractional bias is within 10 percent and the mean fractional error is within 15 percent for all months, with the exception of April (and they are only slightly higher than these thresholds for April). The bias changes from positive to negative during the course of the ozone season, which indicates that CMAQ overestimates ozone early in the ozone

season and underestimates ozone later in the season. The errors are generally consistent throughout the seven-month period, but highest for the summer months (when ozone is also at its highest). Compared to the ranges provided earlier, the bias and error values indicate good model performance for ozone, on average, for the region encompassed by the 12-km grid.

PM2.5 (AQS)

Model performance for total $PM_{2.5}$ (based on AQS data) is summarized in Table 5-4. Table 5-4a presents the statistical performance measures for the 36-km domain, and Table 5-4b presents this same information for the 12-km subdomain. Statistical measures for total $PM_{2.5}$ are summarized for each month and for the entire annual simulation period. Daily (24-hour average) $PM_{2.5}$ values were used to calculate the statistical measures. For most sites, data are available on a daily basis. Only observed $PM_{2.5}$ values greater than 0.10 μgm^{-3} were used in calculating the statistical measures.

Table 5-4a. Summary of CMAQ Model Performance for PM2.5 for the AQS Sites for the 2001 Simulation Period: 36-km Domain.

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	1125	1119	1130	1130	1135	1145	1141	1147	1154	1150	1151	1150	1217
Mean observed	μgm^{-3}	OBS	15.9	12.5	11.9	11.2	11.6	13.4	13.1	14.6	10.8	10.7	13.6	10.7	12.5
Mean simulated	μgm^{-3}	SIM	15.0	12.5	12.3	10.5	9.2	10.1	9.9	11.2	10.1	10.7	12.9	10.6	11.3
Ratio of means		RATIO	0.9	1.0	1.0	0.9	0.8	0.8	0.8	0.8	0.9	1.0	1.0	1.0	0.9
Mean bias	μgm^{-3}	MB	-0.9	0.0	0.4	-0.7	-2.4	-3.3	-3.2	-3.4	-0.6	0.1	-0.7	0.0	-1.2
Mean fractional bias	%	MFB	-11.2	-6.7	-2.1	-12.6	-27.0	-32.3	-29.1	-28.6	-8.0	-3.8	-9.7	-5.8	-16.1
Mean error	μgm^{-3}	ME	5.9	4.3	3.4	3.4	3.5	4.3	4.4	4.5	2.6	3.2	4.9	4.5	3.2
Mean fractional error	%	MFE	39.8	36.2	30.8	33.0	36.0	39.5	39.3	37.9	26.0	30.2	37.8	41.9	29.5
Correlation		R	0.308	0.322	0.526	0.508	0.602	0.730	0.619	0.712	0.536	0.461	0.238	0.196	0.599
Correlation coefficient		R2	0.095	0.104	0.277	0.258	0.362	0.533	0.383	0.507	0.287	0.213	0.057	0.038	0.359

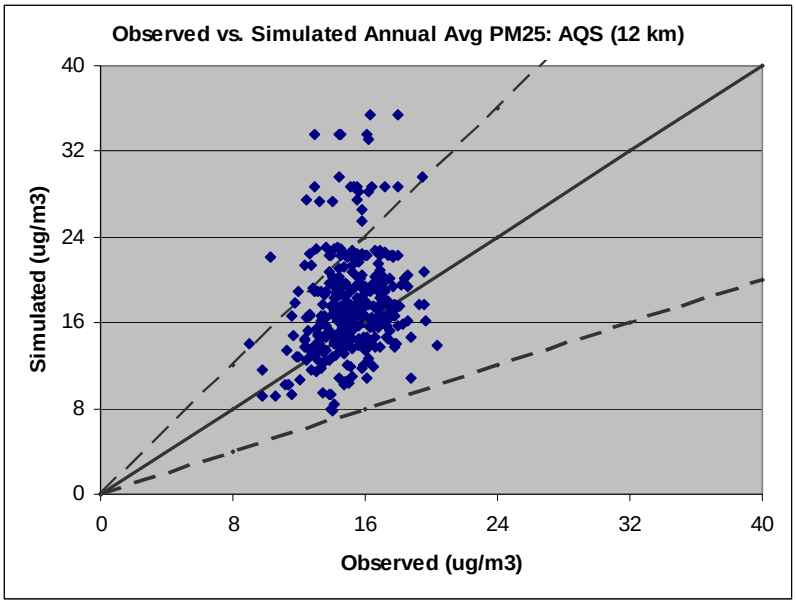
Table 5-4b. Summary of CMAQ Model Performance for PM2.5 for the AQS Sites for the 2001 Simulation Period: VDEQ 12-km Subdomain.

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	339	335	339	336	337	338	337	337	340	343	346	344	358
Mean observed	μgm^{-3}	OBS	17.8	13.9	12.8	13.3	15.3	18.9	16.7	21.2	13.2	12.1	15.0	11.3	15.1
Mean simulated	μgm^{-3}	SIM	25.3	19.1	16.8	16.1	14.7	16.8	16.1	20.1	16.0	18.0	21.6	18.1	18.5
Ratio of means		RATIO	1.4	1.4	1.3	1.2	1.0	0.9	1.0	1.0	1.2	1.5	1.4	1.6	1.2
Mean bias	μgm^{-3}	MB	7.5	5.2	3.9	2.8	-0.6	-2.1	-0.7	-1.0	2.8	5.9	6.6	6.7	3.4
Mean fractional bias	%	MFB	28.9	25.9	23.2	15.8	-7.0	-14.4	-6.0	-6.1	17.7	33.6	32.6	38.5	11.4
Mean error	μgm^{-3}	ME	8.1	5.9	4.4	3.9	4.1	4.3	4.4	4.4	3.5	6.3	8.1	7.1	4.6
Mean fractional error	%	MFE	33.7	31.7	27.6	23.7	26.3	23.3	25.9	21.3	23.0	36.9	40.4	42.2	20.9
Correlation		R	0.480	0.252	0.522	0.147	-0.113	0.219	0.182	0.222	0.155	0.330	-0.022	0.452	0.225
Correlation coefficient		R2	0.230	0.064	0.272	0.022	0.013	0.048	0.033	0.049	0.024	0.109	0.000	0.204	0.050

For the 36-km grid (Table 5-4a), the ratio of mean simulated to mean observed $PM_{2.5}$ ranges form 0.8 to 1. The mean fractional bias is within 35 percent and is negative for all months, indicating that $PM_{2.5}$ concentrations are underestimated. The underestimation is most pronounced during the summer months. On an annual basis, the mean fractional bias is -16.1 percent. The mean fractional error is within about 40 percent for all months, and is 29.5 percent for the annual period. Based on the ranges provided earlier, these values are indicative of reasonable model performance for $PM_{2.5}$ on the national scale.

For the 12-km grid (Table 5-4b), the ratio of mean simulated to mean observed $PM_{2.5}$ ranges from 0.9 to 1.6 and is 1.2 for the year. The mean fractional bias is within 35 percent, with the exception of December. The bias is positive for January through April and September through December, and negative for the remaining (summer) months. Thus there is a mix of over- and underestimation, which results in an annual bias of 11.4 percent. The mean fractional error is within about 40 percent for all months, and is 20.9 percent for the annual period. These values are indicative of reasonable model performance for $PM_{2.5}$ on the regional scale. Figure 5-3 compares simulated and observed annual average $PM_{2.5}$ for all AQS sites within the 12-km subdomain. Each point in the scatter diagram represents a different AQS site. The dashed lines designate agreement within 50 percent of the observed value.

Figure 5-3. Scatter Diagram Comparing Simulated and Observed Annual Average PM2.5 Concentrations for the AQS Sites for the 2001 Simulation Period: VDEQ 12-km Subdomain.



PM2.5 (IMPROVE)

Model performance for total and speciated $PM_{2.5}$ (based on IMPROVE data) is summarized in Table 5-5. Table 5-5a presents the statistical performance measures for total $PM_{2.5}$ for the 36-km domain, and Table 5-5b presents the performance metrics for $PM_{2.5}$ and several component species for the 12-km subdomain. Statistical measures for total $PM_{2.5}$ are summarized for each month and for the entire annual simulation period. Daily (24-hour average) species values were used to calculate the statistical measures. For the IMPROVE sites, the measurements are taken every three days. The statistical measures are calculated using monthly and annual average species concentrations, a cut-off value of 0.01 μgm^{-3} was assigned for each species to avoid using very low concentrations in the calculations.

Table 5-5a. Summary of CMAQ Model Performance for PM2.5 for the IMPROVE Sites for the 2001 Simulation Period: 36-km Domain.

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	104	103	113	120	125	126	128	129	131	133	132	133	135
Mean observed	μgm^{-3}	OBS	3.9	3.8	4.5	6.2	6.8	7.4	7.3	8.4	6.0	5.4	5.3	3.5	5.8
Mean simulated	μgm^{-3}	SIM	4.8	4.5	5.2	5.2	4.8	5.4	5.6	6.5	5.8	5.7	5.9	4.5	5.6
Ratio of means		RATIO	1.2	1.2	1.2	0.8	0.7	0.7	0.8	0.8	1.0	1.1	1.1	1.3	1.0
Mean bias	μgm^{-3}	MB	0.9	0.7	0.7	-1.0	-2.0	-2.0	-1.7	-1.9	-0.3	0.3	0.6	1.0	-0.3
Mean fractional bias	%	MFB	18.2	12.7	11.0	-29.3	-41.4	-30.2	-22.2	-25.1	-7.9	-0.9	2.2	19.0	-9.2
Mean error	μgm^{-3}	ME	1.7	1.5	1.5	2.3	2.2	2.6	2.6	3.1	1.8	1.7	2.0	1.8	1.4
Mean fractional error	%	MFE	39.9	36.4	32.5	45.0	44.7	39.7	39.0	42.7	30.1	27.9	35.0	42.4	27.4
Correlation		R	0.839	0.823	0.851	0.683	0.832	0.797	0.717	0.725	0.660	0.770	0.781	0.731	0.9
Correlation coefficient		R2	0.704	0.677	0.724	0.466	0.692	0.635	0.514	0.526	0.436	0.593	0.610	0.534	0.731

Table 5-5b. Summary of CMAQ Model Performance for PM2.5 for the IMPROVE Sites for the 2001 Simulation Period: VDEQ 12-km Subdomain.

PM2.5

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	11	11	13	14	16	16	16	16	15	16	15	15	16
Mean observed	μgm^{-3}	OBS	7.7	7.8	8.2	10.4	12.8	15.5	12.5	19.8	10.7	8.5	9.9	6.6	11.4
Mean simulated	μgm^{-3}	SIM	12.8	11.5	11.5	11.8	11.0	13.0	12.1	16.4	12.9	12.3	14.9	10.6	12.8
Ratio of means		RATIO	1.7	1.5	1.4	1.1	0.9	0.8	1.0	0.8	1.2	1.5	1.5	1.6	1.1
Mean bias	μgm^{-3}	MB	5.1	3.7	3.4	1.4	-1.8	-2.5	-0.4	-3.4	2.2	3.8	4.9	4.0	1.4
Mean fractional bias	%	MFB	37.6	28.8	27.2	7.8	-19.6	-20.1	-3.1	-25.2	14.6	27.6	28.3	34.8	8.0
Mean error	μgm^{-3}	ME	5.1	3.7	3.4	2.3	2.2	2.7	4.2	5.0	2.6	3.9	5.6	4.0	1.9
Mean fractional error	%	MFE	37.6	28.9	27.2	17.0	21.8	21.7	35.3	33.1	17.7	28.1	34.1	34.8	13.3
Correlation		R	0.910	0.849	0.824	0.379	0.765	0.726	0.427	0.324	0.314	0.726	0.342	0.893	0.812
Correlation coefficient		R2	0.828	0.721	0.679	0.144	0.585	0.528	0.183	0.105	0.099	0.527	0.117	0.798	0.659

Sulfate (SO4)

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	11	11	13	14	16	16	16	16	15	16	15	15	16
Mean observed	μgm^{-3}	OBS	2.5	2.7	3.0	3.7	5.1	6.9	6.1	10.1	4.8	2.8	3.1	2.1	4.6
Mean simulated	µgm-3	SIM	2.5	2.6	2.7	4.1	5.1	6.7	6.4	9.7	6.4	3.8	3.9	2.4	4.7
Ratio of means		RATIO	1.0	1.0	0.9	1.1	1.0	1.0	1.1	1.0	1.3	1.4	1.3	1.1	1.0
Mean bias	μgm^{-3}	MB	0.0	-0.1	-0.3	0.4	0.0	-0.2	0.3	-0.4	1.6	1.0	0.8	0.3	0.1
Mean fractional bias	%	MFB	2.3	-3.6	-9.9	8.6	-1.5	-2.7	5.1	-3.9	23.4	26.5	20.3	10.9	2.5
Mean error	μgm^{-3}	ME	0.4	0.3	0.4	0.6	0.4	0.7	0.8	1.9	1.6	1.0	0.8	0.4	0.3
Mean fractional error	%	MFE	18.6	11.4	15.7	14.2	7.7	10.4	12.0	18.6	23.5	26.5	20.3	16.6	6.0
Correlation		R	0.838	0.850	0.800	0.192	0.682	0.739	0.789	0.608	0.093	0.569	0.530	0.666	0.800
Correlation coefficient		R2	0.702	0.722	0.640	0.037	0.466	0.546	0.622	0.369	0.009	0.324	0.281	0.443	0.641

Nitrate (NO3)

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	11	11	13	14	16	16	16	16	15	16	15	15	16
Mean observed	μgm^{-3}	OBS	1.7	1.2	1.6	1.0	0.7	0.4	0.3	0.4	0.4	0.5	1.1	1.3	0.8
Mean simulated	μgm^{-3}	SIM	2.1	1.9	2.7	1.5	0.5	0.5	0.4	0.4	0.5	1.5	2.4	1.3	1.4
Ratio of means		RATIO	1.2	1.6	1.7	1.5	0.7	1.3	1.1	1.1	1.4	3.0	2.1	0.9	1.7
Mean bias	μgm^{-3}	MB	0.4	0.7	1.1	0.5	-0.2	0.1	0.0	0.1	0.2	1.0	1.3	-0.1	0.6
Mean fractional bias	%	MFB	8.8	34.1	39.1	15.2	-207.1	-134.2	-160.3	-405.7	-50.6	58.1	43.7	-26.0	28.4
Mean error	μgm^{-3}	ME	0.5	0.8	1.1	0.5	0.2	0.3	0.2	0.3	0.3	1.0	1.3	0.4	0.6
Mean fractional error	%	MFE	32.7	38.7	43.7	31.3	211.3	169.6	185.6	439.9	83.4	59.8	48.4	40.9	34.0
Correlation		R	0.934	0.894	0.903	0.697	0.936	0.847	0.590	0.696	0.762	0.875	0.697	0.833	0.894
Correlation coefficient		R2	0.873	0.799	0.816	0.486	0.877	0.717	0.348	0.485	0.581	0.766	0.486	0.694	0.799

Organic Carbon (OC)

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	11	11	13	14	16	16	16	16	15	16	15	15	16
Mean observed	μgm^{-3}	OBS	1.6	1.6	1.3	1.5	1.8	1.9	1.8	2.2	1.5	1.9	2.7	1.2	1.8
Mean simulated	μgm^{-3}	SIM	2.6	2.4	1.8	2.1	1.7	1.6	1.5	1.5	1.8	2.3	2.9	2.2	2.0
Ratio of means		RATIO	1.7	1.6	1.4	1.4	0.9	0.8	0.8	0.7	1.1	1.2	1.1	1.8	1.1
Mean bias	μgm^{-3}	MB	1.0	0.9	0.5	0.6	-0.2	-0.4	-0.4	-0.7	0.2	0.4	0.2	1.0	0.2
Mean fractional bias	%	MFB	31.7	28.4	20.3	22.8	-13.9	-31.6	-31.3	-54.8	6.1	12.7	3.8	37.6	7.1
Mean error	μgm^{-3}	ME	1.2	1.0	0.7	0.7	0.3	0.5	0.5	0.8	0.4	0.5	1.3	1.1	0.4
Mean fractional error	%	MFE	43.3	36.2	35.3	28.2	20.1	37.8	36.7	59.3	20.8	18.2	42.0	44.6	18.5
Correlation		R	0.808	0.583	0.396	0.427	0.720	0.783	0.538	0.334	0.418	0.594	0.221	0.742	0.657
Correlation coefficient		R2	0.653	0.340	0.156	0.182	0.518	0.613	0.289	0.111	0.174	0.353	0.049	0.550	0.432

Elemental Carbon (EC)

Metric Descriptor	Units	Metric ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
No. of obs/sim pairs		N	11	11	13	14	16	16	16	16	15	16	15	15	16
Mean observed	μgm^{-3}	OBS	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.5	0.4	0.4	0.5	0.3	0.4
Mean simulated	μgm^{-3}	SIM	0.6	0.5	0.4	0.4	0.3	0.4	0.3	0.4	0.4	0.5	0.6	0.5	0.4
Ratio of means		RATIO	1.4	1.2	1.2	1.1	0.8	0.8	0.8	0.7	0.8	1.1	1.1	1.5	1.0
Mean bias	μgm^{-3}	MB	0.2	0.1	0.1	0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.1	0.2	0.0
Mean fractional bias	%	MFB	13.4	-3.9	2.1	0.9	-48.4	-35.7	-41.0	-59.9	-40.4	-4.3	-4.5	15.4	-12.7
Mean error	μgm^{-3}	ME	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.2	0.1	0.3	0.2	0.1
Mean fractional error	%	MFE	33.1	34.0	25.4	22.7	53.6	40.5	49.4	64.3	47.0	22.7	41.8	25.1	26.9
Correlation		R	0.950	0.688	0.765	0.856	0.755	0.910	0.793	0.786	0.609	0.823	0.358	0.611	0.855
Correlation coefficient		R2	0.902	0.473	0.585	0.732	0.570	0.829	0.629	0.618	0.371	0.677	0.128	0.373	0.731

For the 36-km grid (Table 5-5a), the ratio of mean simulated to mean observed $PM_{2.5}$ ranges form 0.7 to 1.3. The mean fractional bias is within 30 percent for all months with the exception of May. It is positive during the cooler months (January through March, November and December) and negative (and somewhat larger) for the remaining (typically warmer) months. On an annual basis, the mean fractional bias is -9.2 percent. The mean fractional error is within 45 percent for all months, and is 27.4 percent for the annual period (based on annual average $PM_{2.5}$ concentrations). Overall $PM_{2.5}$ is less well simulated for the more rural IMPROVE sites, compared to the AQS sites.

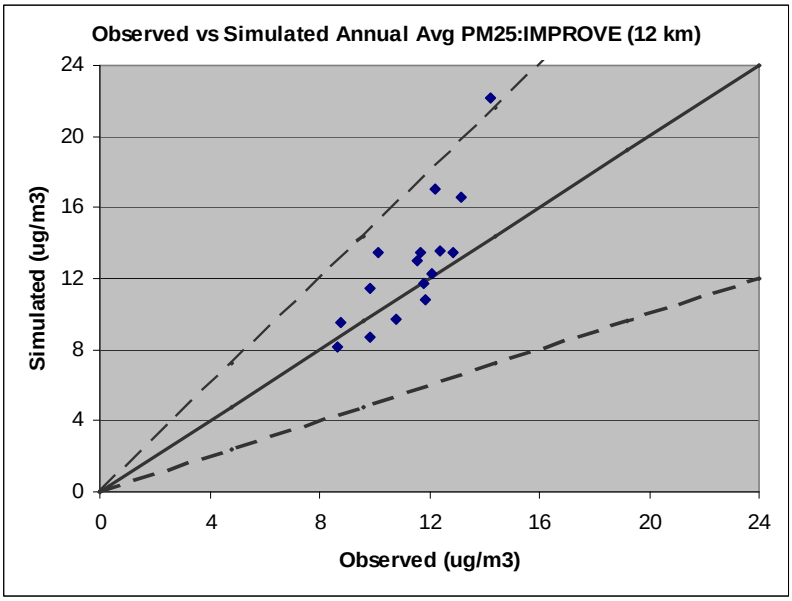
For the 12-km grid (Table 5-5b), the ratio of mean simulated to mean observed $PM_{2.5}$ ranges from 0.8 to 1.7 and is 1.1 for the year. The mean fractional bias is within about 35 percent. The bias is positive for January through April and September through December, and negative for the remaining (summer) months. Thus there is a mix of over- and underestimation, which results in an annual bias of 8 percent. The mean fractional error is also within about 35 percent for all months,

and is 13 percent for the annual period. Based on the ranges provided earlier, these values are indicative of reasonable model performance for $PM_{2.5}$ at the more rural sites within the 12-km domain. The statistical measures for the IMPROVE sites indicate better performance for the higher resolution grid, compared to the full 36-km domain. Considering the component species, model performance for sulfate is similar to that for overall $PM_{2.5}$ (since sulfate is a predominant species). Agreement between the simulated and observed values is less good for OC and EC, especially during the summer months, when both of these components are underestimated. Nitrate is not well represented by CMAQ at the IMPROVE sites, but is present in very small amounts for sites in the region encompassed by the 12-km grid (so small differences in concentration can result in large errors). On an annual average basis, nitrate is overestimated.

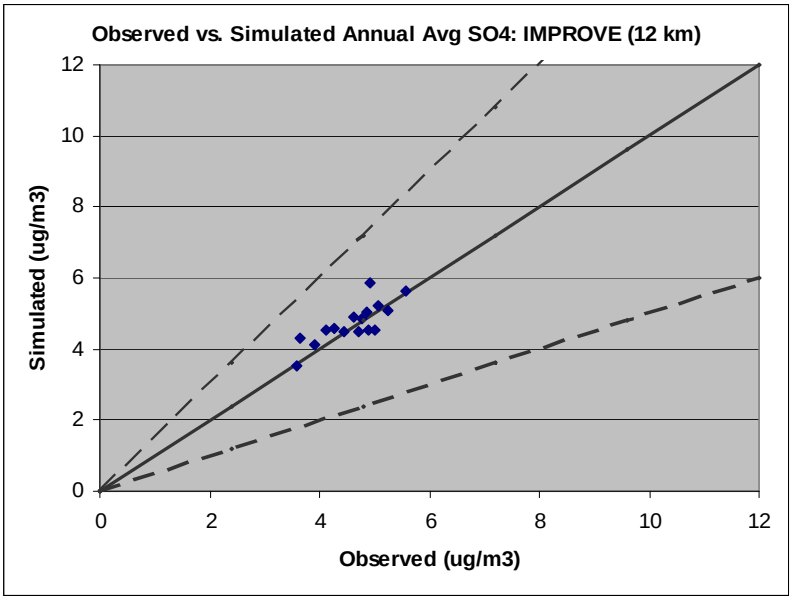
Figure 5-4 compares simulated and observed annual average $PM_{2.5}$ and its component species for all IMPROVE sites within the 12-km subdomain. Each point in the scatter diagram represents a different IMPROVE site. The dashed lines designate agreement within 50 percent of the observed value.

Figure 5-4. Scatter Diagram Comparing Simulated and Observed Annual Average PM2.5 Concentrations for the 2001 Simulation Period: VDEQ 12-km Subdomain.

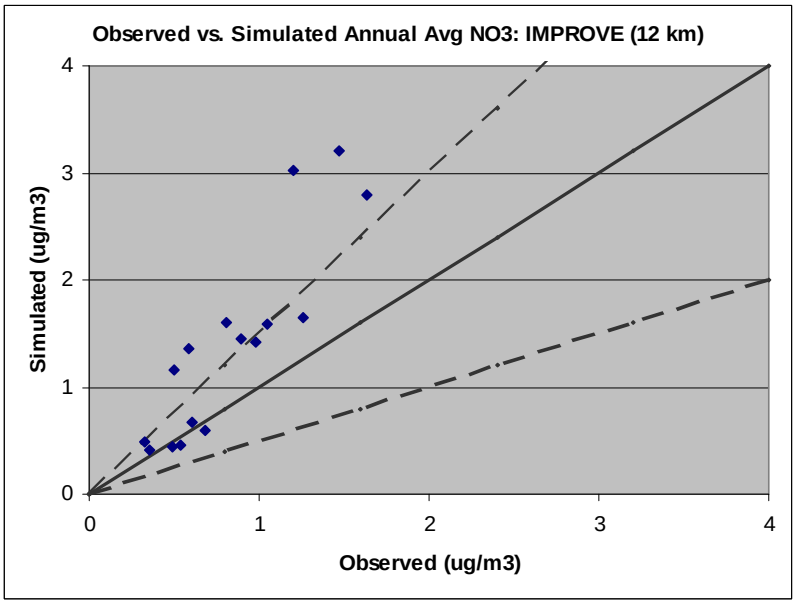
Total PM2.5



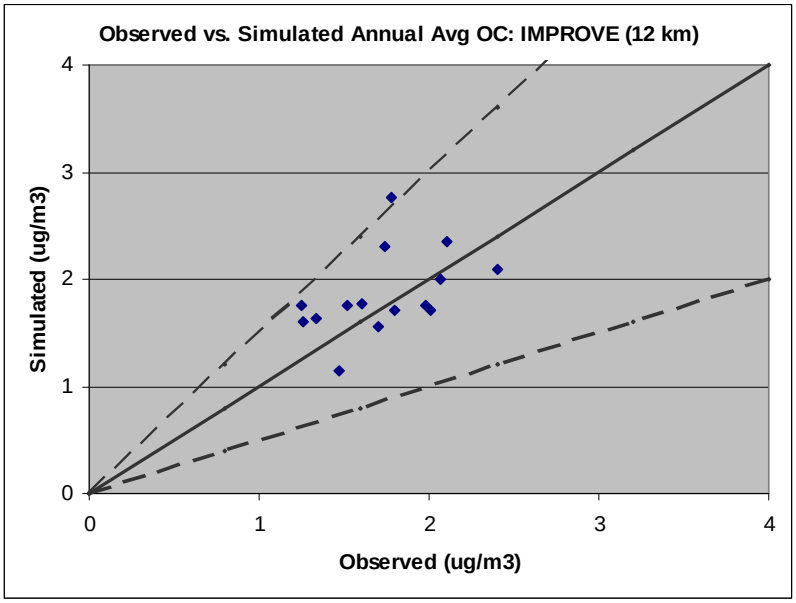
Sulfate (SO4)



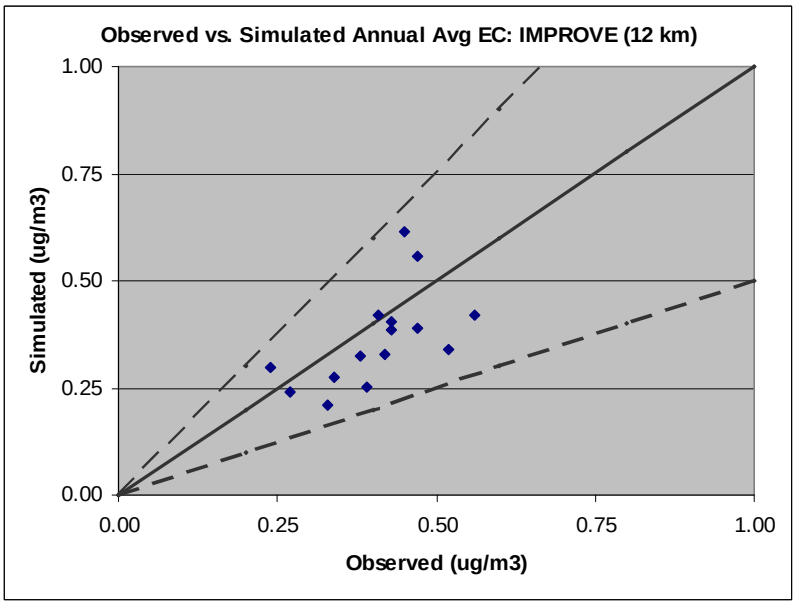
Nitrate (NO3)



Organic Carbon (OC)



Elemental Carbon (EC)



ACID DEPOSITION

Model performance for sulfate, nitrate and ammonium deposition is summarized in Table 5-6. Table 5-6a presents the statistical performance measures for the 36-km domain, and Table 5-6b presents this same information for the 12-km subdomain. These statistics were calculated using data from the NADP monitoring sites. Statistical measures for each species are summarized for each season and for the annual simulation period. Weekly values were used to calculate the statistical measures.

Table 5-6a. Summary of CMAQ Model Performance for Acid Deposition for the NADP Sites for the 2001 Simulation Period: 36-km Domain.

Sulfate Deposition

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	199	217	207	214	152
Mean observed	g km^{-2}	OBS	1.7	2.4	3.4	1.7	10.8
Mean simulated	g km^{-2}	SIM	2.0	2.7	4.4	2.2	13.1
Ratio of means		RATIO	1.2	1.1	1.3	1.2	1.2
Mean bias	g km^{-2}	MB	0.3	0.3	1.0	0.4	2.3
Mean fractional bias	%	MFB	11.1	7.8	18.4	15.1	11.2
Mean error	g km^{-2}	ME	5.9	4.3	3.4	3.4	3.2
Mean fractional error	%	MFE	39.8	36.2	30.8	33.0	29.5
Correlation		R	0.308	0.322	0.526	0.508	0.599
Correlation coefficient		R2	0.095	0.104	0.277	0.258	0.359

Nitrate Deposition

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	219	218	212	220	152
Mean observed	g km^{-2}	OBS	1.5	2.2	2.8	1.4	9.2
Mean simulated	g km^{-2}	SIM	1.7	1.8	2.0	1.4	8.1
Ratio of means		RATIO	1.2	0.8	0.7	1.0	0.9
Mean bias	g km^{-2}	MB	0.3	-0.4	-0.8	0.0	-1.1
Mean fractional bias	%	MFB	6.8	-16.6	-31.5	-0.1	-19.6
Mean error	g km^{-2}	ME	0.7	0.7	1.1	0.5	2.3
Mean fractional error	%	MFE	46.8	40.8	48.9	41.5	32.1
Correlation		R	0.705	0.736	0.703	0.776	0.755
Correlation coefficient		R2	0.497	0.542	0.494	0.602	0.570

Ammonium Deposition

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	167	201	201	184	152
Mean observed	g km^{-2}	OBS	0.3	0.7	0.7	0.4	2.2
Mean Simulated	g km^{-2}	SIM	0.3	0.5	0.8	0.4	2.1
Ratio of means		RATIO	0.8	0.8	1.1	0.9	1.0
Mean bias	g km^{-2}	MB	-0.1	-0.1	0.1	0.0	-0.1
Mean fractional bias	%	MFB	-24.9	-18.5	7.1	-6.0	-6.0
Mean error	g km^{-2}	ME	0.1	0.3	0.3	0.2	0.6
Mean fractional error	%	MFE	48.8	42.4	41.1	42.6	31.7
Correlation		R	0.461	0.673	0.566	0.685	0.708
Correlation coefficient		R2	0.213	0.453	0.320	0.469	0.501

Table 5-6b. Summary of CMAQ Model Performance for Acid Deposition for the NADP Sites for the 2001 Simulation Period: VDEQ 12-km Subdomain.

Sulfate Deposition

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	44	44	44	44	44
Mean observed	g km^{-2}	OBS	2.7	4.2	6.5	2.6	16.0
Mean simulated	g km^{-2}	SIM	3.6	5.5	8.0	3.2	20.3
Ratio of means		RATIO	1.3	1.3	1.2	1.3	1.3
Mean bias	g km^{-2}	MB	0.9	1.3	1.5	0.7	4.3
Mean fractional bias	%	MFB	24.5	19.9	11.9	15.1	18.0
Mean error	g km^{-2}	ME	1.1	1.7	2.5	1.0	5.2
Mean fractional error	%	MFE	29.4	29.8	31.3	29.9	24.4
Correlation		R	0.540	0.507	0.418	0.823	0.643
Correlation coefficient		R2	0.292	0.257	0.175	0.678	0.413

Nitrate Deposition

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	44	44	44	44	44
Mean observed	g km^{-2}	OBS	2.1	3.4	4.0	1.7	11.1
Mean simulated	g km^{-2}	SIM	2.9	2.9	2.6	1.7	10.1
Ratio of means		RATIO	1.4	0.9	0.7	1.0	0.9
Mean bias	g km^{-2}	MB	0.8	-0.5	-1.3	0.0	-1.0
Mean fractional bias	%	MFB	25.7	-19.8	-65.9	-6.3	-13.5
Mean error	g km^{-2}	ME	0.8	0.9	1.5	0.4	1.7
Mean fractional error	%	MFE	27.3	32.6	72.3	31.0	19.1
Correlation		R	0.648	0.586	0.323	0.860	0.761
Correlation coefficient		R2	0.420	0.343	0.104	0.740	0.578

Ammonium Deposition

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	44	44	44	44	44
Mean observed	g km^{-2}	OBS	0.3	0.8	0.9	0.4	2.5
Mean simulated	g km^{-2}	SIM	0.3	0.8	1.1	0.4	2.6
Ratio of means		RATIO	1.0	1.0	1.2	0.9	1.1
Mean bias	g km^{-2}	MB	0.0	0.0	0.2	0.0	0.2
Mean fractional bias	%	MFB	-9.8	-5.2	9.2	-6.2	1.8
Mean error	g km^{-2}	ME	0.1	0.2	0.4	0.1	0.5
Mean fractional error	%	MFE	40.0	30.5	29.5	33.5	20.1
Correlation		R	0.246	0.434	0.481	0.779	0.606
Correlation coefficient		R2	0.060	0.188	0.231	0.607	0.367

The statistical measures indicate good agreement with observed deposition data for both the 36-km and 12-km domains.

MERCURY

Model performance for mercury wet deposition (based on MDN data) is summarized in Table 5-7. Table 5-7a presents the statistical performance measures for the 36-km domain, and Table 5-7b presents the statistical information for the 12-km subdomain. The measures for mercury are summarized for each season and for the entire annual simulation period. Approximately weekly values were used to calculate the statistical measures. The measurement periods vary in length throughout the year and are different for each site. Thus, in order to calculate the statistics, the simulation days were matched to the observation periods for each site. Then monthly, seasonal, and annual deposition amounts were calculated.

Table 5-7a. Summary of CMAQ Model Performance for Mercury Wet Deposition for the MDN Sites for the 2001 Simulation Period: 36-km Domain.

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	52	52	52	52	52
Mean Observed	g km^{-2}	OBS	1.3	2.4	3.7	2.0	9.3
Mean Simulated	g km^{-2}	SIM	1.9	2.6	2.8	2.1	9.4
Ratio of means		RATIO	1.4	1.1	0.8	1.1	1.0
Mean bias	g km^{-2}	MB	0.6	0.2	-0.9	0.2	0.1
Mean fractional bias	%	MFB	21.3	-1.1	-33.8	7.4	-4.2
Mean error	g km^{-2}	ME	0.8	0.9	1.5	0.7	2.7
Mean fractional error	%	MFE	40.9	34.7	53.9	33.9	28.9
Correlation		R	0.666	0.453	0.598	0.718	0.627
Correlation coefficient		R2	0.444	0.205	0.357	0.516	0.393

Table 5-7b. Summary of CMAQ Model Performance for Mercury Wet Deposition for the MDN Sites for the 2001 Simulation Period: 12-km Domain.

Metric Descriptor	Units	Metric ID	Winter	Spring	Summer	Autumn	Annual
No. of obs/sim pairs		N	13	13	13	13	13
Mean Observed	g km^{-2}	OBS	1.4	2.7	3.4	1.5	9.0
Mean Simulated	g km^{-2}	SIM	1.9	2.7	2.4	1.4	8.3
Ratio of means		RATIO	1.4	1.0	0.7	0.9	0.9
Mean bias	g km^{-2}	MB	0.5	0.0	-1.0	-0.1	-0.7
Mean fractional bias	%	MFB	24.5	-9.7	-58.4	-23.2	-13.7
Mean error	g km^{-2}	ME	0.5	0.9	1.3	0.5	1.7
Mean fractional error	%	MFE	25.8	35.6	65.0	49.6	21.8
Correlation		R	0.845	-0.241	0.251	0.815	0.610
Correlation coefficient		R2	0.714	0.058	0.063	0.664	0.372

For the 36-km grid (Table 5-7a), the ratio of mean simulated to mean observed mercury wet deposition ranges from 0.8 (for the summer months) to 1.4 (for the winter months). The mean fractional bias also indicates that mercury deposition is overestimated (on average) during the winter (by 21.3 percent) and underestimated during the summer months (by 33.4 percent). On an annual basis, the mean fractional bias is -4.2 percent. The mean fractional error is 28.9 percent for the annual period, but larger than this for all of the individual seasonal periods.

For the 12-km grid (Table 5-7b), the ratio of mean simulated to mean observed mercury wet deposition ranges from 0.7 (for the summer months) to 1.4 (for the winter months). The mean fractional bias indicates that mercury deposition is overestimated (on average) during the winter months, but underestimated during the remaining three seasonal periods. On an annual basis,

the mean fractional bias is -13.7 percent. The mean fractional error is 21.8 percent for the annual period, but larger than this for all of the individual seasonal periods.

The simulated and observed mercury wet deposition values are graphically compared in Figures 5-5 and 5-6. Figure 5-5 compares simulated and observed wet deposition totals, by season and for the year, averaged over all sites for the 36- and 12-km domains. Figure 5-6 focuses on the annual deposition totals for each site, and each point in the scatter diagram represents a different MDN site. The dashed lines designate agreement within 50 percent of the observed value.

Figure 5-5a. Comparison of Simulated and Observed Mercury Wet Deposition Averaged over all MDN Sites for Each Season and the Full 2001 Simulation Period: VDEQ 36-km Subdomain.

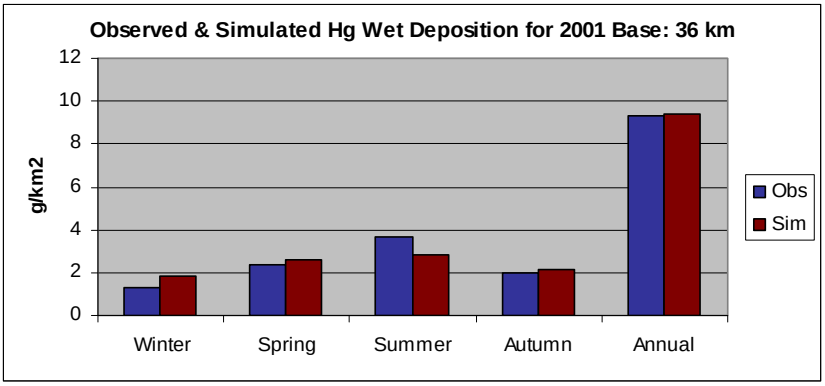


Figure 5-5b. Comparison of Simulated and Observed Mercury Wet Deposition Averaged over all MDN Sites for Each Season and the Full 2001 Simulation Period: VDEQ 12-km Subdomain.

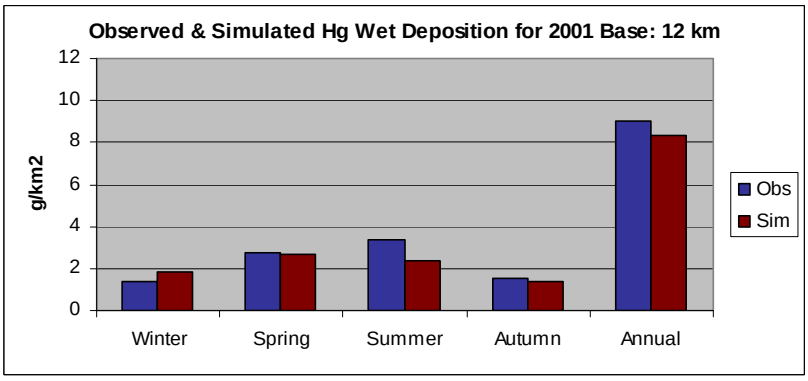


Figure 5-6a. Scatter Diagram Comparing Simulated and Observed Annual Mercury Wet Deposition Totals for the MDN Sites for the 2001 Simulation Period: VDEQ 36-km Subdomain.

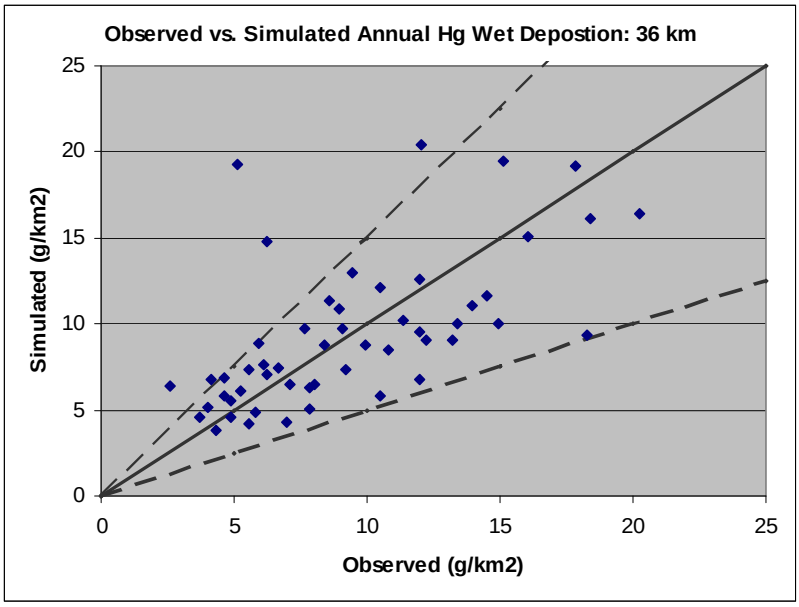
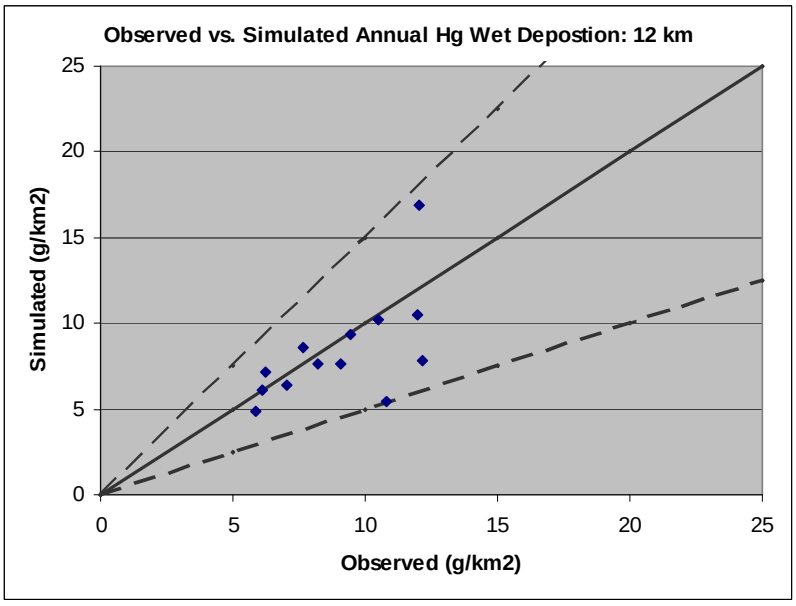


Figure 5-6b. Scatter Diagram Comparing Simulated and Observed Annual Mercury Wet Deposition Totals for the MDN Sites for the 2001 Simulation Period: VDEQ 12-km Subdomain.



Finally, 5-7 compares simulated and observed mercury wet deposition totals, by season and for the year, for the Virginia sites only. The simulated values are compared with the estimated data for 2001, as discussed earlier in this section.

Figure 5-7a. Comparison of Simulated and Estimated Mercury Wet Deposition Averaged over all MDN Sites in Virginia for Each Season and the Full 2001 Simulation Period.

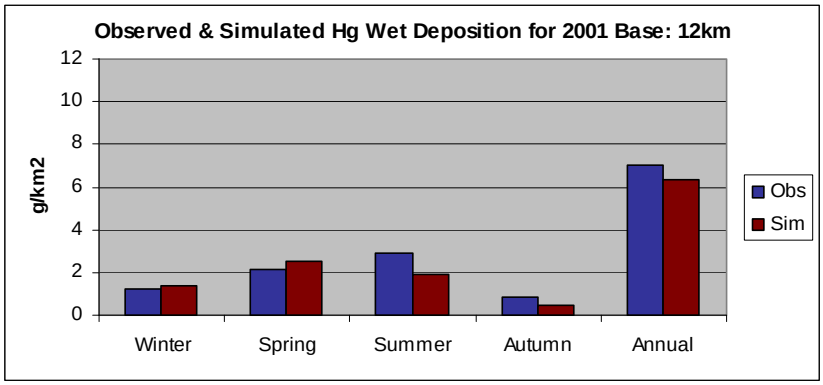
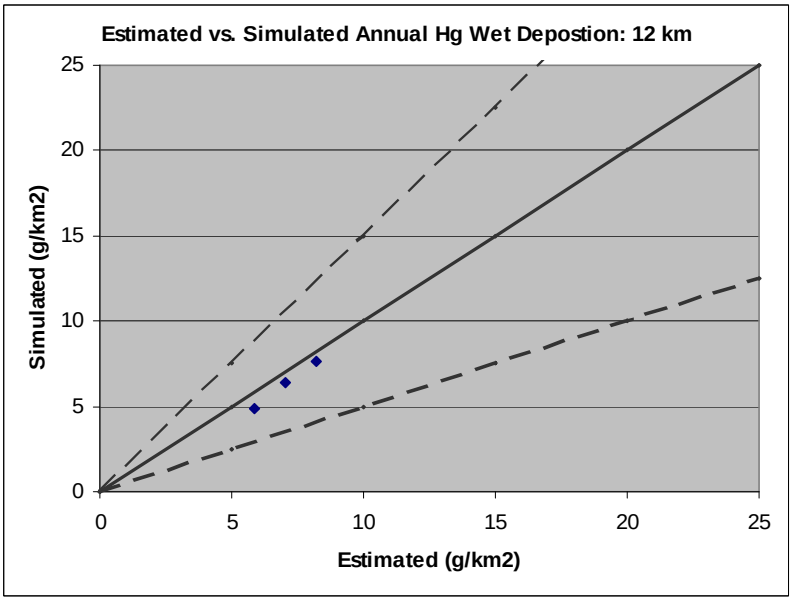


Figure 5-7b. Scatter Diagram Comparing Simulated and Estimated Annual Mercury Wet Deposition Totals for the Virginia MDN Sites for the 2001 Simulation Period.



Overall model performance for mercury wet deposition appears reasonable, especially when considering the annual deposition. Differences between the simulated and observed values are attributable to a number of different factors including the numerical approximations and physical parameterizations used in the CMAQ model, imperfect representation of the meteorological conditions (in particular the timing and amount of rainfall), uncertainties in the emission inventory and boundary condition estimates, and even uncertainties in the measurements. Nevertheless, the simulated annual deposition amounts on average are within 10 percent of the observed values for both the 36- and 12-km domains.

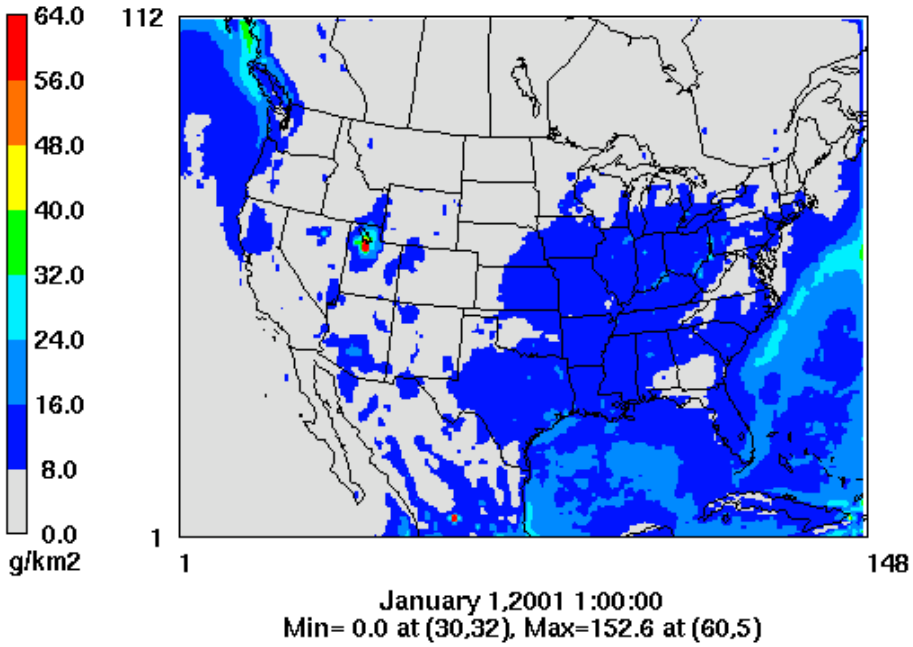
Earlier in this section, it was noted that the simulated deposition amounts are sensitive to rainfall and other meteorological factors. In the remainder of this section, the contributions of the emissions and the boundary conditions to the simulated deposition amounts are examined.

5.1.3. Base Year Mercury Deposition Results

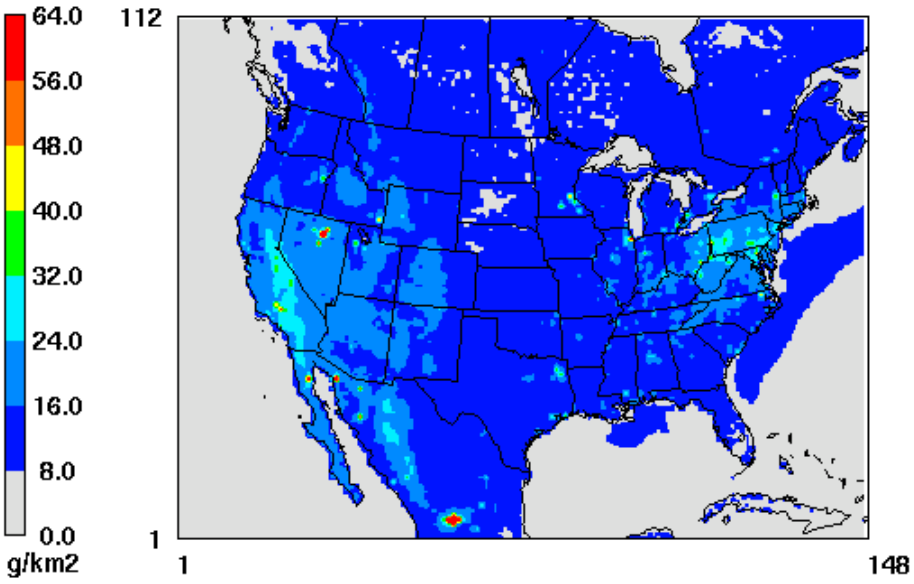
Figures 5-8 and 5-9 display the CMAQ-derived, base-year, annual mercury deposition results for the 36-km (outer) domain. Figure 5-8 displays wet, dry and annual total mercury deposition. Wet deposition (Figure 5-8a) is generally greater in the eastern U.S. compared to the western U.S. and this is consistent with higher annual precipitation amounts in this part of the domain. Dry deposition (Figure 5-8b) is distributed throughout the domain. The dry deposition pattern reflects the distribution of emissions and is characterized by relatively high values over the mid-Atlantic states, in northern Nevada, and over the central valley of California. Alternatively, Figure 5-9 displays total mercury deposition for the elemental (HG0), reactive gaseous (HG2), and particle-bound (HGP) phases. Most of the deposition is in the form of reactive gaseous mercury, with some contribution from particles.

Figure 5-8. CMAQ Simulated Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 36-km Modeling Domain: Wet, Dry and Total Deposition.

(a) Wet Mercury Deposition

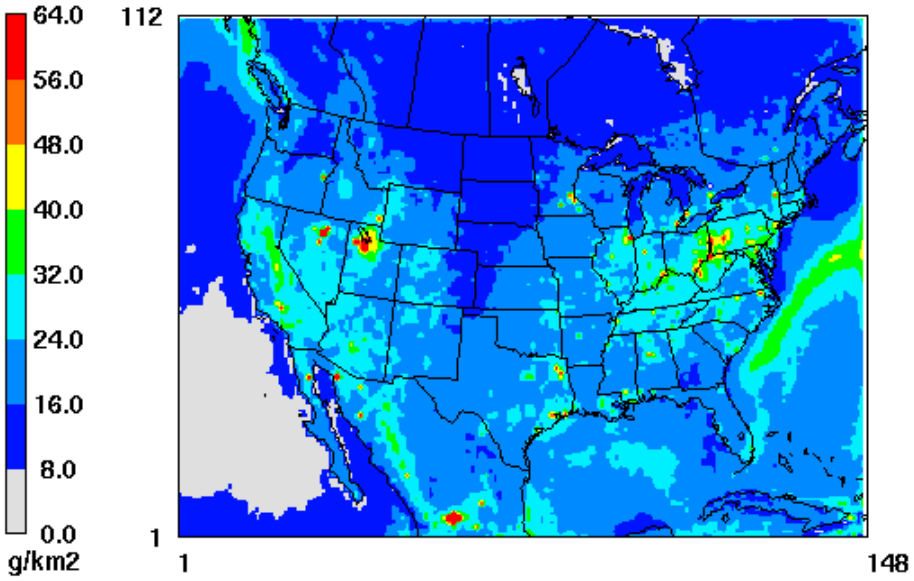


(b) Dry Mercury Deposition



January 1,2001 1:00:00
Min= 1.3 at (24,93), Max=587.6 at (60,5)

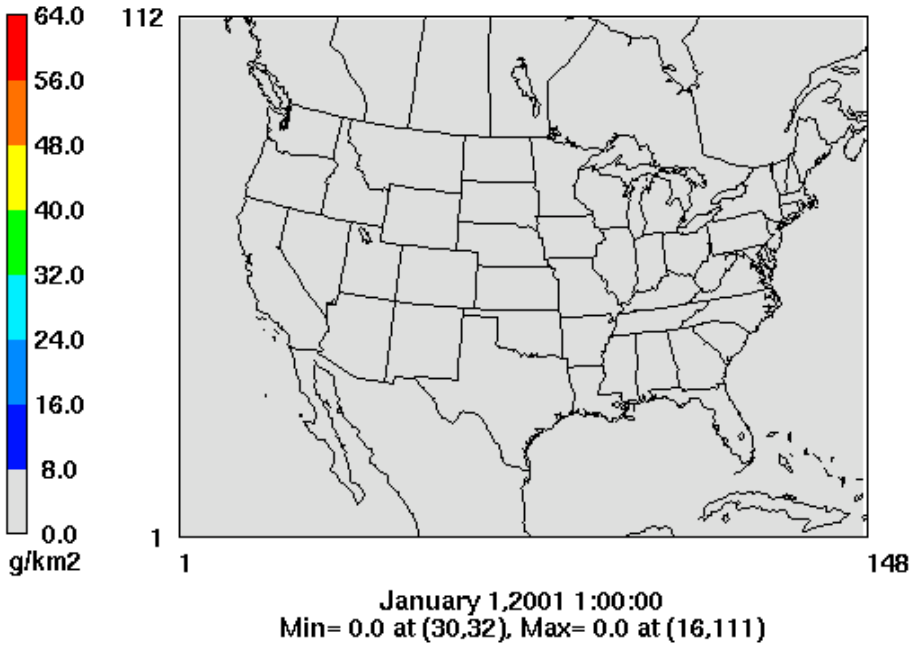
(c) Total Mercury Deposition



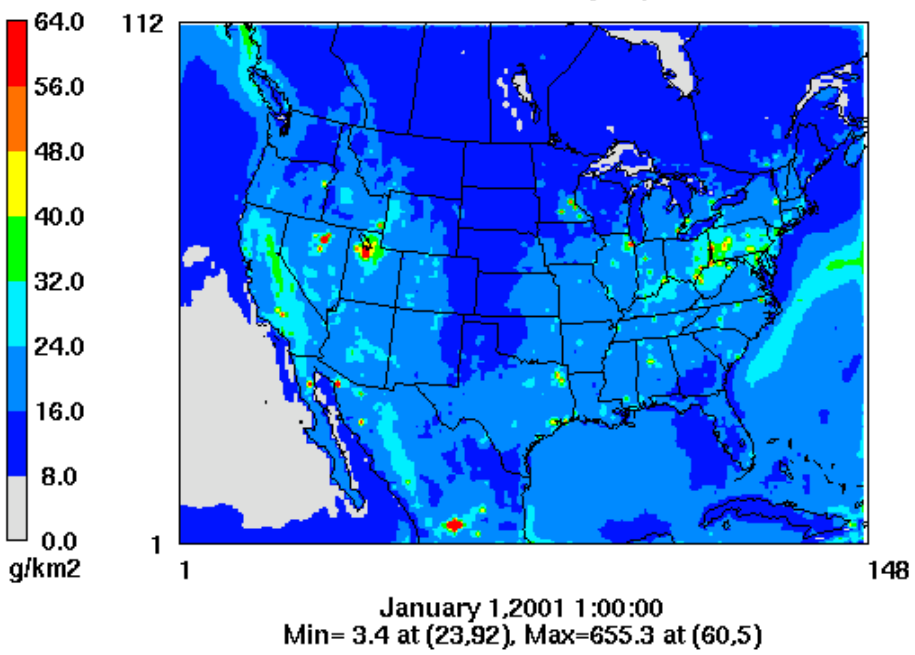
January 1,2001 1:00:00
Min= 4.0 at (23,92), Max=740.2 at (60,5)

Figure 5-9. CMAQ Simulated Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 36-km Modeling Domain: Elemental, Reactive Gaseous, and Particulate Phases.

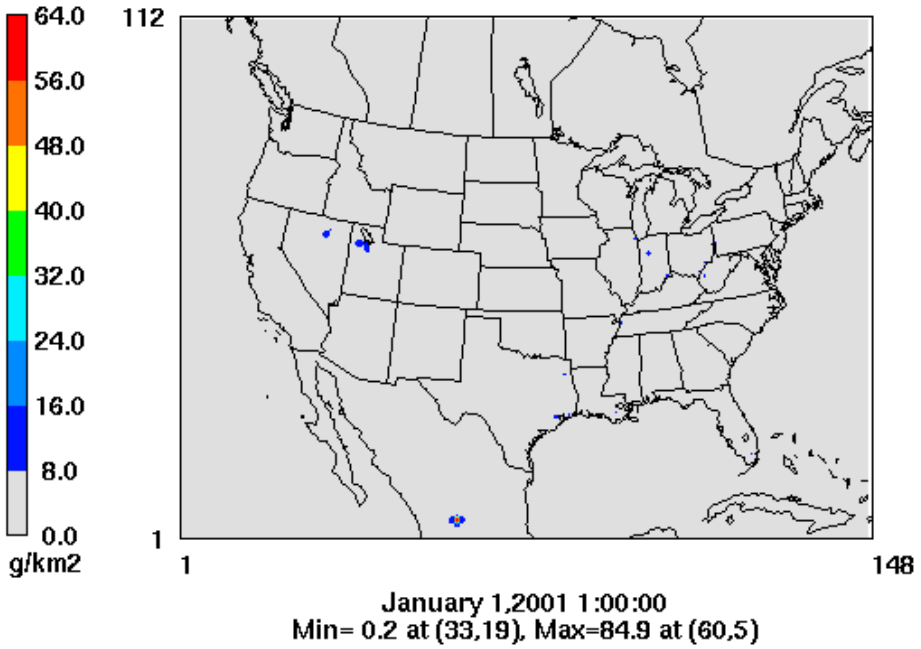
(a) Elemental Mercury Deposition (Wet Only)



(b) Reactive Gaseous Mercury Deposition



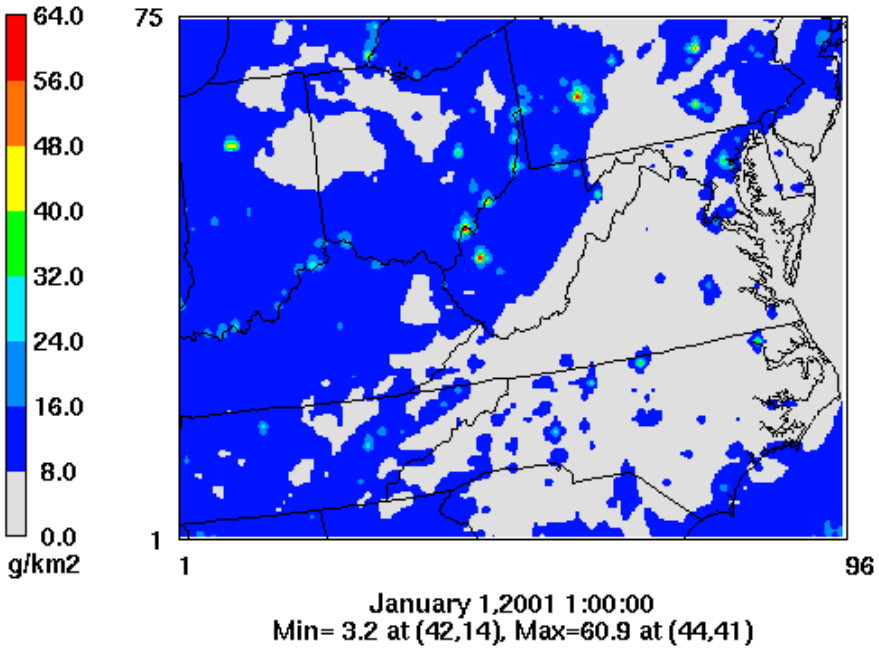
(c) Particulate Mercury Deposition



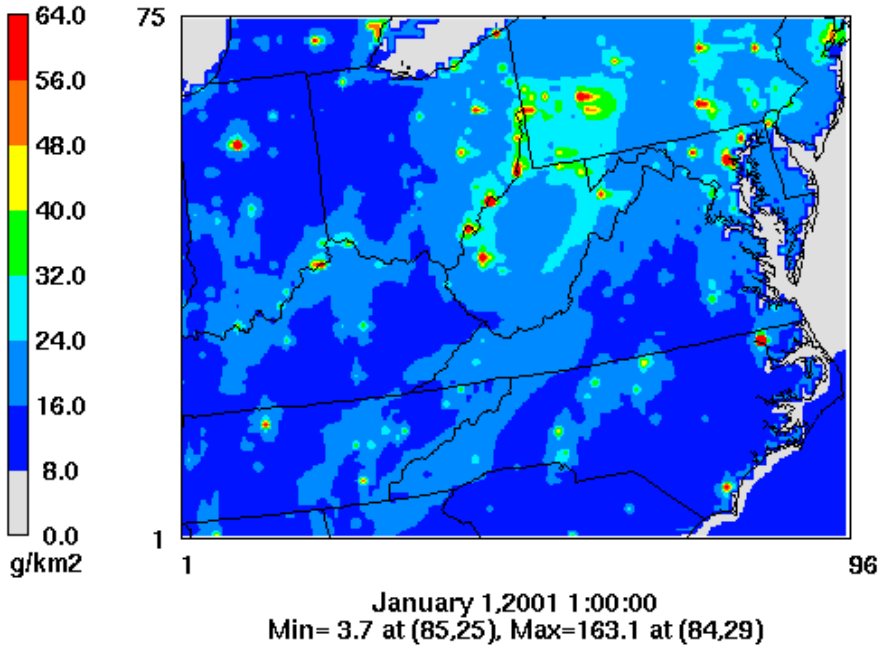
Figures 5-10 and 5-11 display the CMAQ-derived, base-year, annual mercury deposition results for the 12-km domain. Figure 5-10 displays wet, dry and annual total mercury deposition. Most of the wet deposition (Figure 5-10a) occurs to the west and south of Virginia. Figure 5-10b shows that dry deposition is greater than wet deposition over Virginia. The highest dry deposition amounts within the subdomain are over Pennsylvania, West Virginia, and southeastern Ohio. Total deposition (Figure 5-10c) reflects a similar spatial pattern. The locations of the relative maximum values of mercury deposition within Virginia can be correlated with several of the emissions sources located within the Commonwealth. Alternatively, Figure 5-11 displays total mercury deposition for the elemental (HG0), reactive gaseous (HG2), and particle-bound (HGP) phases. Most of the deposition is in the form of reactive gaseous mercury, with some (mostly local) contribution from particles. This local contribution is further examined using the AERMOD model in Section 6.

Figure 5-10. CMAQ Simulated Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 12-km Modeling Domain: Wet, Dry and Total Deposition.

(a) Wet Mercury Deposition



(b) Dry Mercury Deposition



(c) Total Mercury Deposition

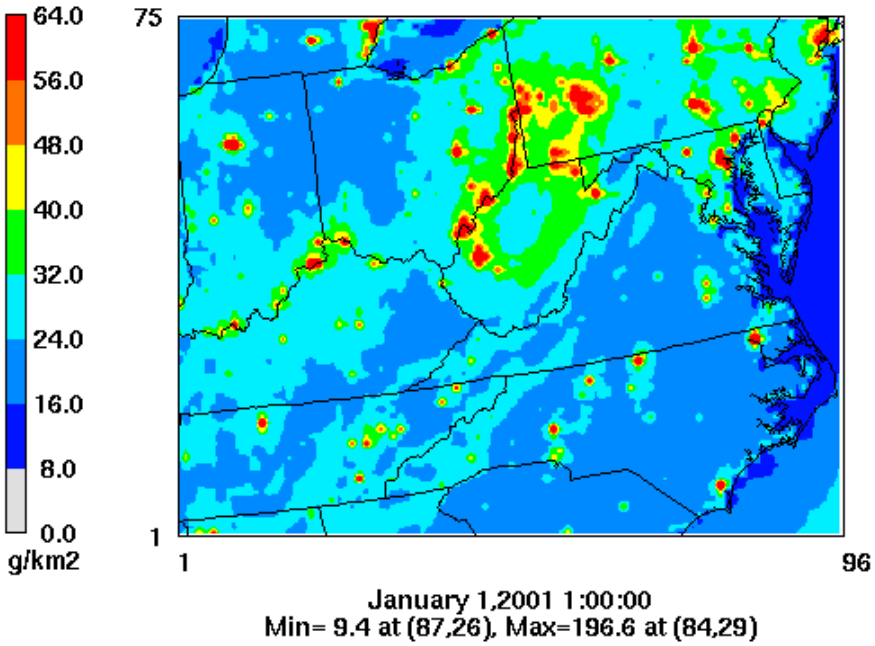
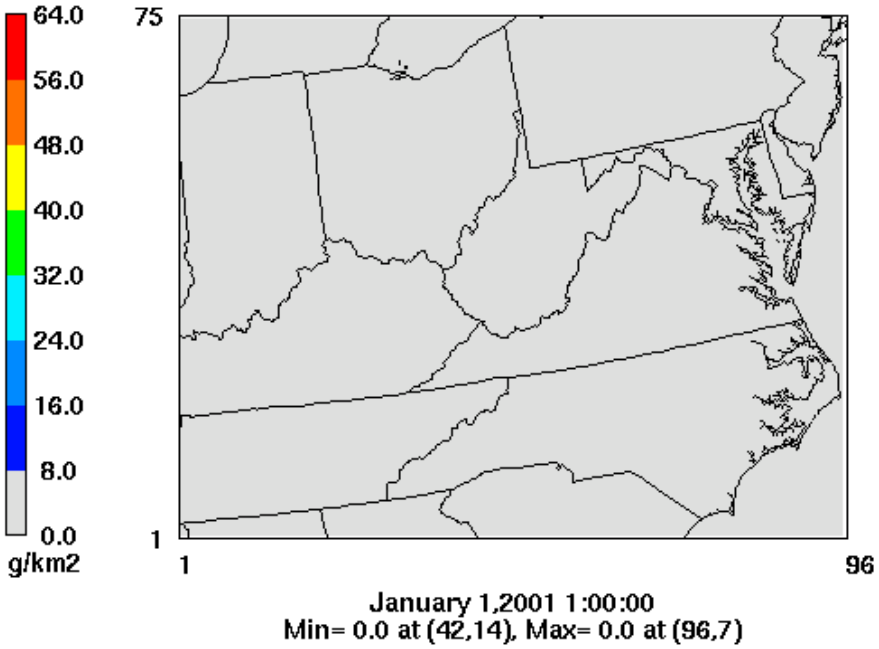
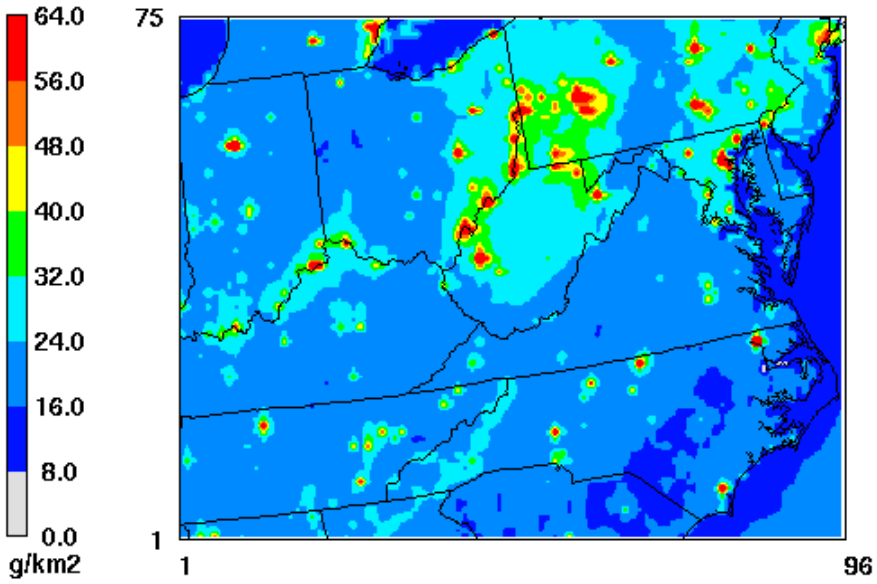


Figure 5-11. CMAQ Simulated Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 12-km Modeling Domain: Elemental, Reactive Gaseous, and Particulate Phases.

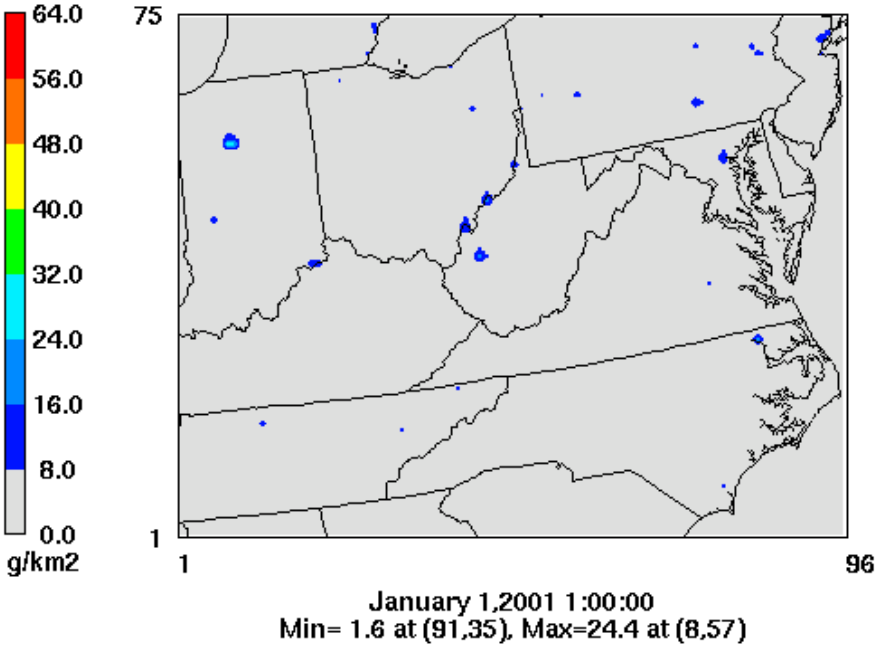
(a) Elemental Mercury Deposition (Wet Only)



(b) Reactive Gaseous Mercury Deposition



(c) Particulate Mercury Deposition



5.1.4. Baseline Contribution Analysis for Virginia

CMAQ/PPTM simulations were conducted using the baseline 2001/2002 emissions inventory to assess the contributions of selected source sectors to simulated mercury deposition.

The first scenario examined the contributions from mercury air emissions sources in 1) Virginia, 2) the remainder of the 12-km modeling domain, 3) all other U.S. states (outside of the 12-km domain), 4) Canada and Mexico, 5) global emissions sources, and 6) natural emissions. Tags were assigned to each of the six regions/categories listed above. An initial/boundary condition tag was used to represent the global impact on deposition. This scenario was run for both the 36- and 12-km domains and the specific tags were defined as follows:

- All anthropogenic emissions sources in Virginia
- All anthropogenic emissions sources in the remainder of the 12-km grid
- All anthropogenic emissions sources in the U.S., excluding those in the 12-km grid
- All anthropogenic emissions sources in Canada & Mexico
- IC/BCs (initial and boundary conditions)
- Natural emissions.

For the 12-km simulation, the tags incorporated information from the 36-km PPTM simulation. This was done to track the contributions from sources outside of the 12-km domain as well as the possible recirculation of emissions from sources within the 12-km domain. Information from the tags for the 36-km simulation was incorporated into the tags for the 12-km simulation as additional species in the IC/BC tags for the subdomain.

The second scenario quantified the contributions from Electric Generating Unit (EGU) and non-EGU facilities in Virginia and the surrounding states. The tags included 1) all of Virginia's EGU sources, 2) all of the non-EGU sources in the state, 3) all EGU sources in the surrounding states (remainder of the 12-km grid), and 4) all non-EGU sources in the surrounding states. The results allow us to quantify and compare the contributions from the EGU and non-EGU source sectors to mercury deposition for any location (grid cell or group of grid cells) within the state or the modeling domain. The specific tags for this scenario were defined as follows:

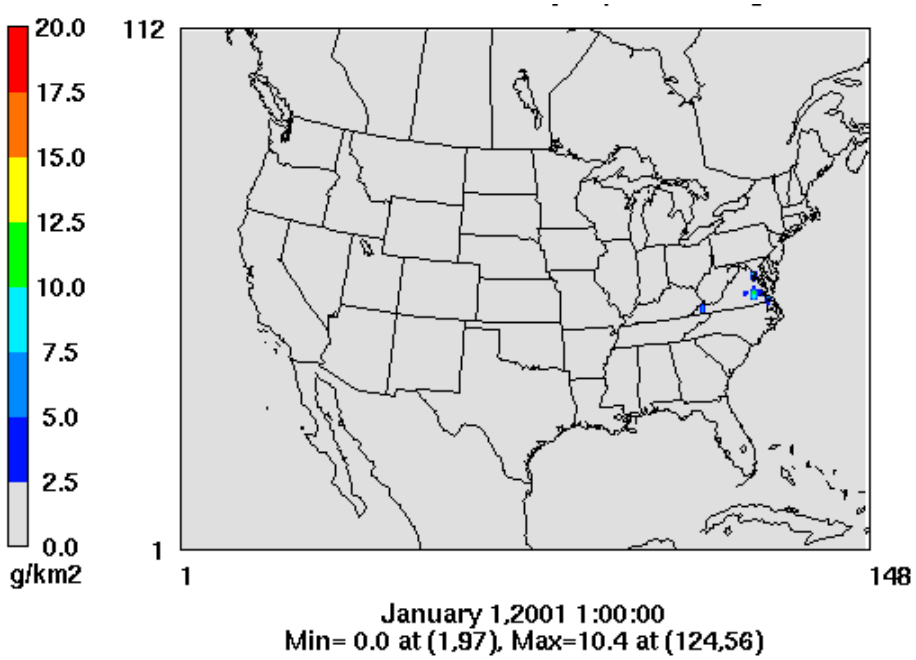
- All EGU sources in Virginia
- All non-EGU sources in Virginia
- All EGU sources in the remainder of the 12-km grid
- All non-EGU sources in the remainder of the 12-km grid.

Selected plots of the PPTM results are shown in Figures 5-12 through 5-14. For the 36-km domain, the contribution to annual total (wet plus dry) mercury deposition from each of the six tags is displayed in Figure 5-12. Note that the scales may differ among the plots.

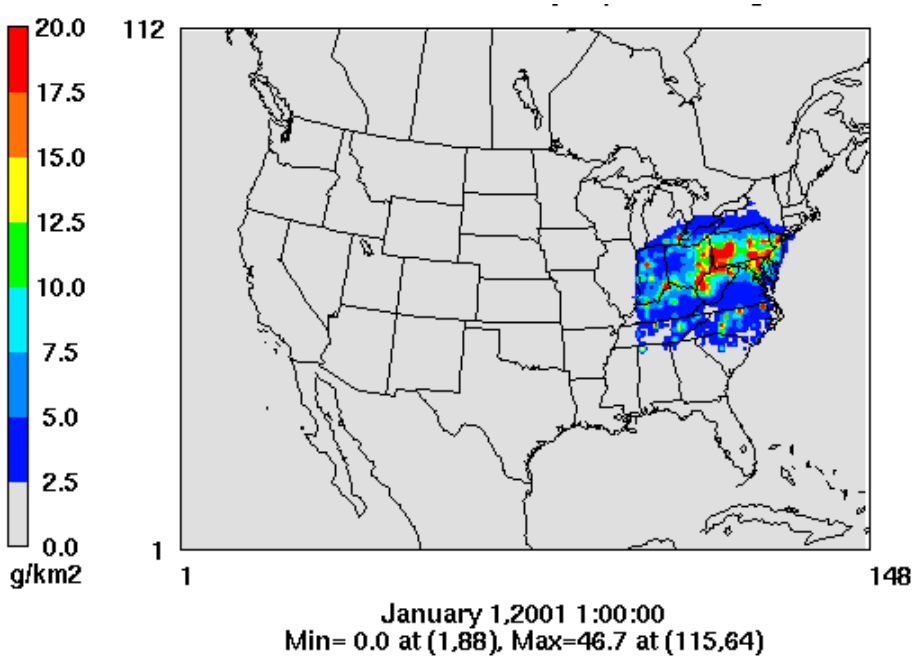
As noted earlier, the spatial plots of mercury deposition use a variety of different scales in order to display the spatial patterns of depositions. Note that the color scheme is not tied to specific ranges of deposition, but is used instead to highlight the patterns of deposition corresponding to each individual plot. The spatial plots are intended to display the spatial patterns. For detailed comparisons of the deposition amounts the reader should refer to the pie charts, bar charts and tables that are also presented in this section.

Figure 5-12. CMAQ/PPTM Simulated Contribution to Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 36-km Modeling Domain.

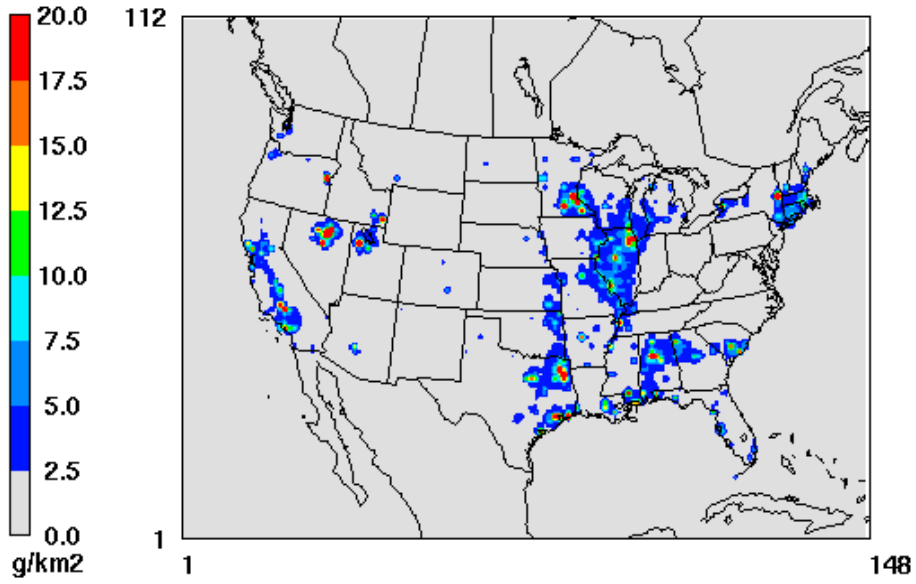
(a) Contribution from Sources in Virginia



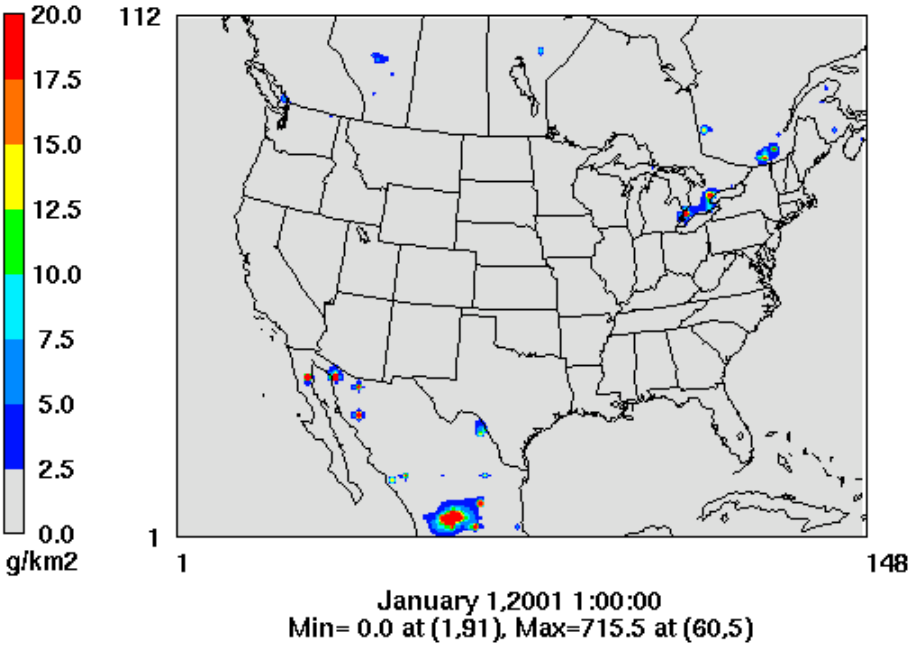
(b) Contribution from Sources in the Remainder of the 12-km Domain



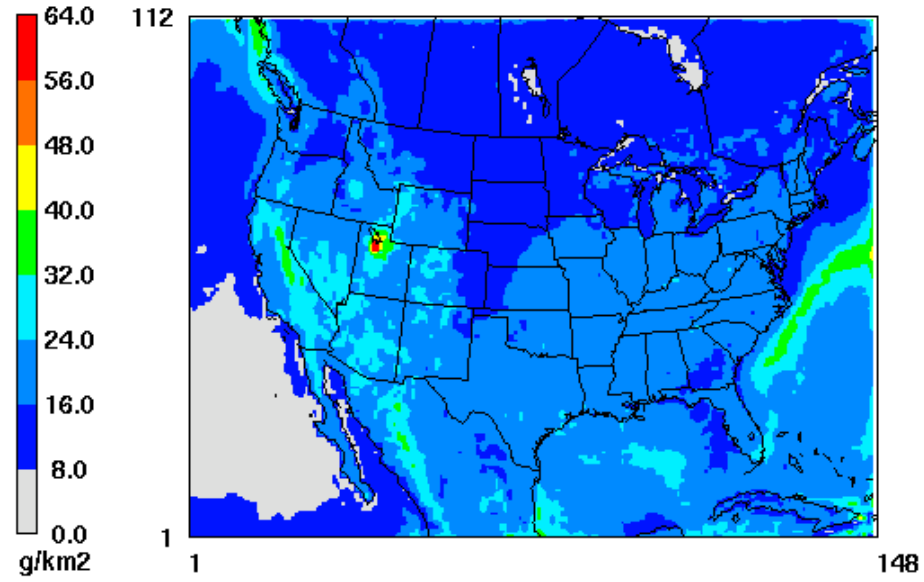
(c) Contribution from Sources in the Remainder of the U.S.



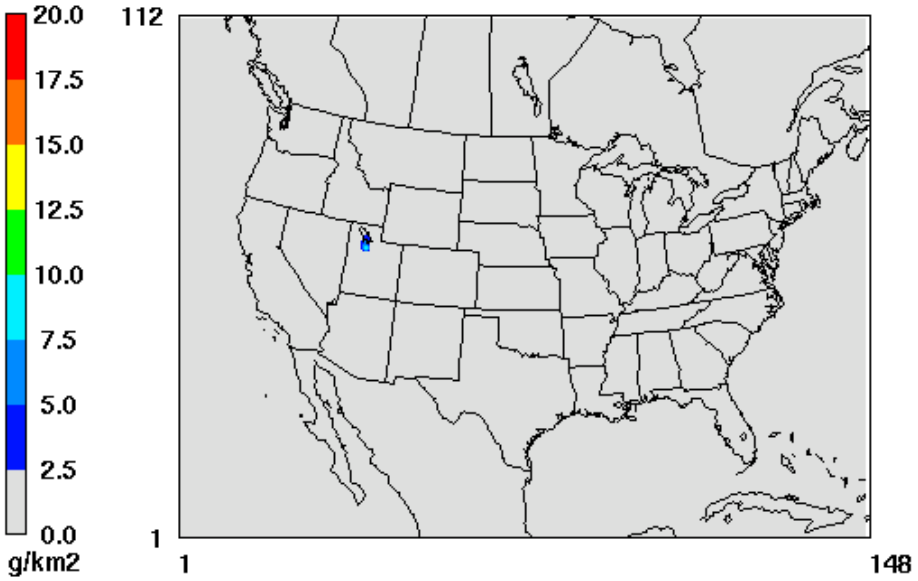
(d) Contribution from Sources in Canada and Mexico



(e) Contribution from 36-km Domain IC/BCs



(f) Contribution from Natural Emissions Sources

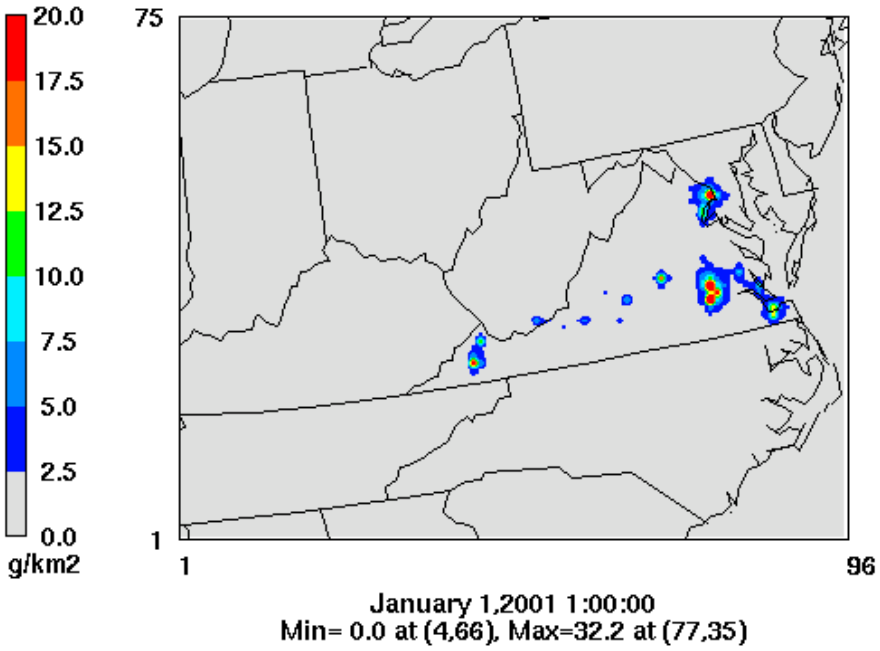


Figures 5-12a through d indicate that anthropogenic mercury emissions sources in the U.S., Canada and Mexico have primarily local to regional impacts during this annual simulation period. Note that these emissions may also contribute to the global background. Figure 5-12e suggests that global background concentrations (represented here by the boundary conditions) contribute significantly to mercury deposition throughout the domain, including in Virginia. Figure 5-12f suggests that contributions from natural emissions are small.

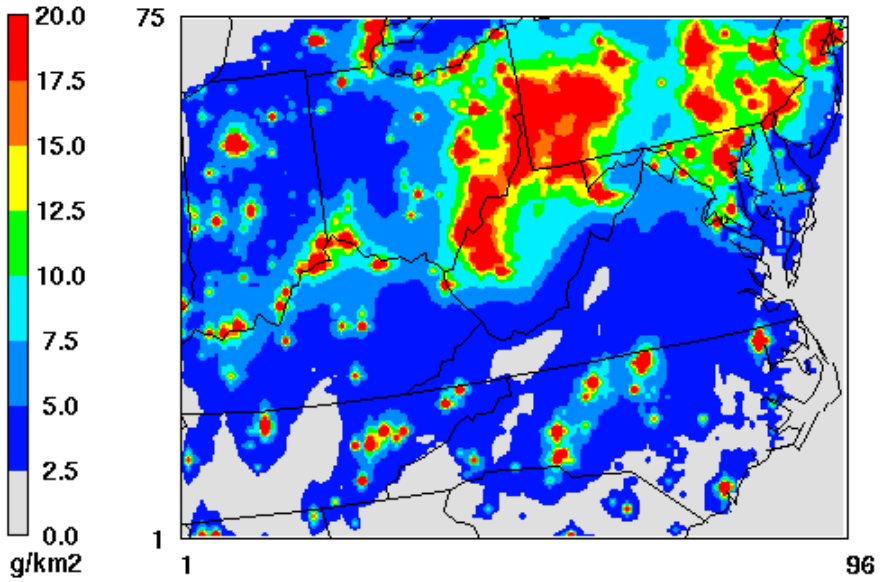
Figure 5-13 focuses on the 12-km domain and displays the contribution to annual total (wet and dry) mercury deposition from these same six tags, as simulated using the higher resolution grid. Note that the scale varies among the plots for each tag.

Figure 5-13. CMAQ/PPTM Simulated Contribution to Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 12-km Modeling Domain.

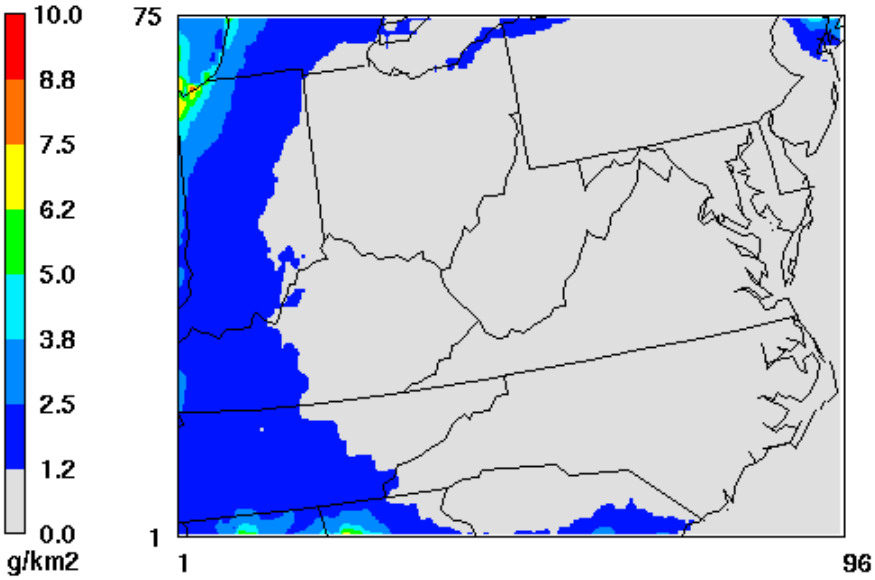
(a) Contribution from Sources in Virginia



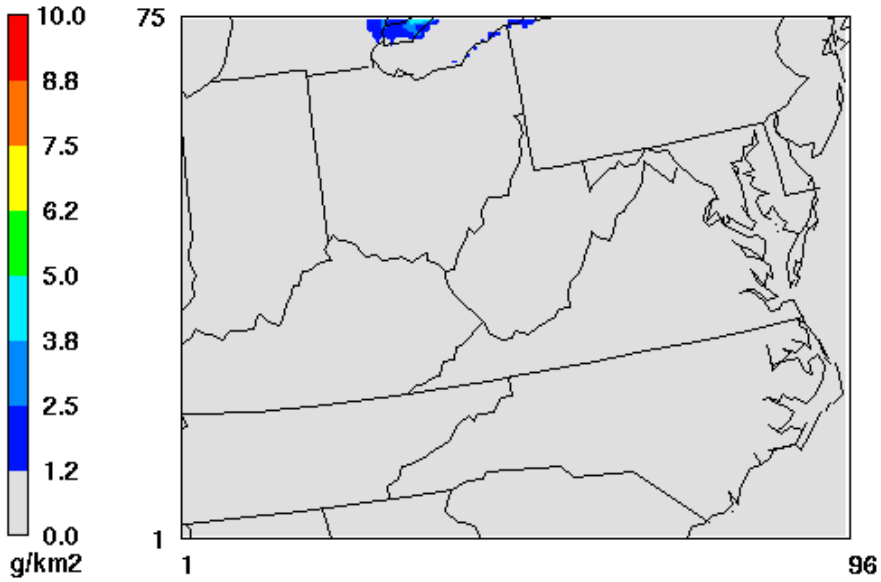
(b) Contribution from Sources in the Remainder of the 12-km Domain



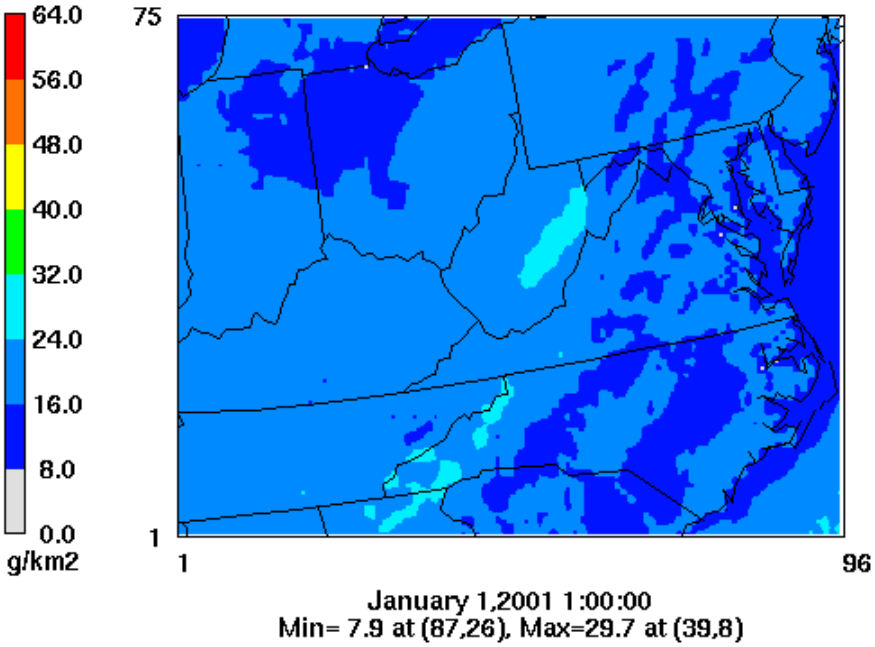
(c) Contribution from Sources in the Remainder of the U.S.



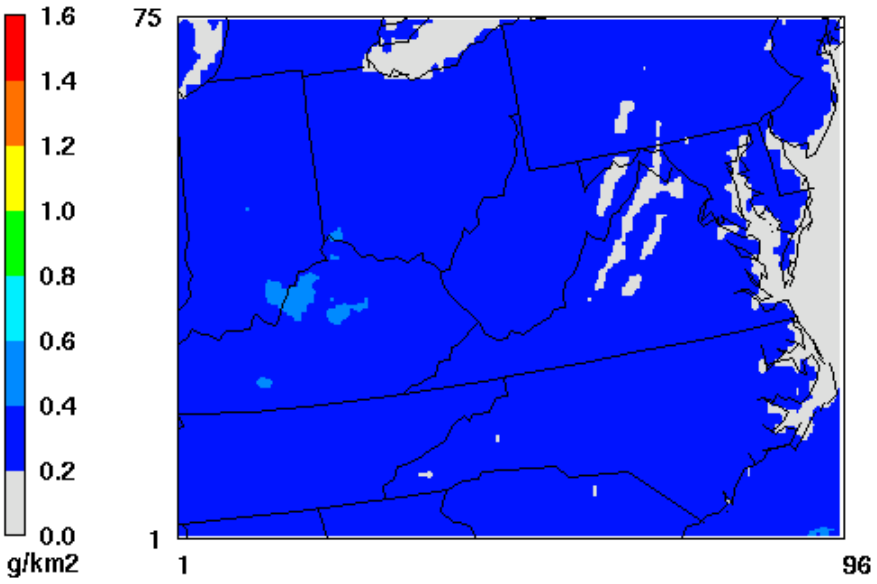
(d) Contribution from Sources in Canada and Mexico



(e) Contribution from 36-km Domain IC/BCs



(f) Contribution from Natural Emissions Sources

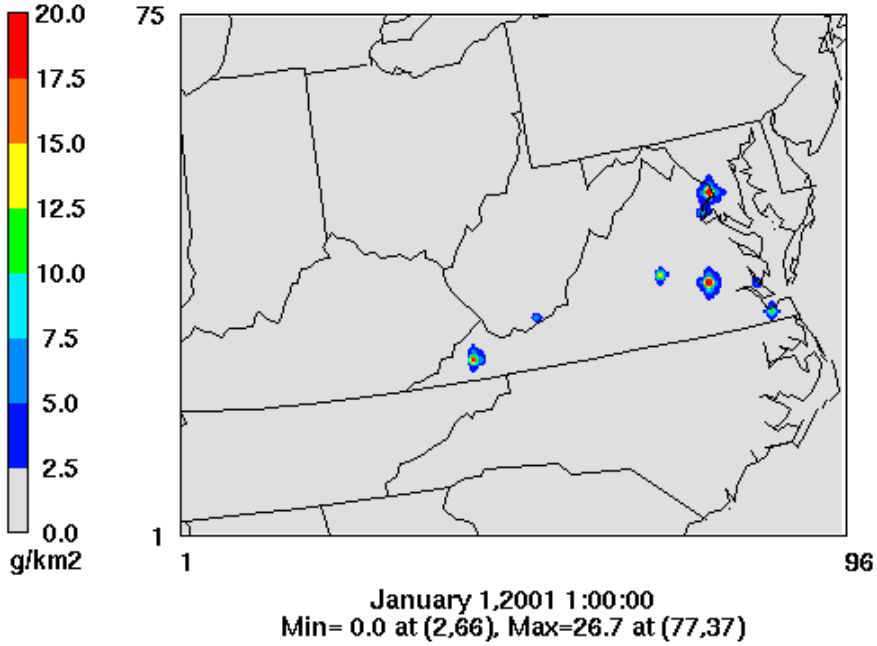


The PPTM results indicate that global background (Figure 5-13e) and emissions from sources in the surrounding states (Figure 5-13b) contribute to mercury deposition in Virginia. The transported mercury is distributed relatively evenly throughout the Commonwealth. Emissions from sources in Virginia (Figure 5-13a) also contribute to mercury deposition and the greatest impacts from the in-state sources are simulated near the source locations.

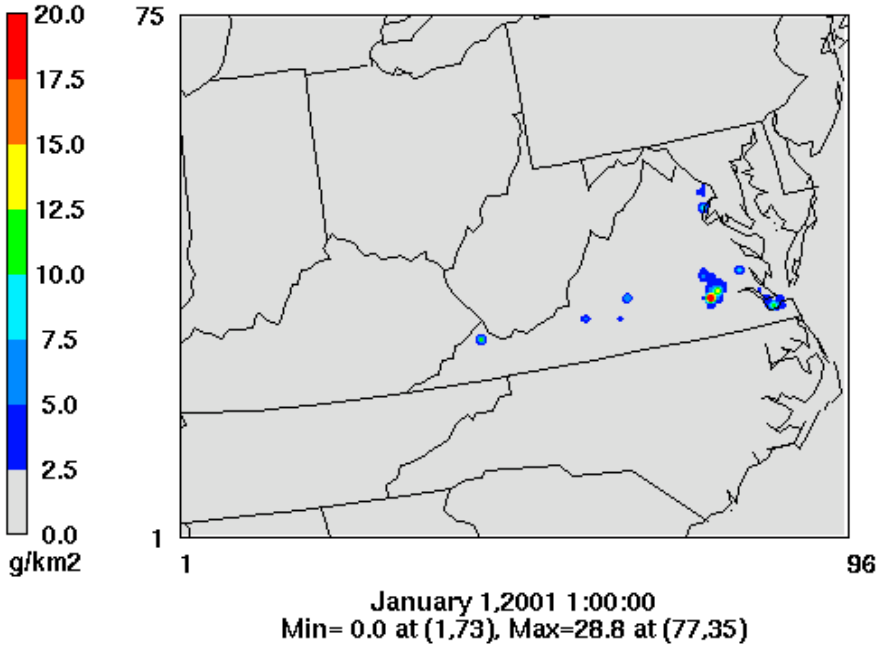
Figure 5-14 further parses the contributions from sources in Virginia and the remainder of the 12-km domain into EGU and non-EGU contributions.

Figure 5-14. CMAQ/PPTM Simulated Contribution to Annual Mercury Deposition (g km^{-2}) for the 2001 Simulation Period for the 12-km Modeling Domain.

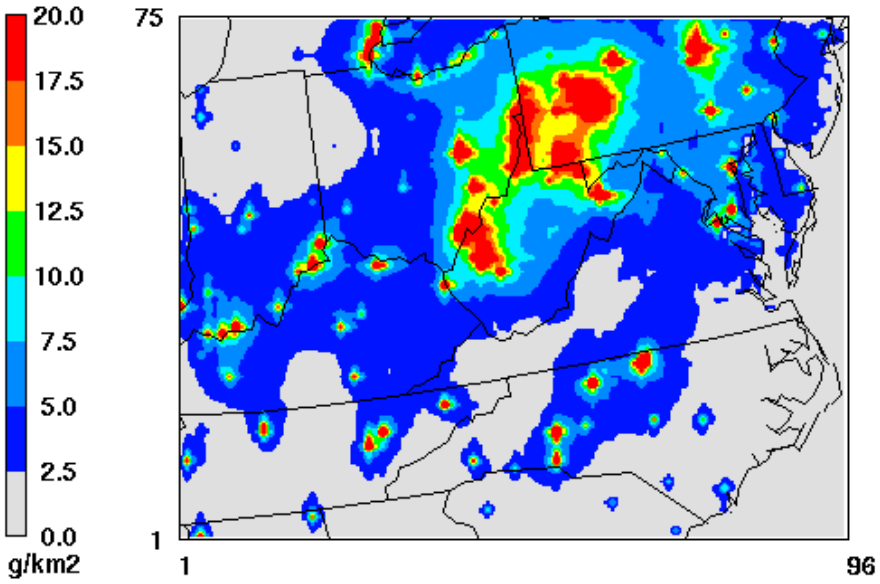
(a) Contribution from EGU Sources in Virginia



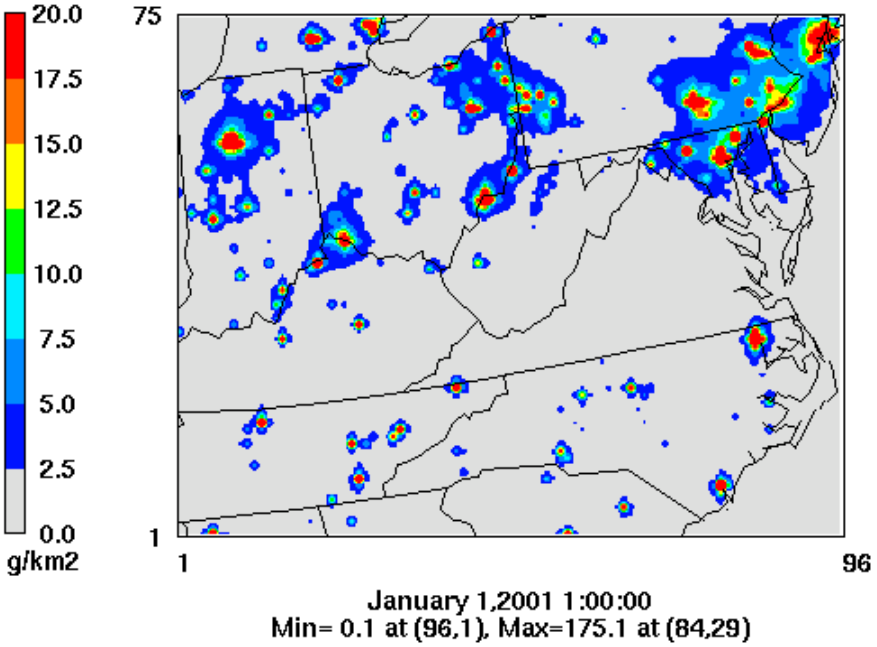
(b) Contribution from Non-EGU Sources in Virginia



(c) Contribution from EGU Sources in the Remainder of the 12-km Domain



(d) Contribution from Non-EGU Sources in the Remainder of the 12-km Domain



Within Virginia, neither source category is dominant. For a given area, the dominant in-state source of simulated mercury deposition is determined based on location relative to EGU and non-EGU sources. There are a greater number of emissions sources within the surrounding states. The deposition patterns for these sources indicate that, overall, EGU sources tend to impact a larger area compared to most non-EGU sources. This is likely due, in part, to greater stack heights and exit velocities for the EGU sources. The EGU sources in the surrounding states contribute more to mercury deposition in Virginia than the non-EGU sources in the surrounding states.

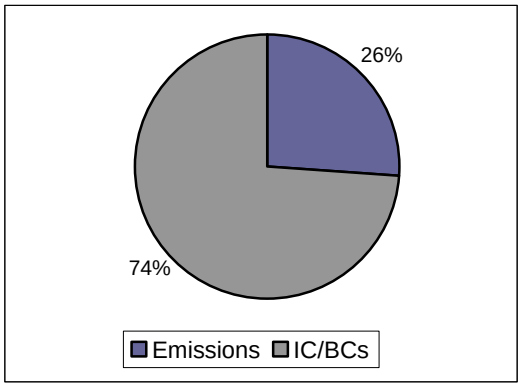
In addition to the spatial contribution patterns, PPTM also provides information on the contributions of the tagged source regions and source categories to simulated mercury deposition in any sub-area of the domain (i.e., any area comprised of one or more grid cells). In Figure 5-15 mercury deposition at the locations of the MDN monitoring sites in Virginia is broken down in various ways. In each case, the area represented is one 12 x 12 km grid cell.

In Figure 5-15, the total deposition for the grid cell is given at the top of the page. The pie chart in the upper left-hand corner of the display summarizes the percent contribution to total deposition from emissions versus IC/BCs. The bar chart in the upper right-hand corner attributes total (overall) and emissions-based deposition to wet and dry deposition. Note that the total or overall deposition is the sum of the deposition from both emissions and IC/BCs. In the next two pie charts, the contributions from emissions sources are broken out in detail. The middle pie chart includes all tags and the lower pie chart includes only the non-background/anthropogenic source tags. Without the IC/BC contribution, the lower pie chart allows a more detailed comparison of the local and regional source contributions.

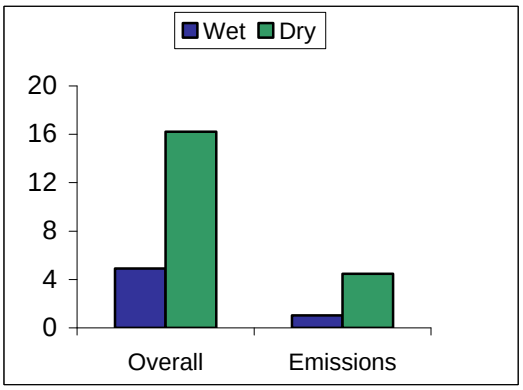
Figure 5-15a. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Culpeper MDN Monitoring Site (VA08).

Simulated Annual Hg Deposition for 2001 for Culpeper, VA (VA08): 21.11 g/km²

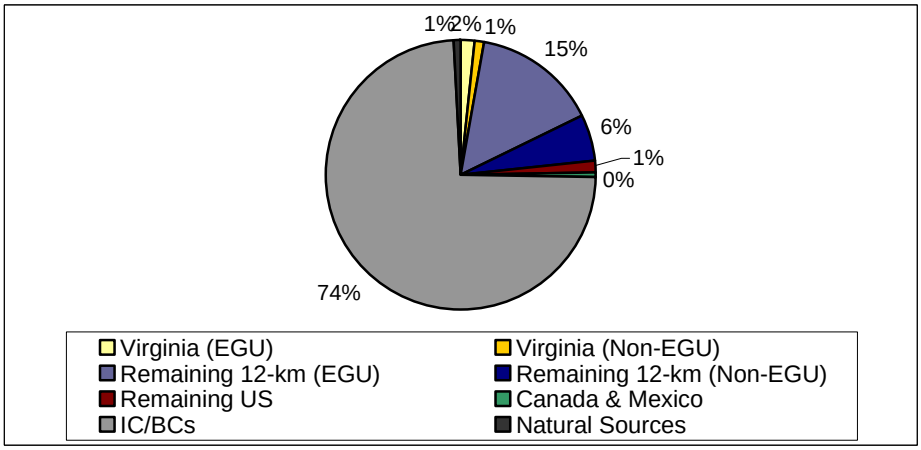
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

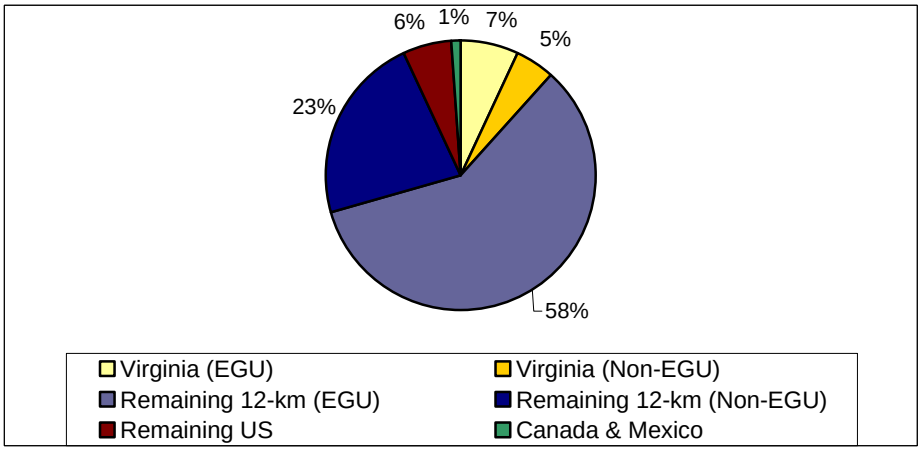
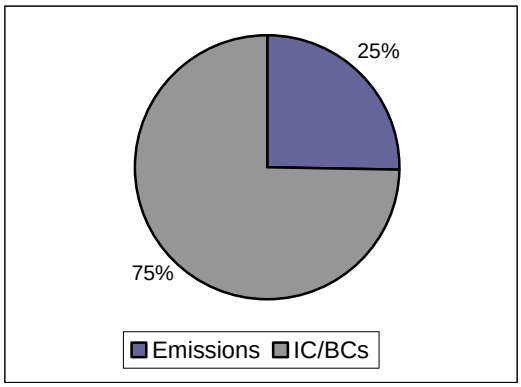


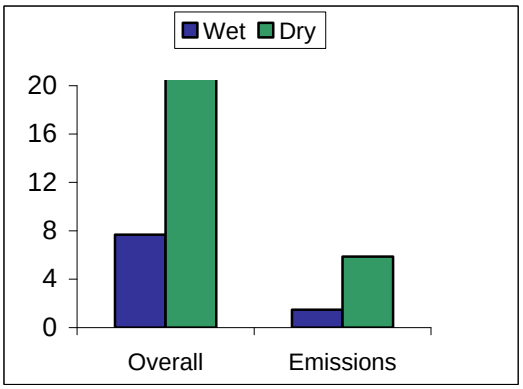
Figure 5-15b. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Shenandoah National Park MDN Monitoring Site (VA28).

Simulated Annual Hg Deposition for 2001 for Shenandoah, VA (VA28): 29.18 g/km²

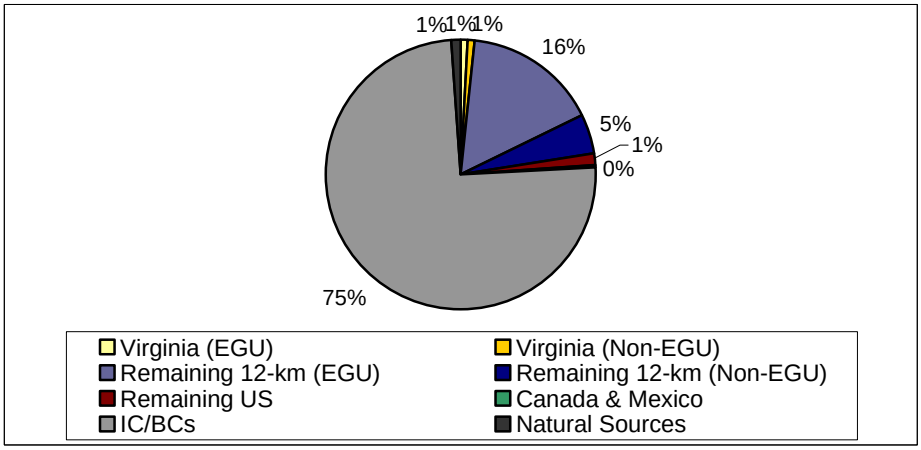
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

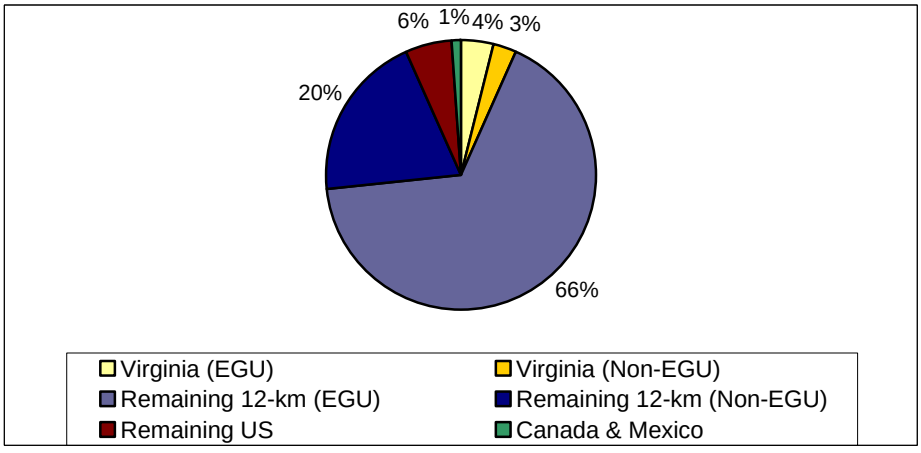
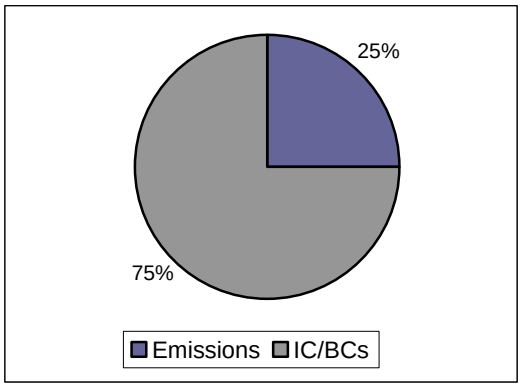


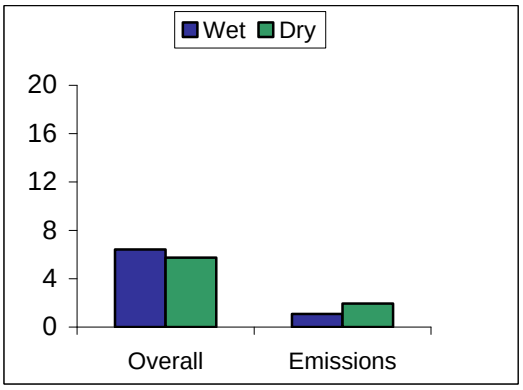
Figure 5-15c. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Harcum MDN Monitoring Site (VA98).

Simulated Annual Hg Deposition for 2001 for Harcum, VA (VA98): 12.16 g/km²

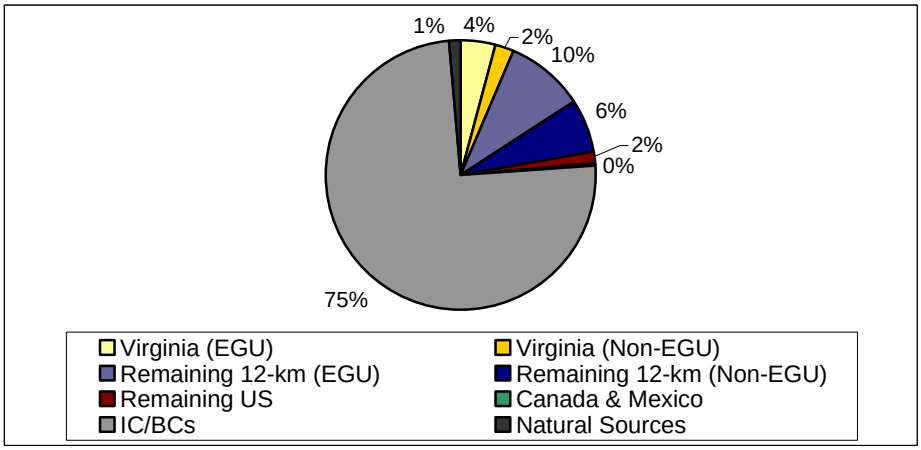
Emissions vs. IC/BC Contributions



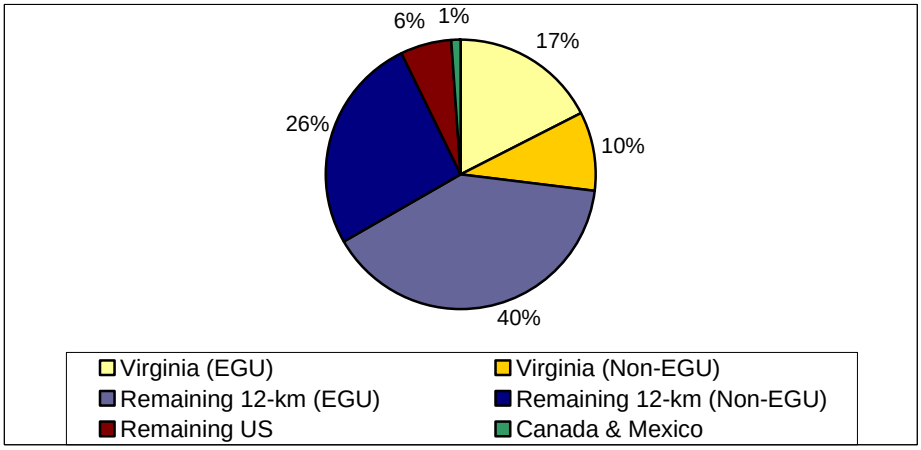
Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



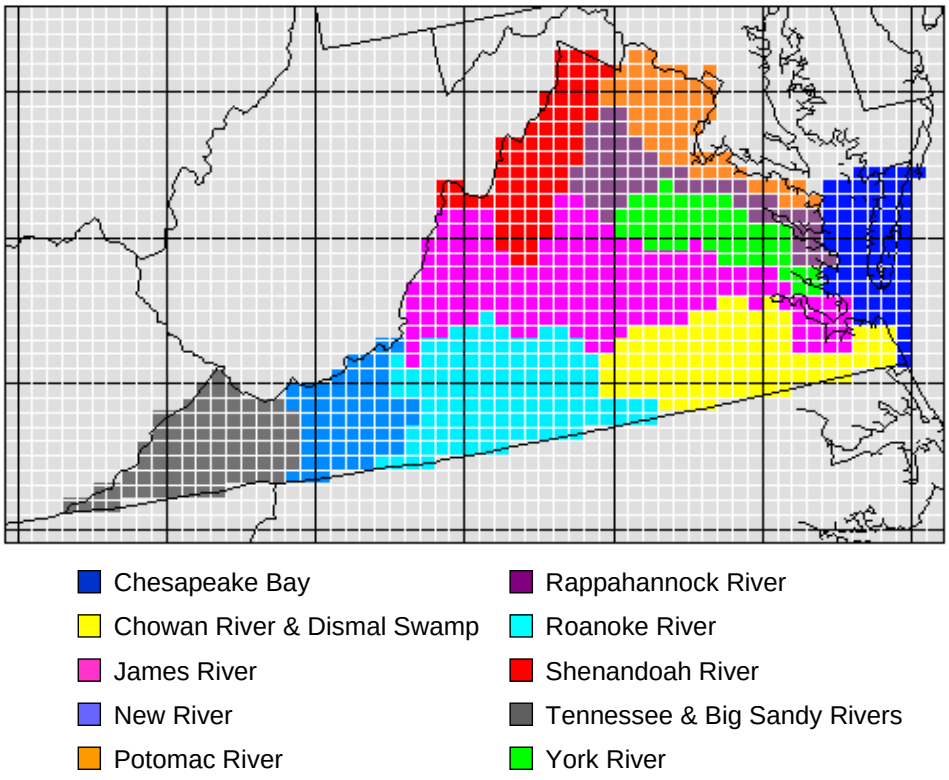
Contribution by Tag w/o Background & Natural Sources



For all three MDN sites, the IC/BCs (global background) contribute about 75 percent of the simulated mercury deposition. For the Culpeper and Shenandoah sites, dry deposition is greater than wet deposition by a factor of two or more, for both overall deposition and emissions-based deposition. For the Harcum site, wet deposition is greater than dry when overall deposition is considered. This is likely because a portion of the grid cell is over water which limits dry deposition. For Culpeper, the non-background/anthropogenic portion of the contribution is broken down as follows: Virginia EGU sources (7 percent), Virginia non-EGU sources (5 percent), other 12-km grid EGU sources (58 percent), other 12-km non-EGU sources (23 percent), remaining U.S. sources (6 percent), and Canada and Mexico (1 percent). For Shenandoah, the non-background/anthropogenic contribution is broken down as follows: Virginia EGU sources (4 percent), Virginia non-EGU sources (3 percent), other 12-km grid EGU sources (66 percent), other 12-km non-EGU sources (20 percent), remaining U.S. sources (6 percent), and Canada and Mexico (1 percent). For Harcum, the contribution from in-state sources is higher and is broken down as: Virginia EGU sources (17 percent), Virginia non-EGU sources (10 percent), other 12-km grid EGU sources (40 percent), other 12-km non-EGU sources (26 percent), remaining U.S. sources (6 percent), and Canada and Mexico (1 percent).

The next series of plots displays mercury deposition in this same manner for each of the major river basins in Virginia and the entire state. Figure 5-16 shows the locations of each of the major river basins (the reader is also referred to Figure 1-1 for more detail).

Figure 5-16. Map of the Major River Basins in Virginia and Corresponding CMAQ 12-km Grid Cells.

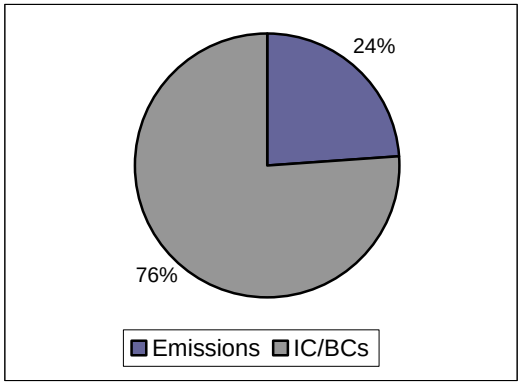


In Figure 5-17, mercury deposition and the sources contributing to deposition for each river basin and the entire state are presented. The results for the river basis are ordered alphabetically. In each case, the area represented consists of multiple grid cells. Deposition is given in terms of the deposition per square kilometer. This facilitates a comparison of the deposition results even though each area is a different size.

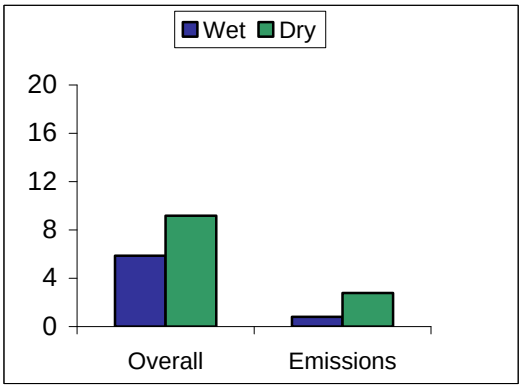
Figure 5-17a. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Chesapeake Bay, Atlantic Ocean, and Small Coastal Waters.

Simulated Annual Hg Deposition for 2001 for Chesapeake Bay: 15.04 g/km²

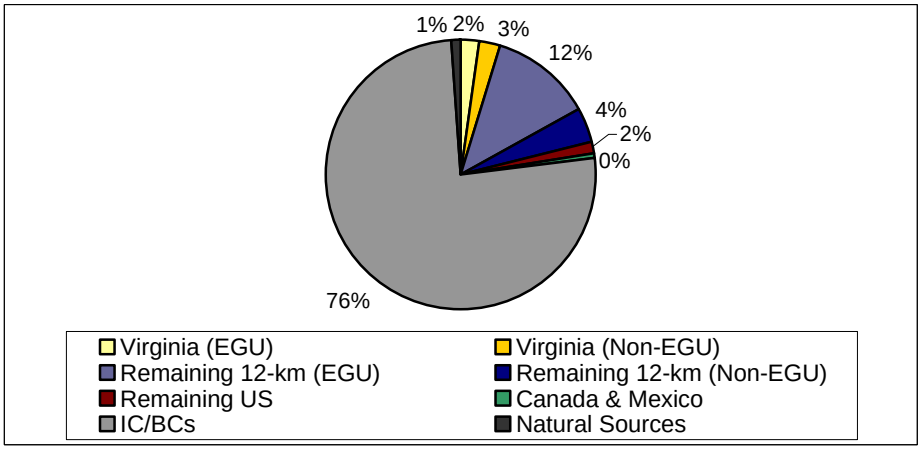
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

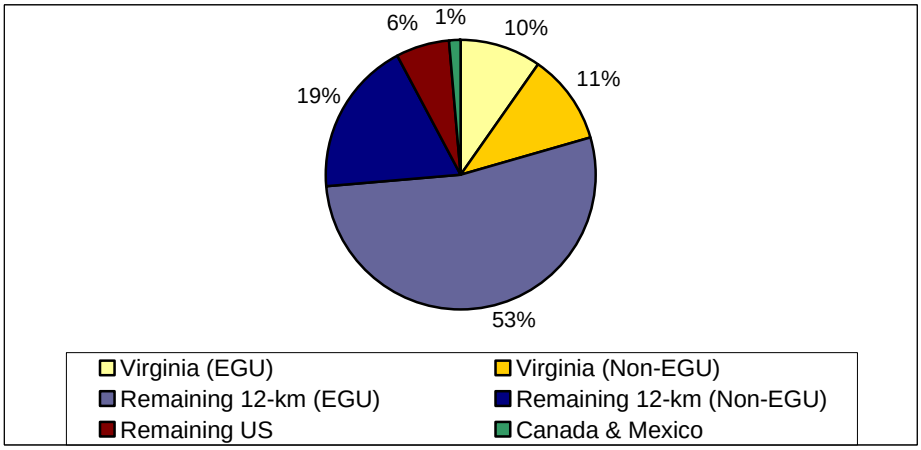
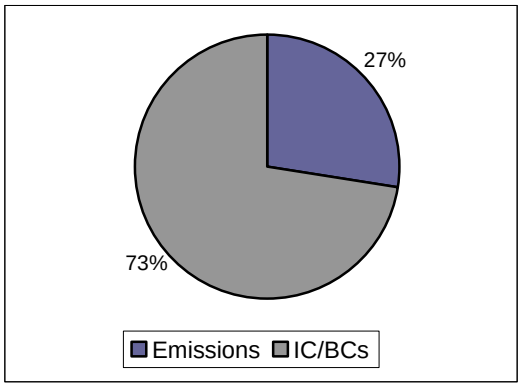


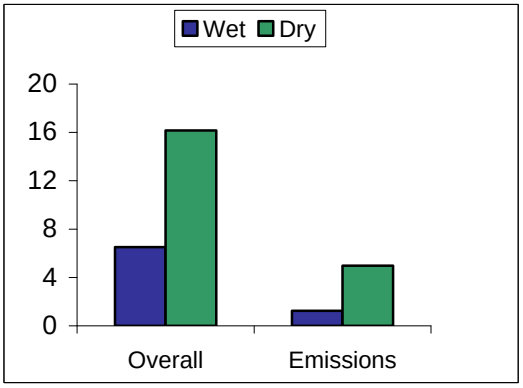
Figure 5-17b. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Chowan River Basin and Great Dismal Swamp.

Simulated Annual Hg Deposition for 2001 for the Chowan River Basin & Dismal Swamp: 22.68 g/km²

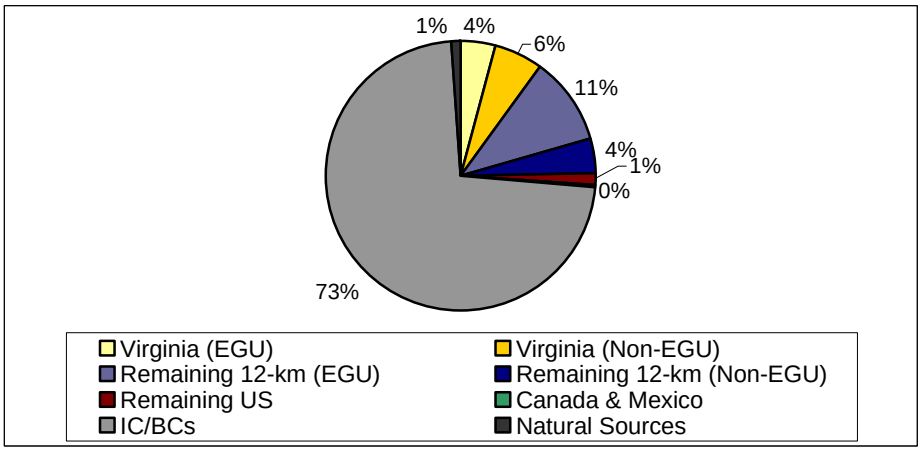
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

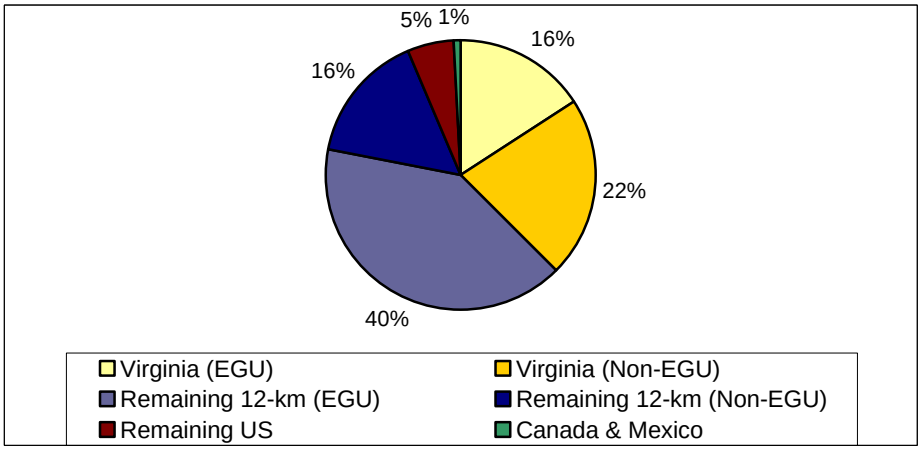
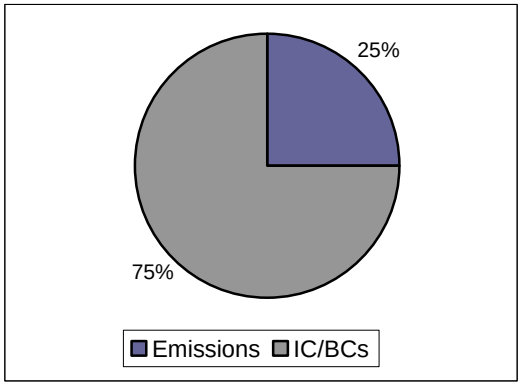


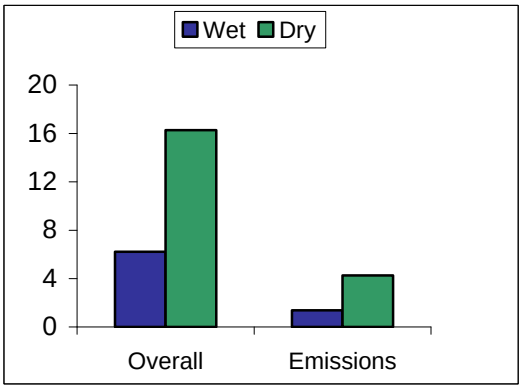
Figure 5-17c. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the James River Basin.

Simulated Annual Hg Deposition for 2001 for the James River Basin: 22.5 g/km²

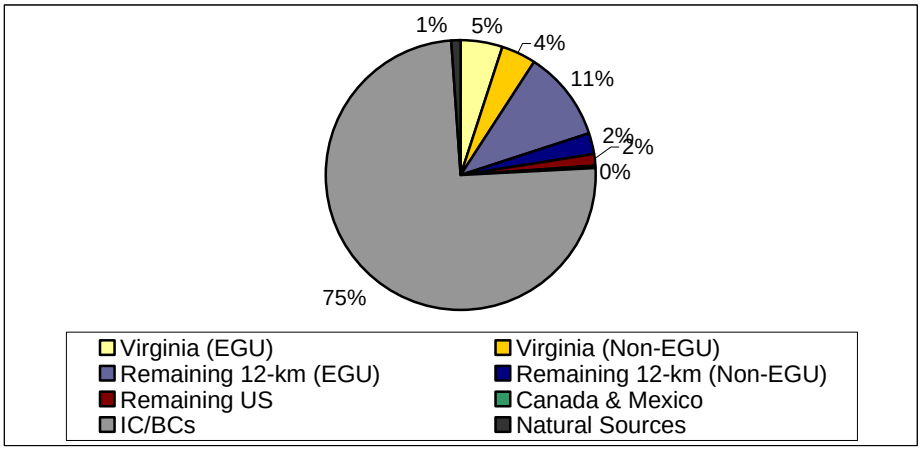
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

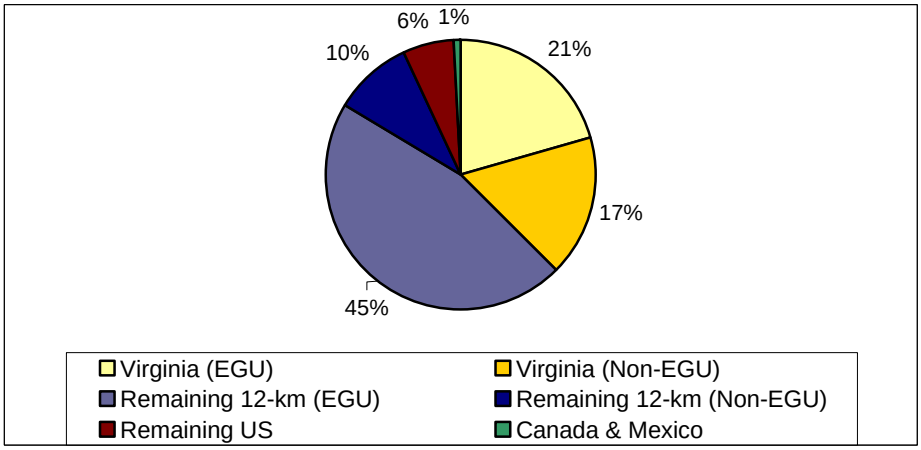
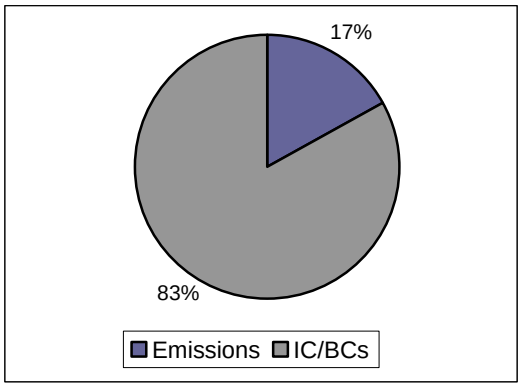


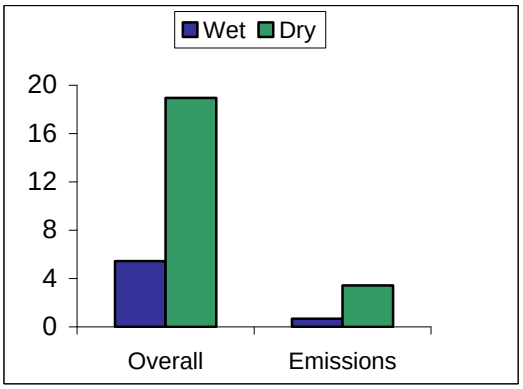
Figure 5-17d. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the New River Basin.

Simulated Annual Hg Deposition for 2001 for the New River Basin: 24.41 g/km²

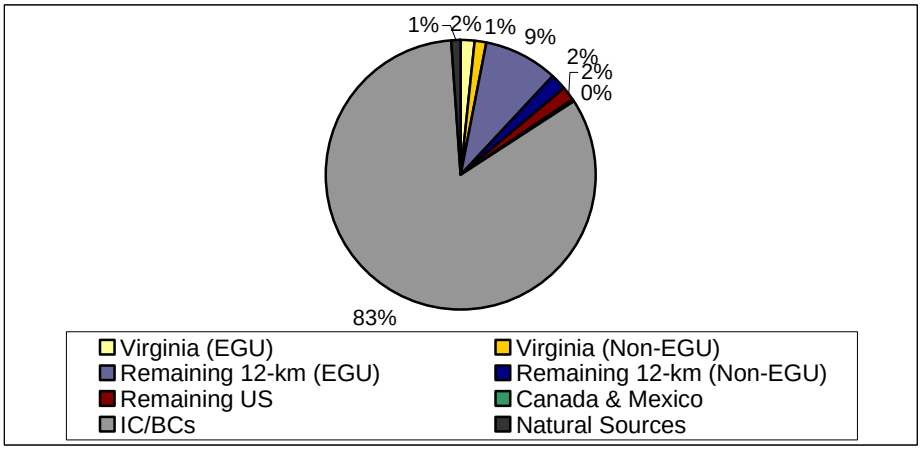
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

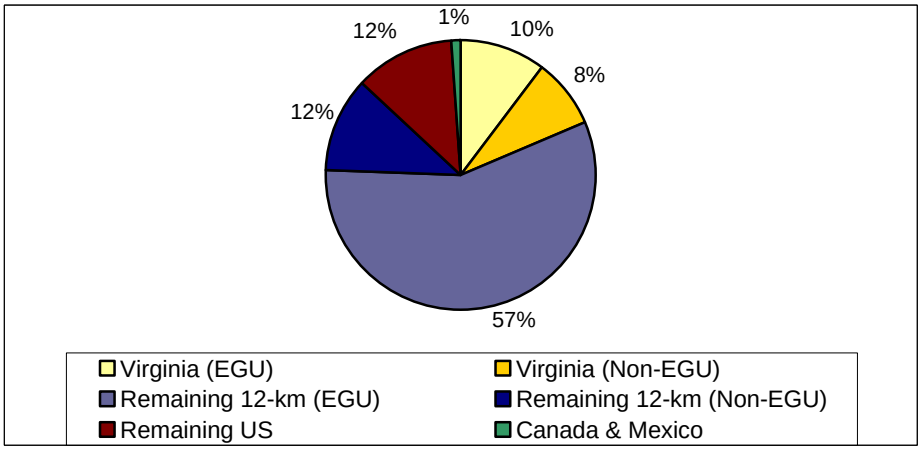
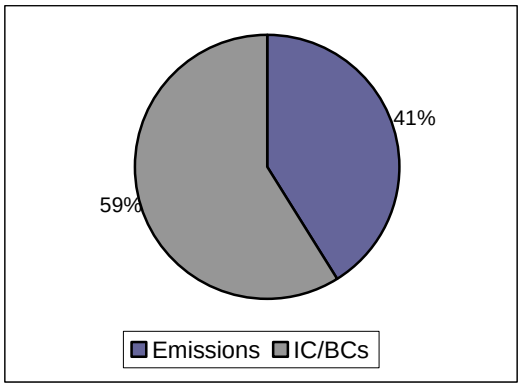


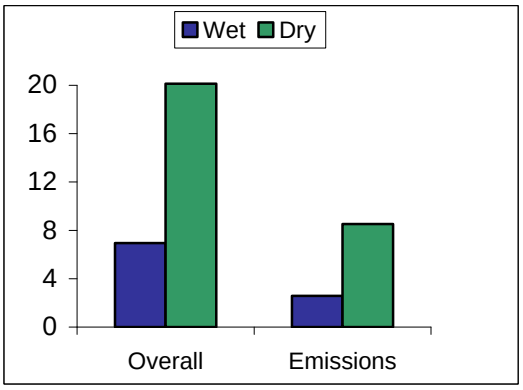
Figure 5-17e. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Potomac River Basin.

Simulated Annual Hg Deposition for 2001 for the Potomac River Basin: 27.07 g/km²

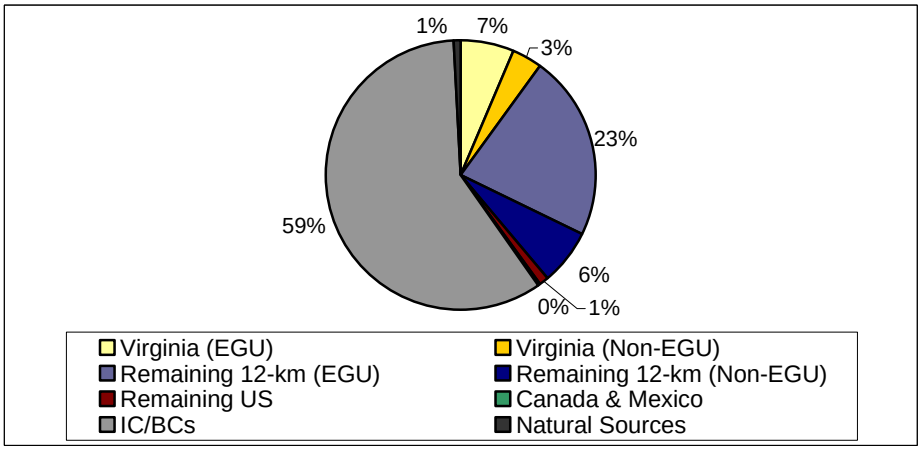
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

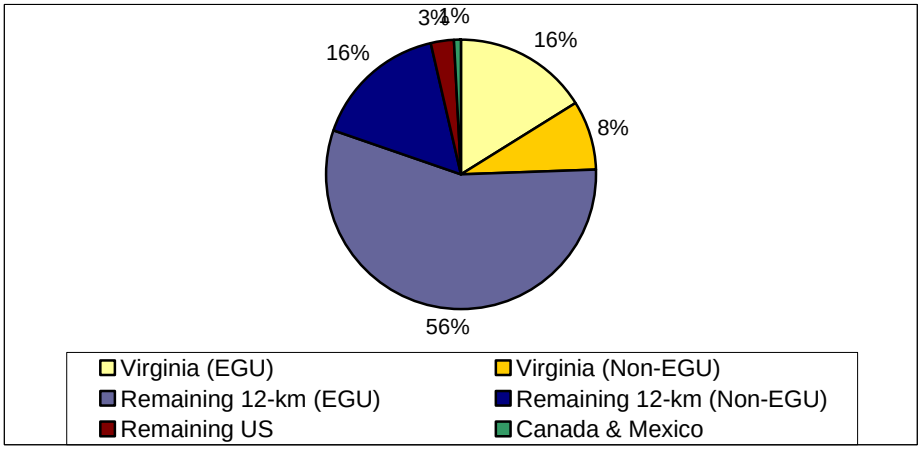
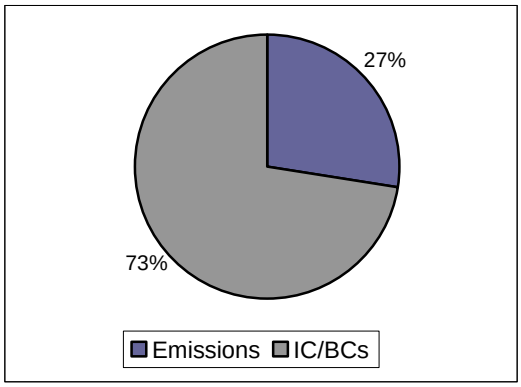


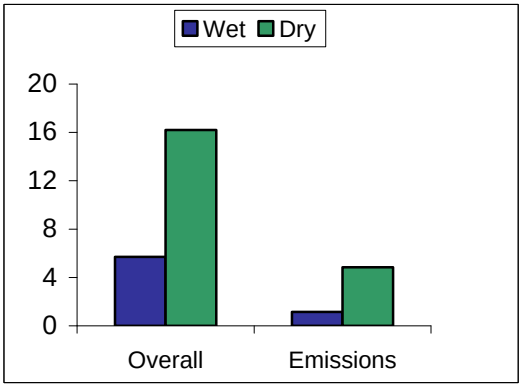
Figure 5-17f. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Rappahannock River Basin.

Simulated Annual Hg Deposition for 2001 for the Rappahannock River Basin: 21.9 g/km²

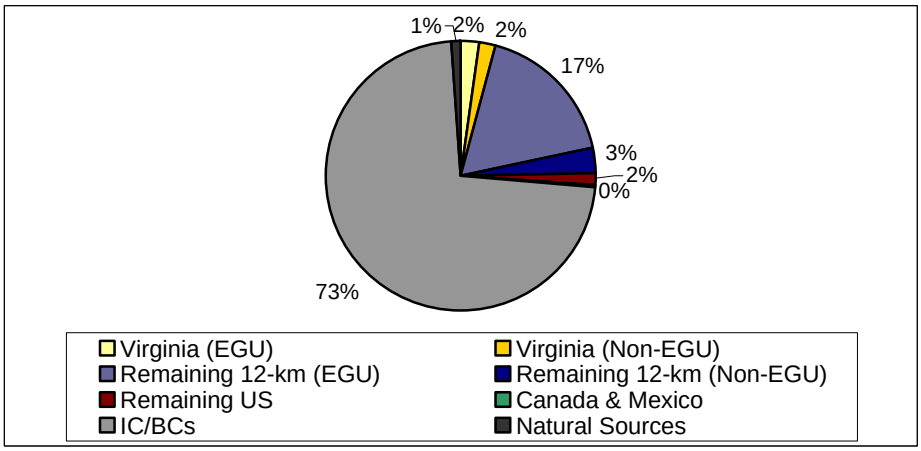
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

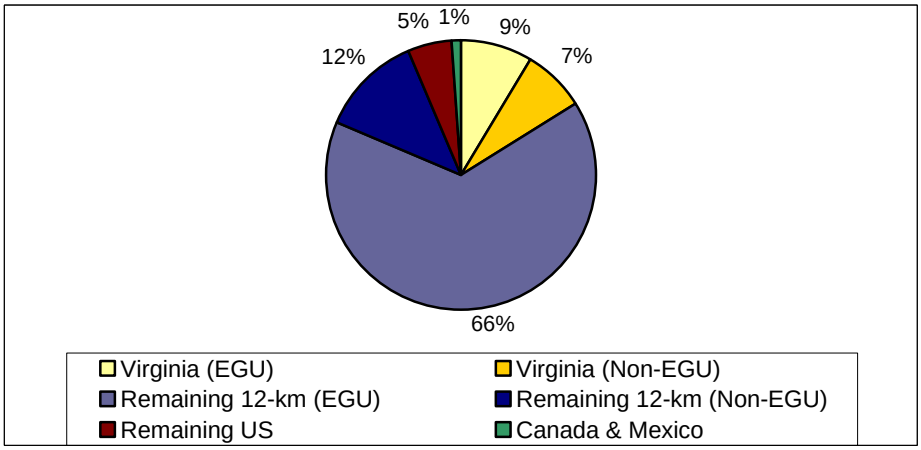
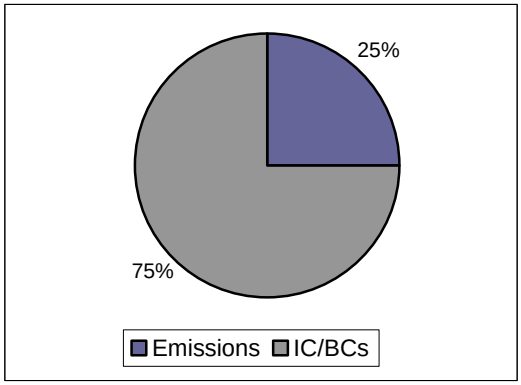


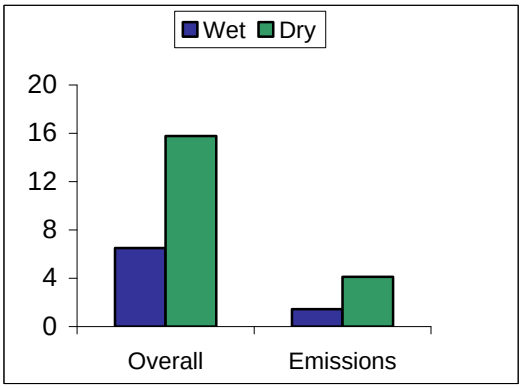
Figure 5-17g. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Roanoke River Basin.

Simulated Annual Hg Deposition for 2001 for the Roanoke River Basin: 22.26 g/km²

Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



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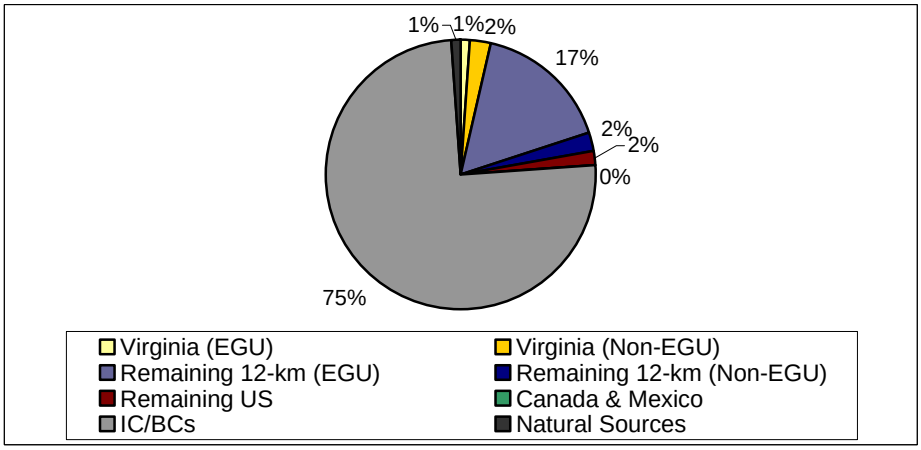


Contribution by Tag w/o Background & Natural Sources

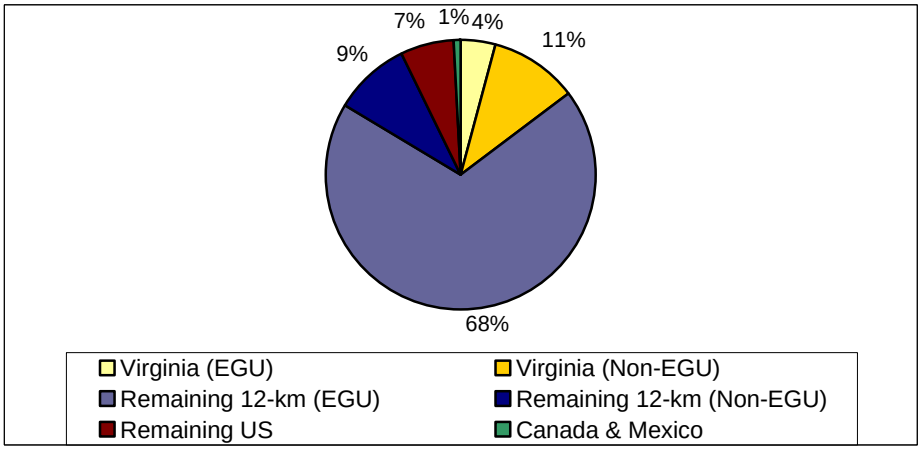
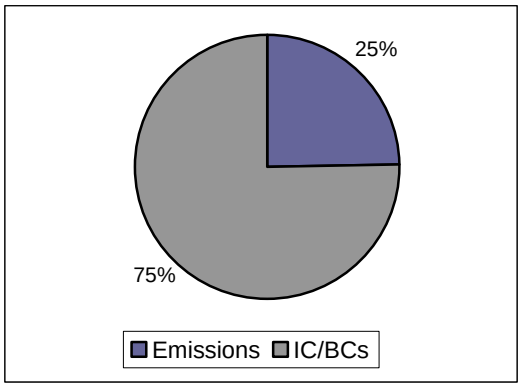


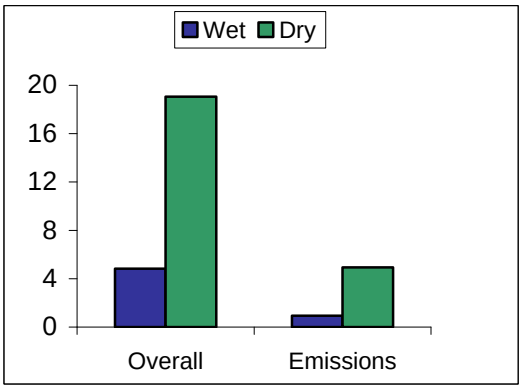
Figure 5-17h. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Shenandoah River Basin.

Simulated Annual Hg Deposition for 2001 for Shenandoah River Basin: 23.9 g/km²

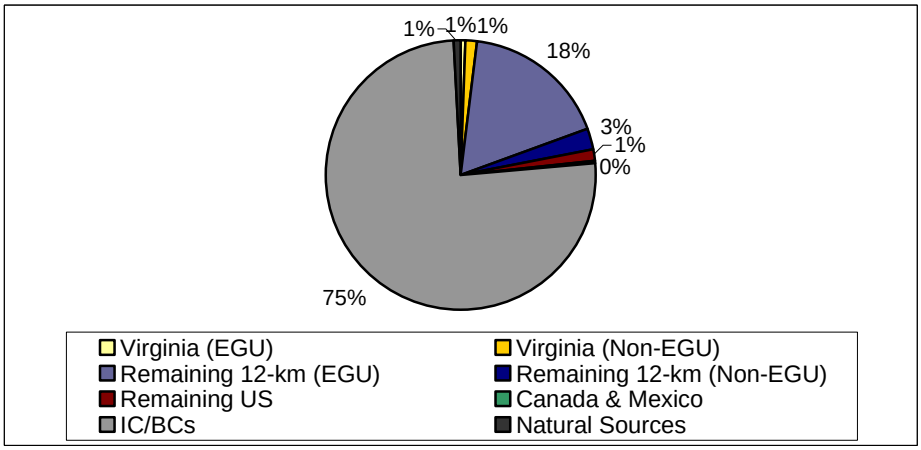
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

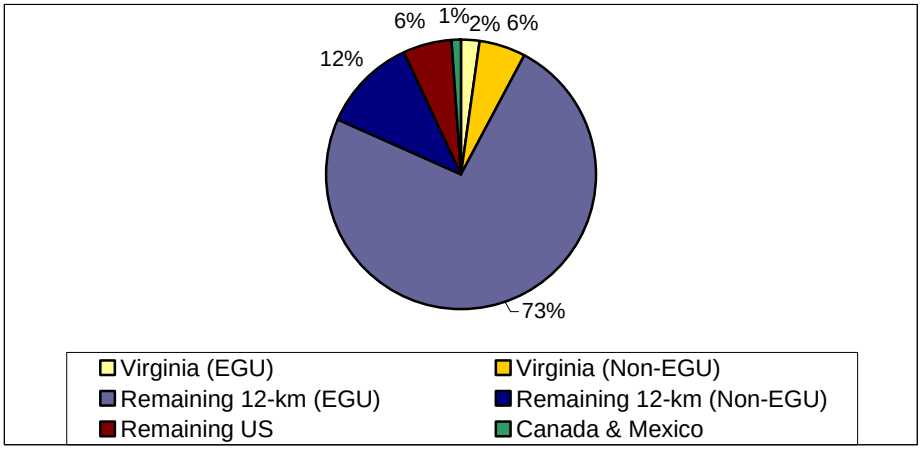
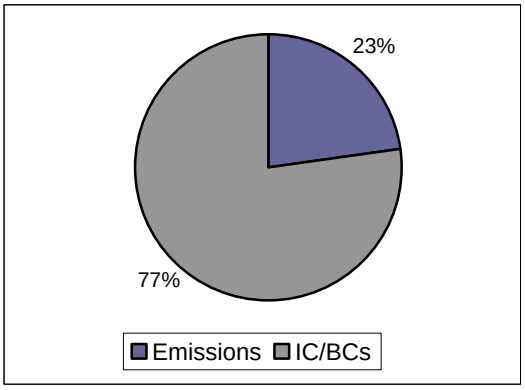


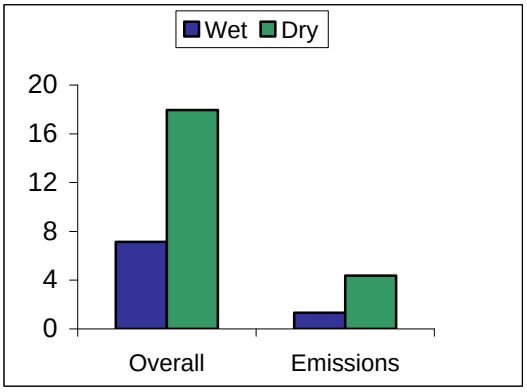
Figure 5-17i. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Tennessee and Big Sandy River Basins.

Simulated Annual Hg Deposition for 2001 for the Tennessee & Big Sandy River Basins: 25.1 g/km²

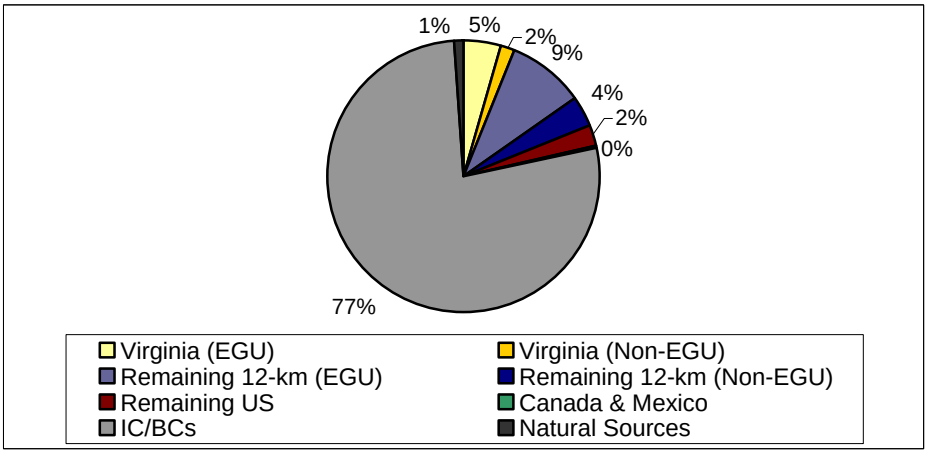
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

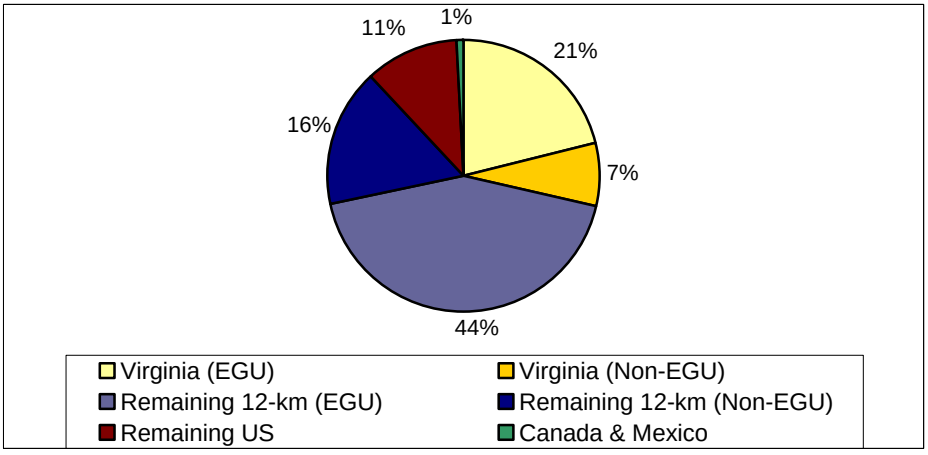
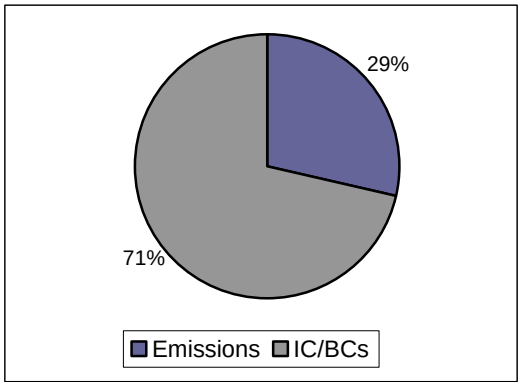


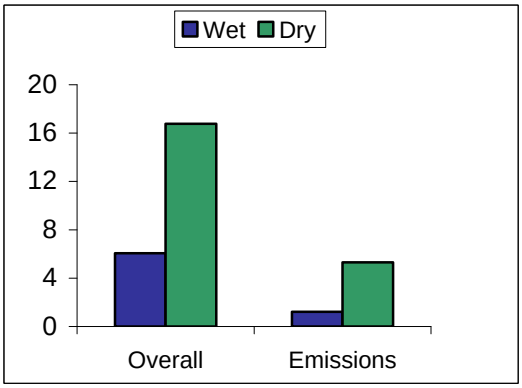
Figure 5-17j. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the York River Basin.

Simulated Annual Hg Deposition for 2001 for the York River Basin: 22.82 g/km²

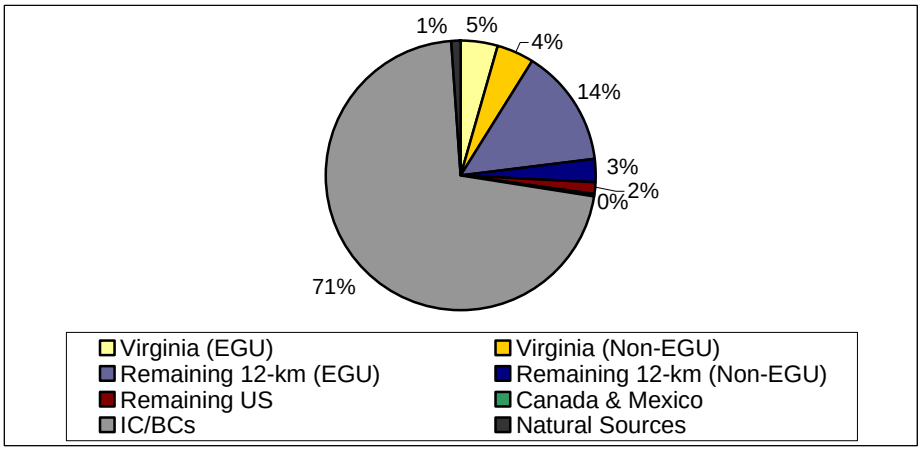
Emissions vs. IC/BC Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources

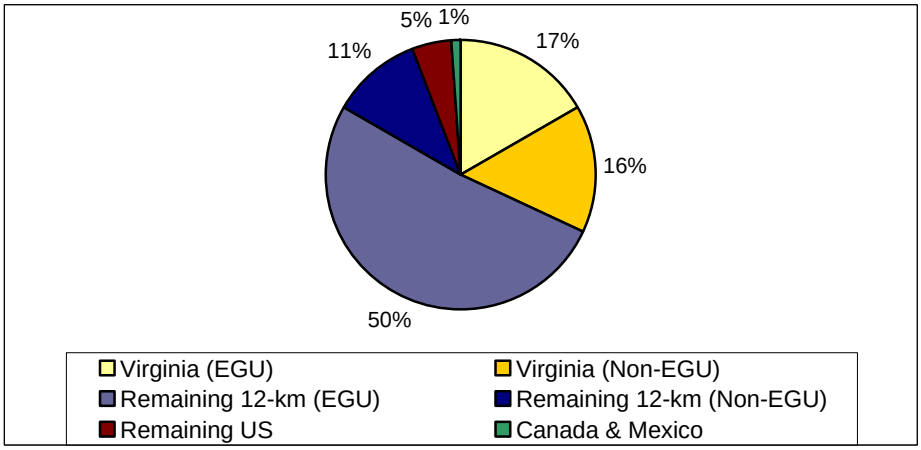
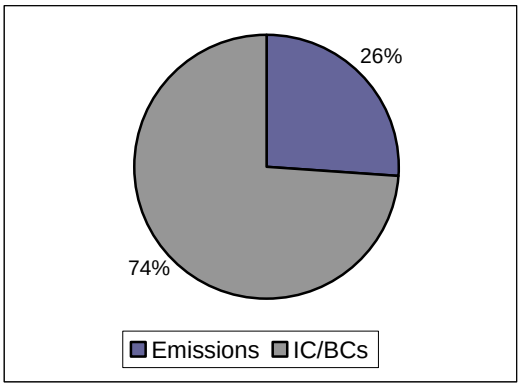


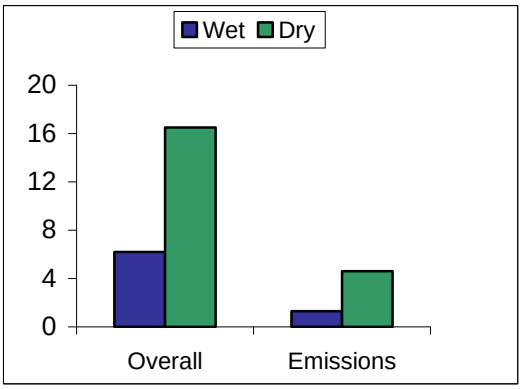
Figure 5-17k. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for Virginia.

Simulated Annual Hg Deposition for 2001 for Virginia: 22.69 g/km²

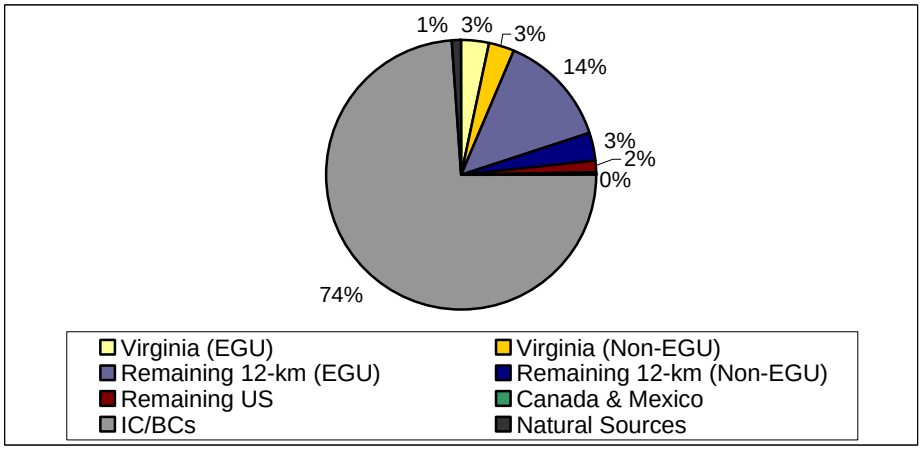
Emissions vs. IC/BC Contributions



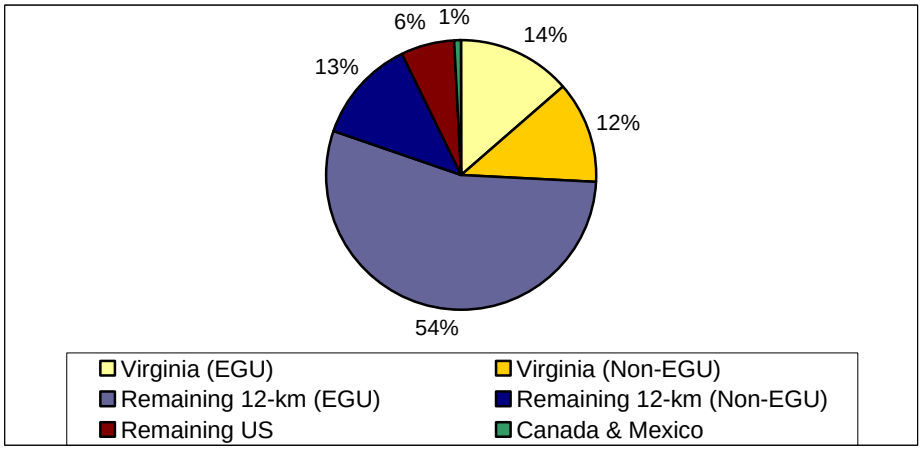
Contribution by Wet & Dry Deposition (g/km2)



Contribution by Tag



Contribution by Tag w/o Background & Natural Sources



Future-year Modeling

CMAQ was applied for 2010, 2015 and 2018, using emissions projected to these years (as presented in Section 3). The future-year modeling results are presented in the remainder of this section.

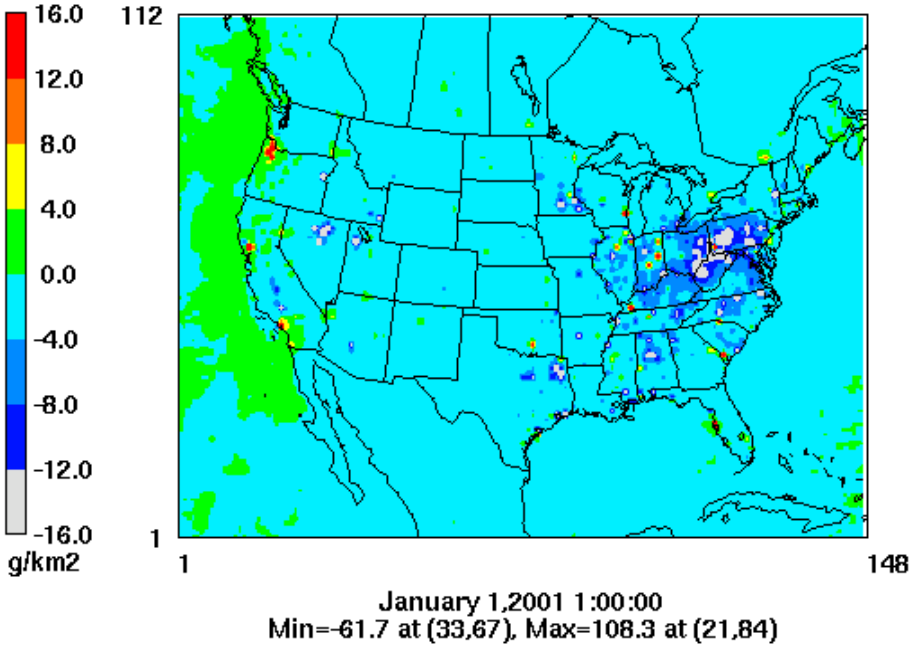
5.1.5. 2010, 2015 and 2018 Modeling Results

For each future year, the simulated change in overall mercury deposition both statewide and within the key areas of interest was examined.

Figures 5-18 through 5-20 display the location and magnitude of the differences in simulated mercury deposition for 2010, 2015, and 2018. Each figure consists of two parts. The first part shows the differences for the 36-km domain and the second part shows the differences for the 12-km subdomain. The differences are calculated as future-year minus base-year, so a negative value indicates a reduction in mercury deposition for the future year.

Figure 5-18. Difference in CMAQ Simulated Annual Total (Wet and Dry) Mercury Deposition (g km^{-2}) for the 2001 Simulation Period: 2010 Minus Base.

(a) 36-km Domain



(b) 12-km Subdomain

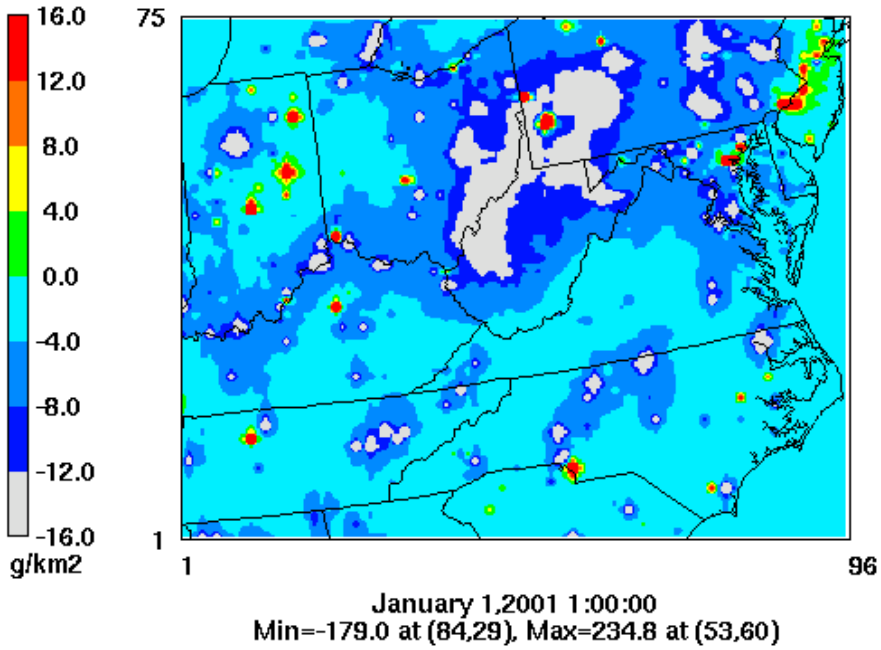
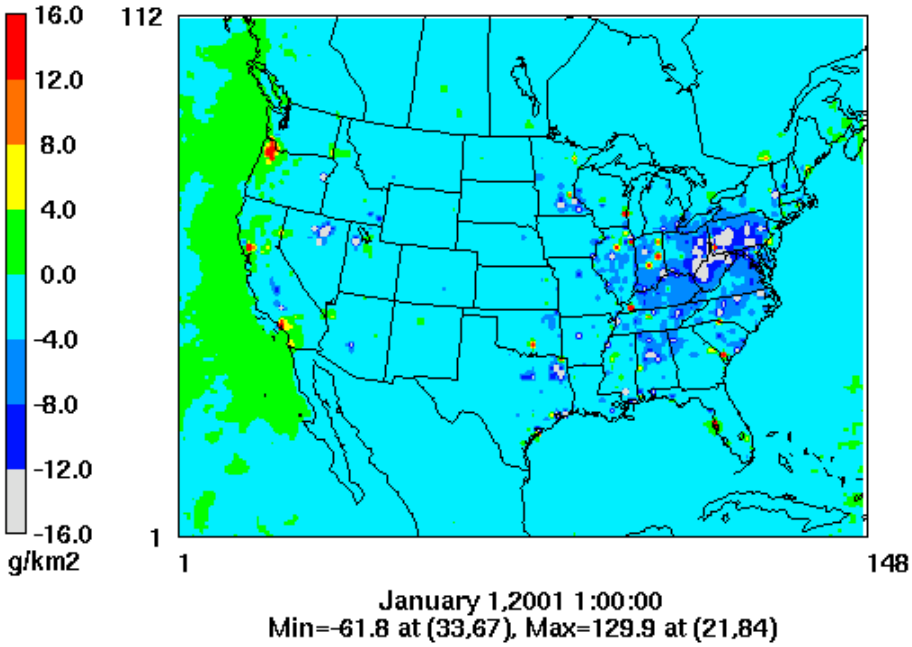


Figure 5-19. Difference in CMAQ Simulated Annual Total (Wet and Dry) Mercury Deposition (g km^{-2}) for the 2001 Simulation Period: 2015 Minus Base.

(a) 36-km Domain



(b) 12-km Subdomain

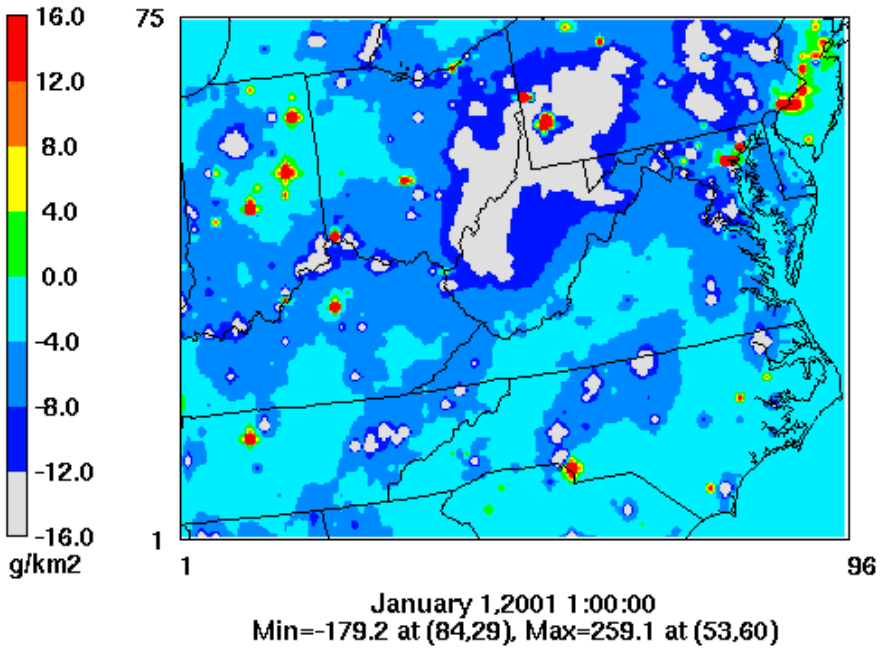
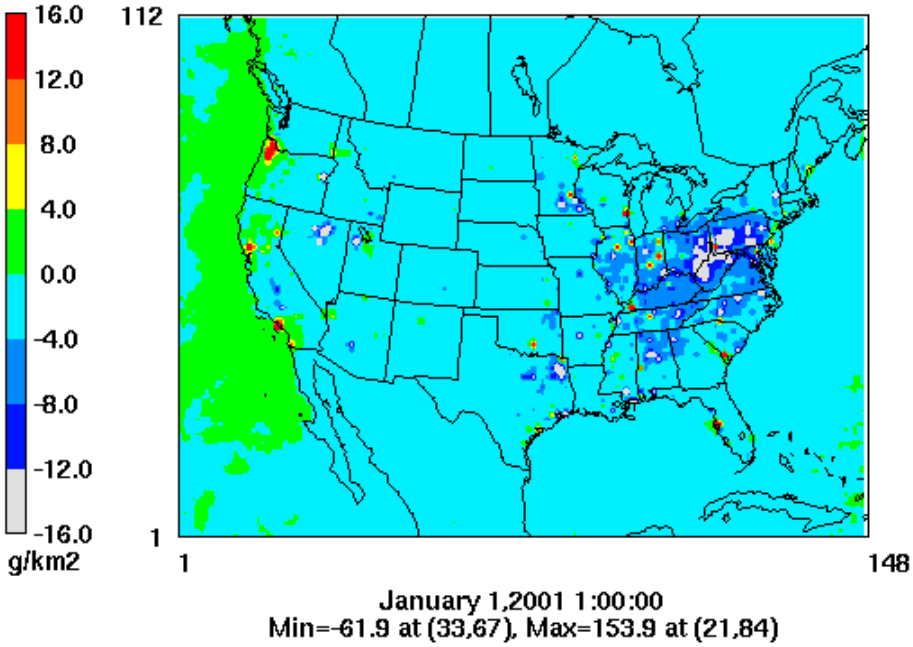
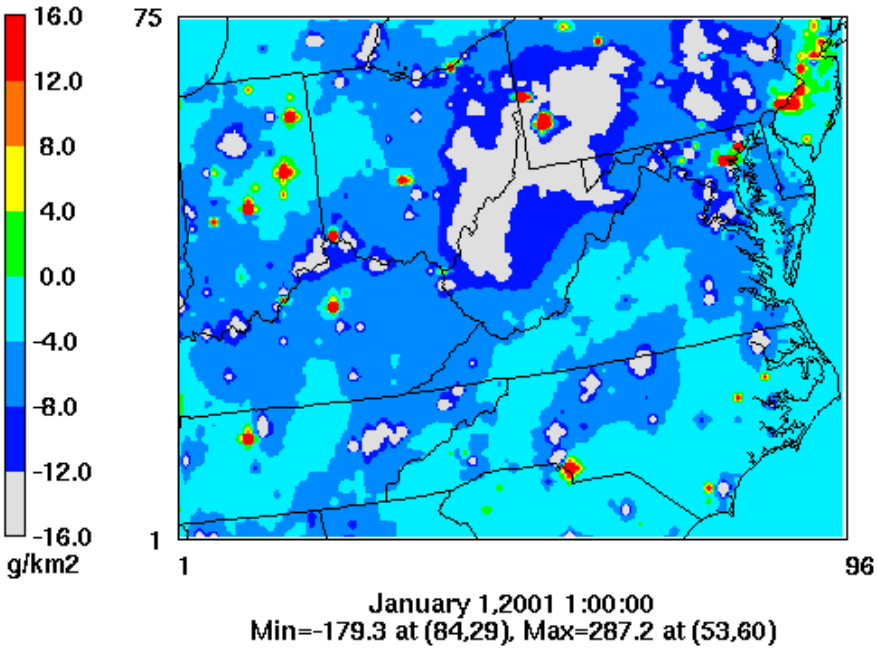


Figure 5-20. Difference in CMAQ Simulated Annual Total (Wet and Dry) Mercury Deposition (g km^{-2}) for the 2001 Simulation Period: 2018 Minus Base.

(a) 36-km Domain



(b) 12-km Subdomain



The difference plots indicate that simulated mercury deposition over Virginia is lower for all three future years – by up to 8 g km^{-2} for most areas and by larger amounts for some more isolated areas. A comparison of the plots for all three years shows that most of this reduction occurs between the base year and 2010. Outside of Virginia, the area of greatest reduction (for both the 12- and 36-km grids) is along the Ohio River Valley. There are also isolated areas of increase that are due to increases in the mercury emissions in the modeling inventories. These increases may be the result of increases in emissions due to projected growth for a source or industry sector. None of the red areas are due to the addition of "generic" EGU units. Rather, they coincide with either non-EGU sources in the future-year inventory that are not in the base-year inventory or increases in emissions for existing sources. In some cases the increases may be due to inconsistencies between the base- and future-year emissions in the national emission inventories, which were used for states other than Virginia.

Figure 5-21 further summarizes the projected deposition changes for each of the major river basins in Virginia. The size of the area is different for each river basin. To allow a comparison of the results among the river basins, the first plot (Figure 5-21a) gives the average deposition for each river basin in units of g km^{-2}. Another way to compare the base and future-year results is to sum the deposition over each river basin. This information is presented in Figure 5-21b which gives total deposition in units of kg. Both plots show that the amount of reduction between modeled years is greatest between the base year and 2010. Of course, this period is also the longest in terms of the number of years represented. The reductions are much smaller between 2010 and 2015 and then 2015 and 2018. Figure 5-21a shows that the Potomac River Basin has the highest simulated deposition per unit area, but also experiences the greatest reduction between the base and future years. Figure 5-21 shows that the James River Basin (one of the largest in terms of area) has the highest overall amount of simulated mercury deposition and that this is reduced by about 16 percent by 2010. Additional analysis of these results is presented in Section 7.

Figure 5-21a. CMAQ Simulated Annual Total (Wet and Dry) Mercury Deposition (g km^{-2}) for the Major River Basins in Virginia for 2001/2002, 2010, 2015 and 2018: Deposition Amount per Unit Area.

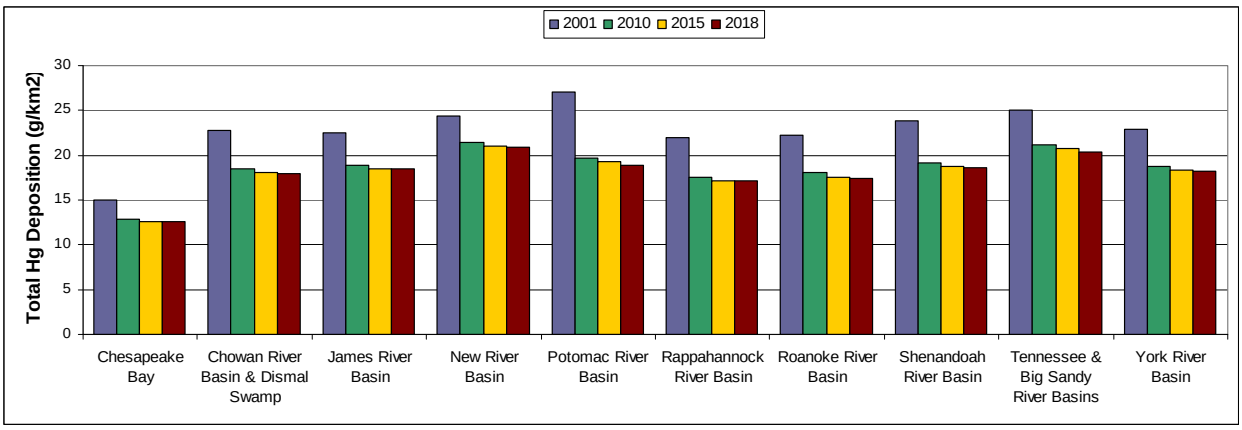
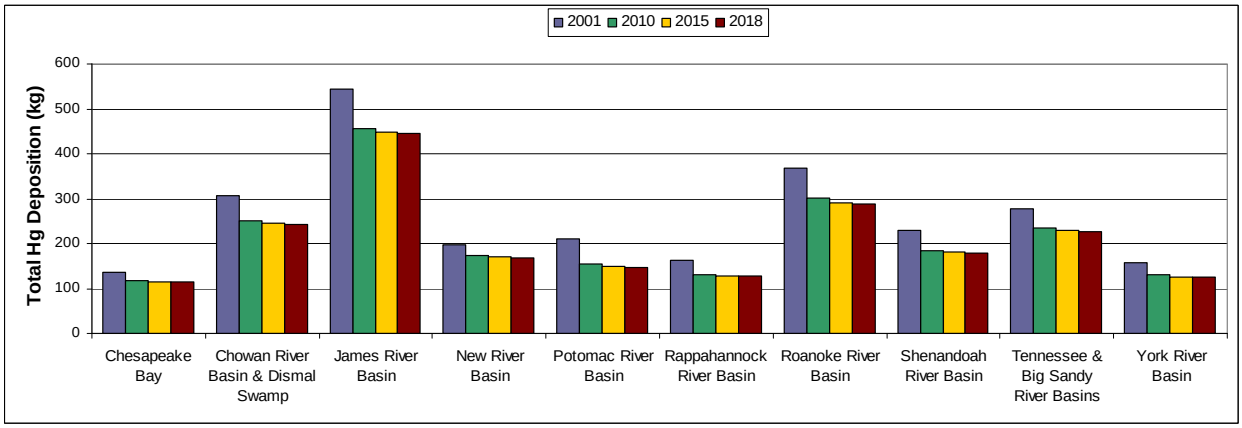


Figure 5-21b. CMAQ Simulated Annual Total (Wet and Dry) Mercury Deposition (kg) for the Major River Basins in Virginia for 2001/2002, 2010, 2015 and 2018: Deposition Total for the Area.

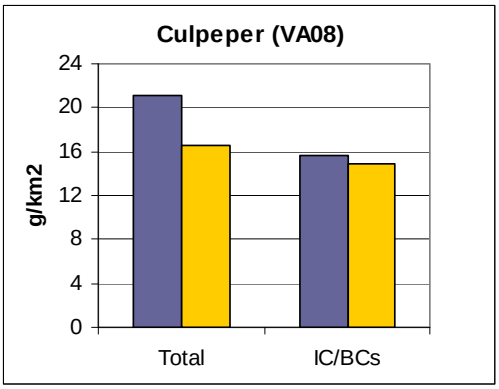


5.1.6. 2018 Contribution Analysis for Virginia

For 2018, the same CMAQ/PPTM scenarios that were run for the baseline were also run for the future year. The PPTM results were used to attribute the future-year reductions in mercury deposition for 2018 for each area of interest to the specific tagged sources or source categories.

We begin with the results for the MDN monitoring sites. In Figure 5-22, total mercury deposition and deposition associated with each tagged source category or area is plotted for each MDN monitoring site and for the base year and 2018. Total deposition and the IC/BC contribution are plotted in the upper bar chart. The results for the remaining tags are plotted in the lower bar chart, using a reduced scale range (to facilitate the comparison of the base and future year results for the smaller contributors). Note also that the scales differ among the sites.

Figure 5-22a. CMAQ/PPTM 12-km Mercury Tagging Results for the Culpeper MDN Monitoring Site (VA08) for 2001/2002 and 2018.



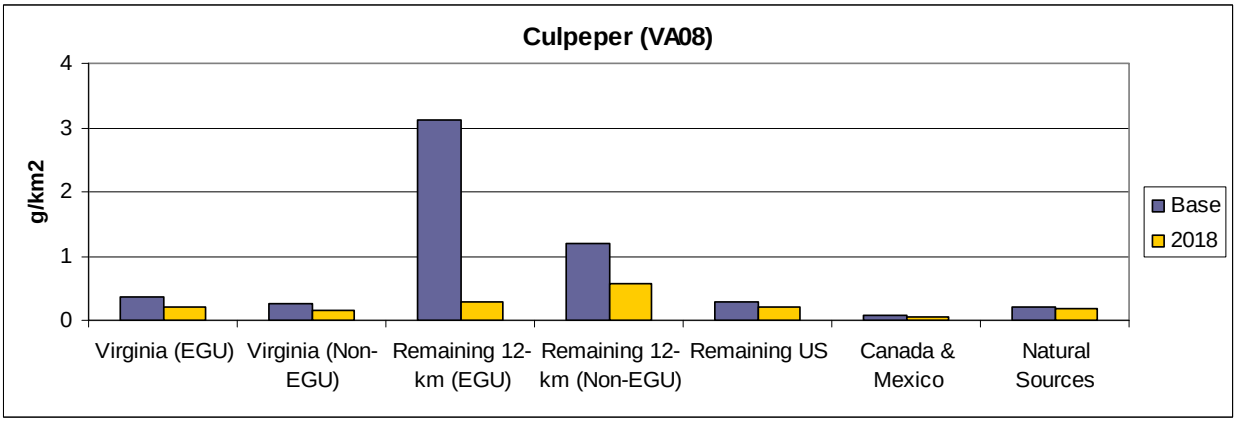
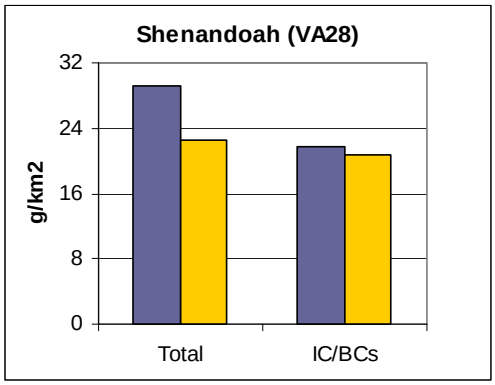


Figure 5-22b. CMAQ/PPTM 12-km Mercury Tagging Results for the Shenandoah National Park MDN Monitoring Site (VA28) for 2001/2002 and 2018.



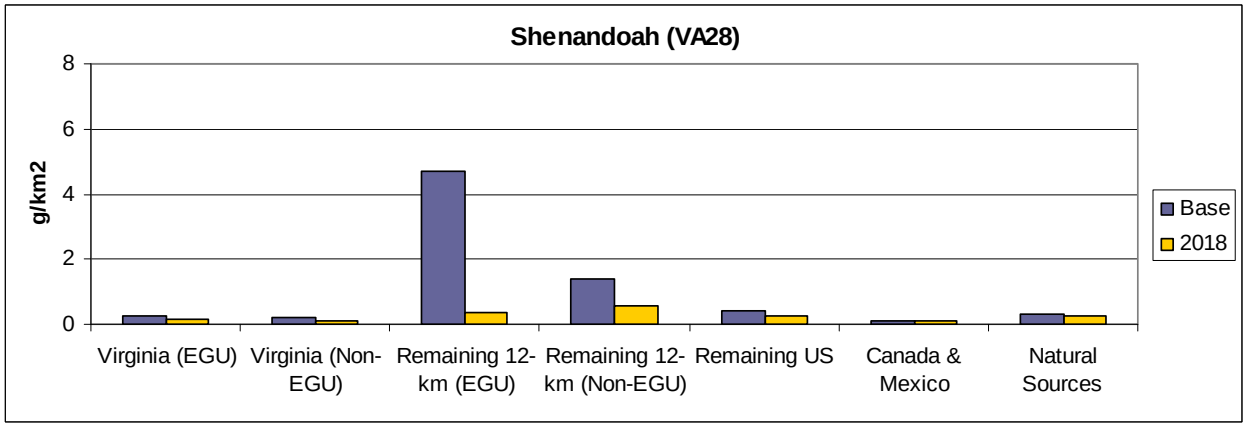
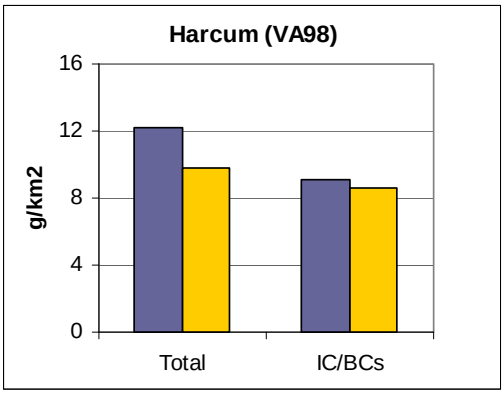
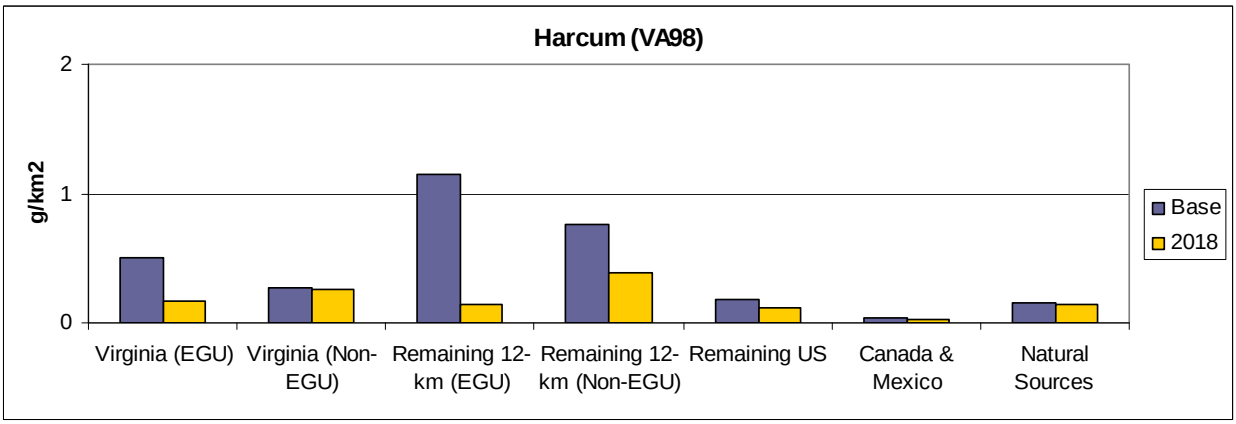


Figure 5-22c. CMAQ/PPTM 12-km Mercury Tagging Results for the Harcum MDN Monitoring Site (VA98) for 2001/2002 and 2018.

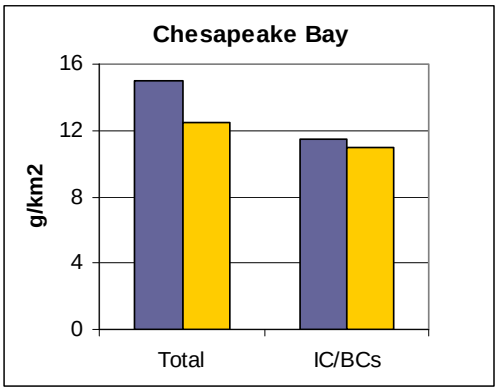




For all three MDN sites, simulated mercury deposition is about 20 percent lower for 2018 compared to the base year. A majority of this reduction is attributable to reductions in emissions from EGU and non-EGU sources in the surrounding states (remainder of the 12-km domain). Lower emissions from Virginia EGU sources are also important to the overall reduction at Harcum. Although the differences between the 2018 and base contributions are relatively small for the other categories, the contributions from all tags are lower for 2018. While the IC/BCs and natural emissions used as input to the model are the same for both years, there is also a reduction in the contribution from these tags. This is due to lower regional-scale concentrations of ozone and other species in the future year, which results in less conversion of HG0 (from the boundary conditions and natural emissions) to HG2 and less deposition. Recall that most of the mercury deposition is in the form of HG2.

Figure 5-23 displays this same information for each of the major river basins in Virginia.

Figure 5-23a. CMAQ/PPTM 12-km Mercury Tagging Results for the Chesapeake Bay, Atlantic Ocean, and Small Coastal Waters for 2001/2002 and 2018.



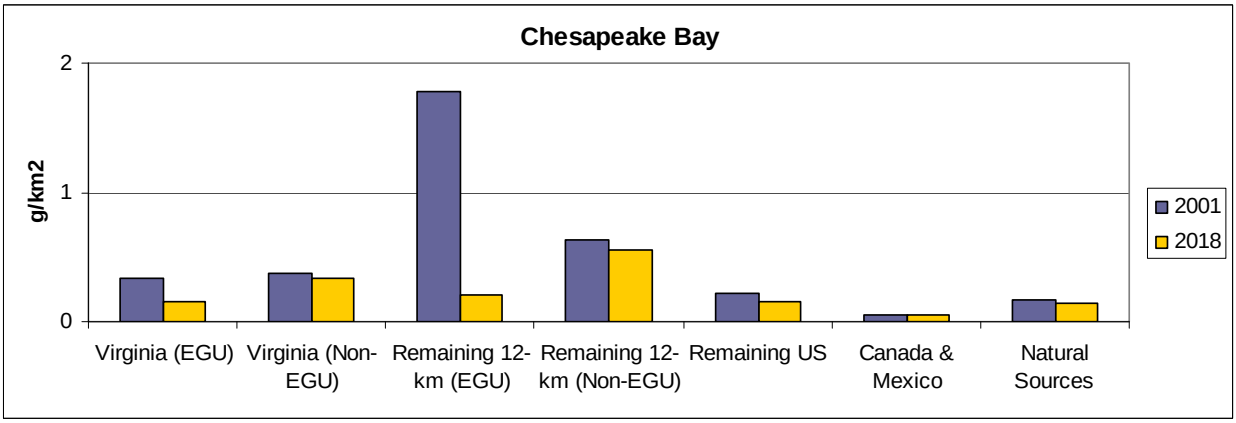
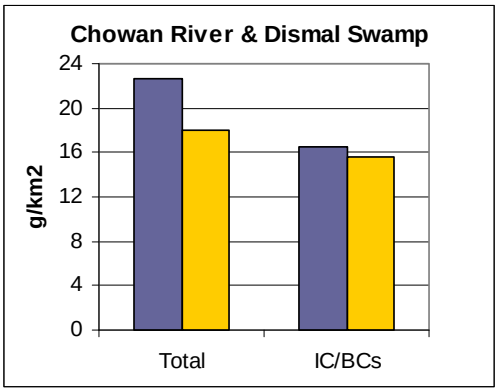


Figure 5-23b. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Chowan River Basin and Great Dismal Swamp for 2001/2002 and 2018.



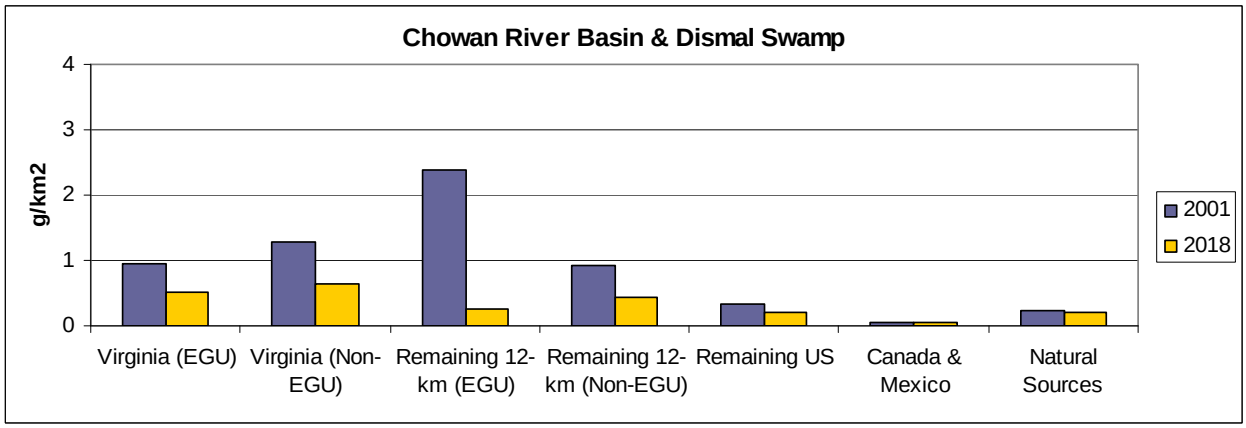
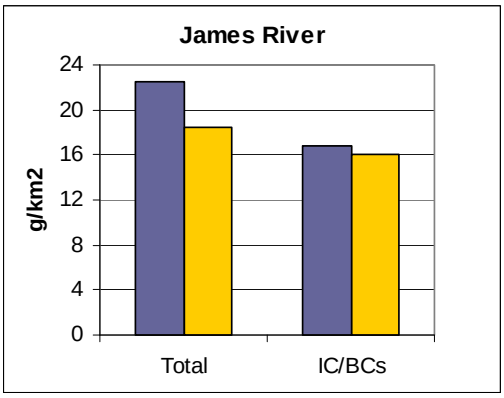


Figure 5-23c. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the James River Basin for 2001/2002 and 2018.



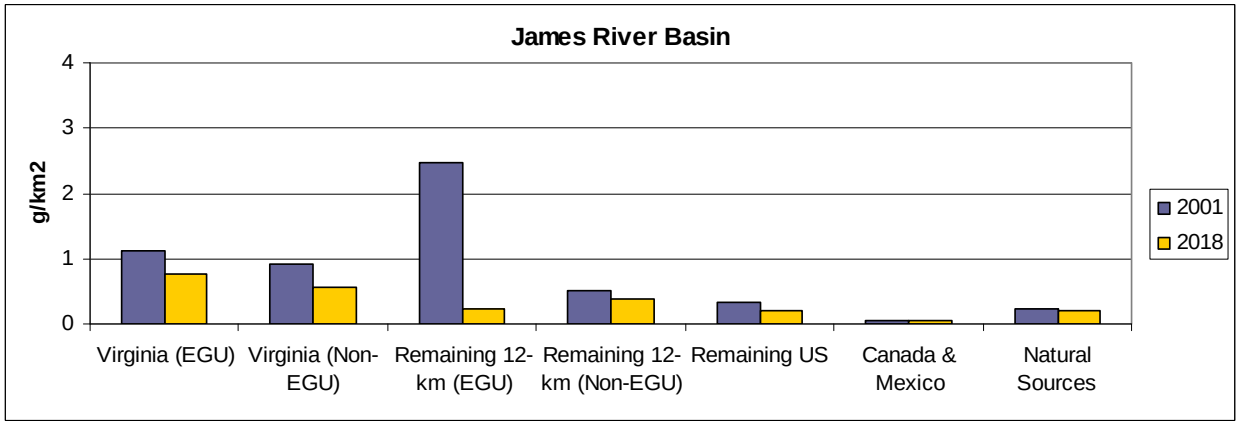
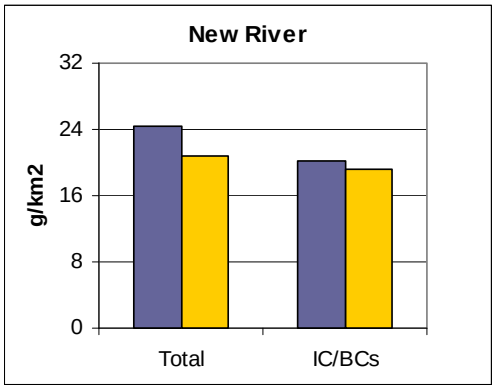


Figure 5-23d. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the New River Basin for 2001/2002 and 2018.



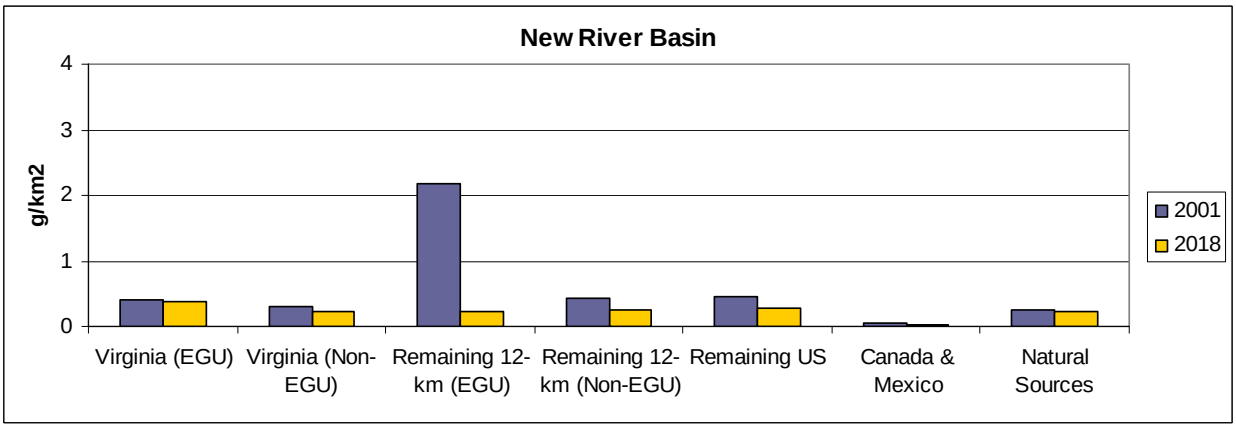
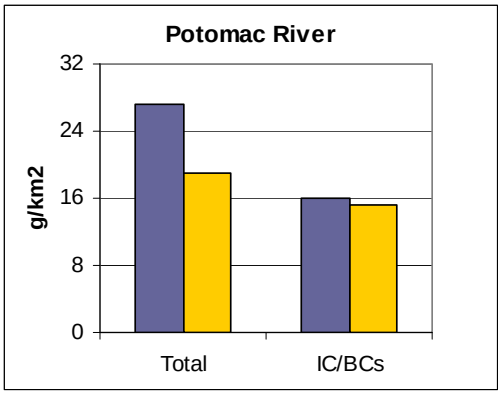


Figure 5-23e. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Potomac River Basin for 2001/2002 and 2018.



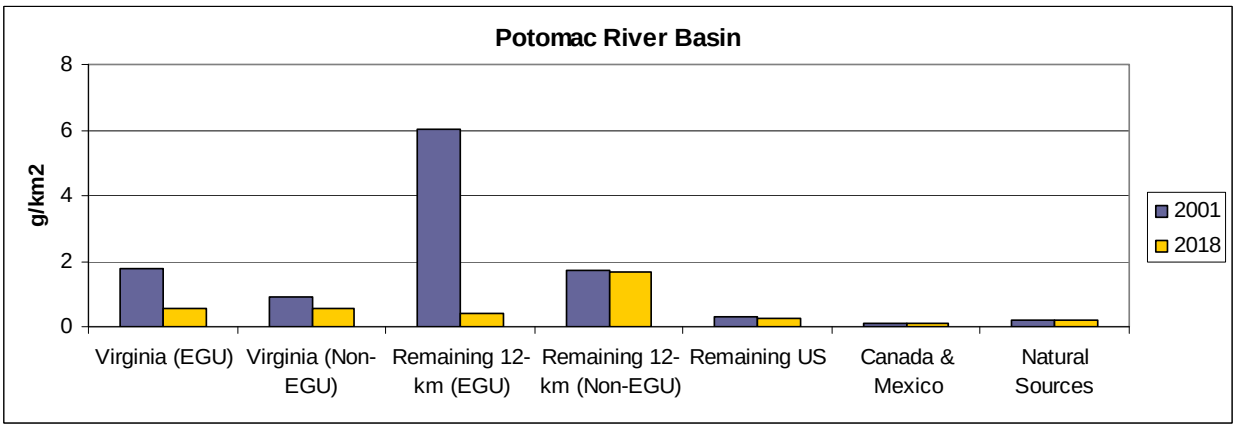
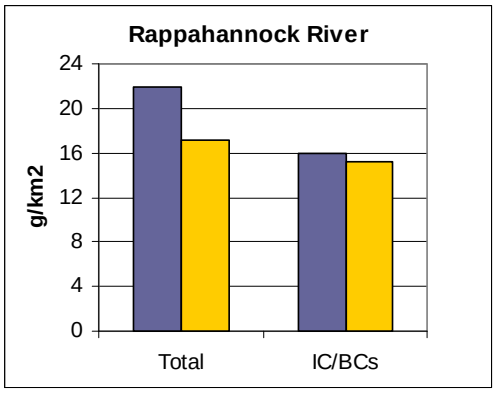


Figure 5-23f. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Rappahannock River Basin for 2001/2002 and 2018.



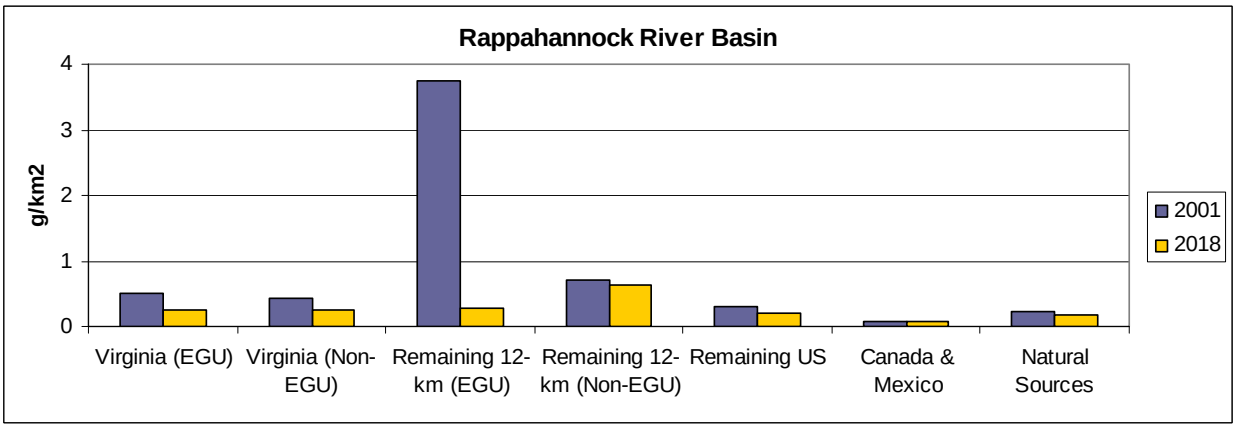
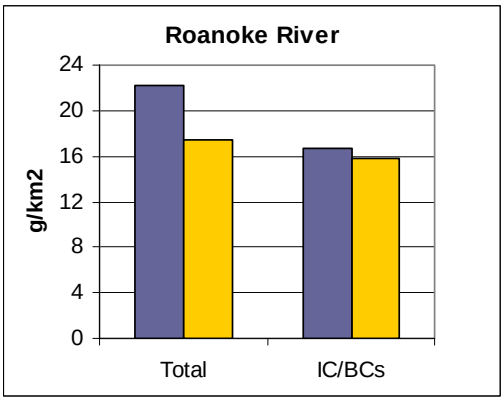


Figure 5-23g. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Roanoke River Basin for 2001/2002 and 2018.



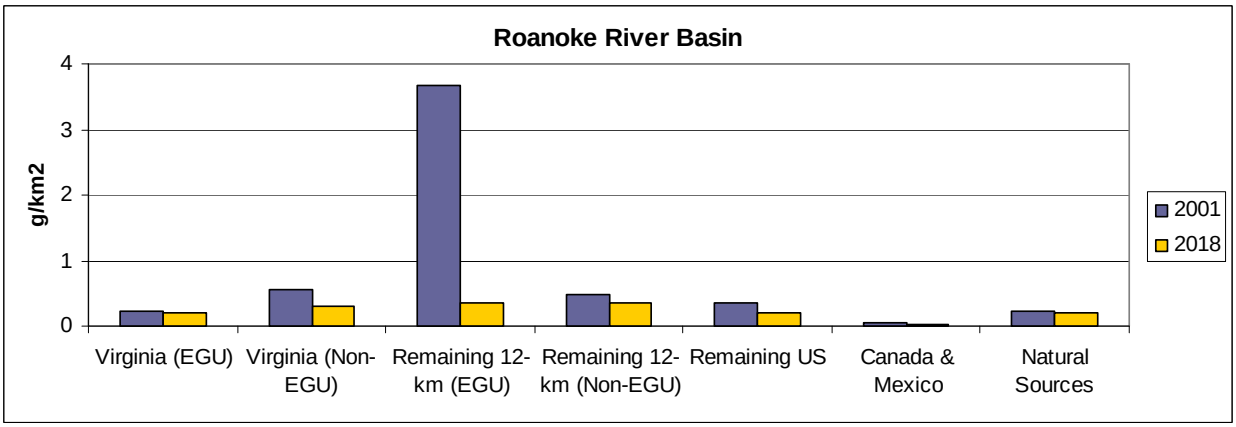
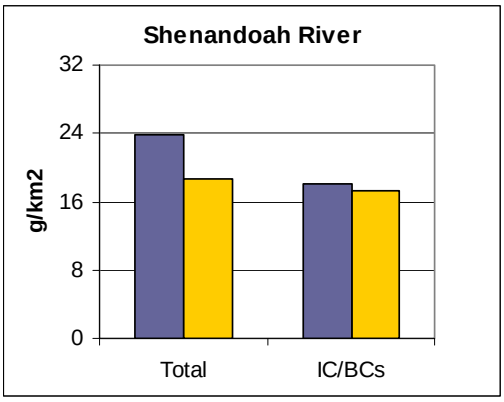


Figure 5-23h. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Shenandoah River Basin for 2001/2002 and 2018.



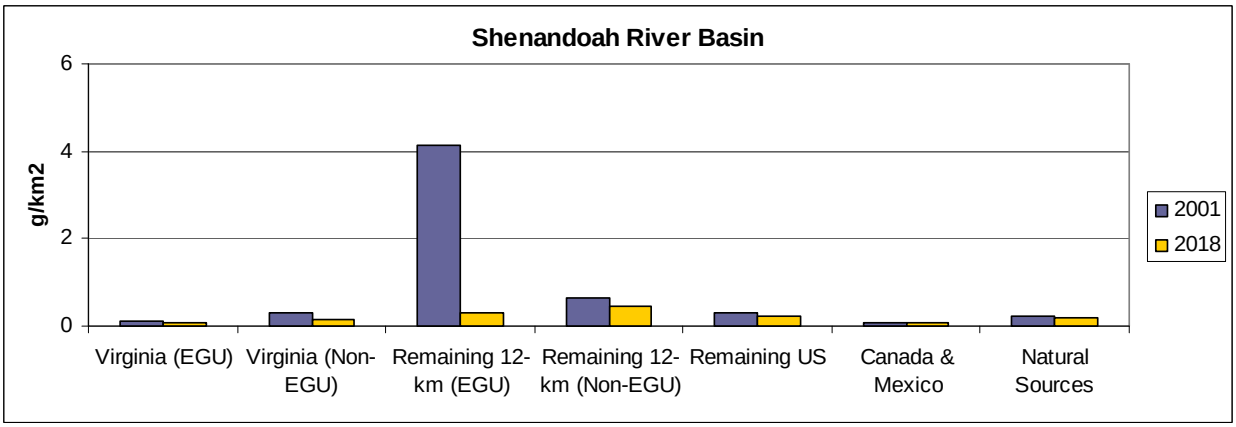
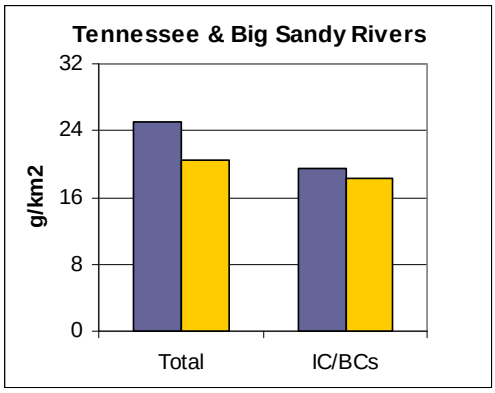


Figure 5-23i. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the Tennessee and Big Sandy River Basins for 2001/2002 and 2018.



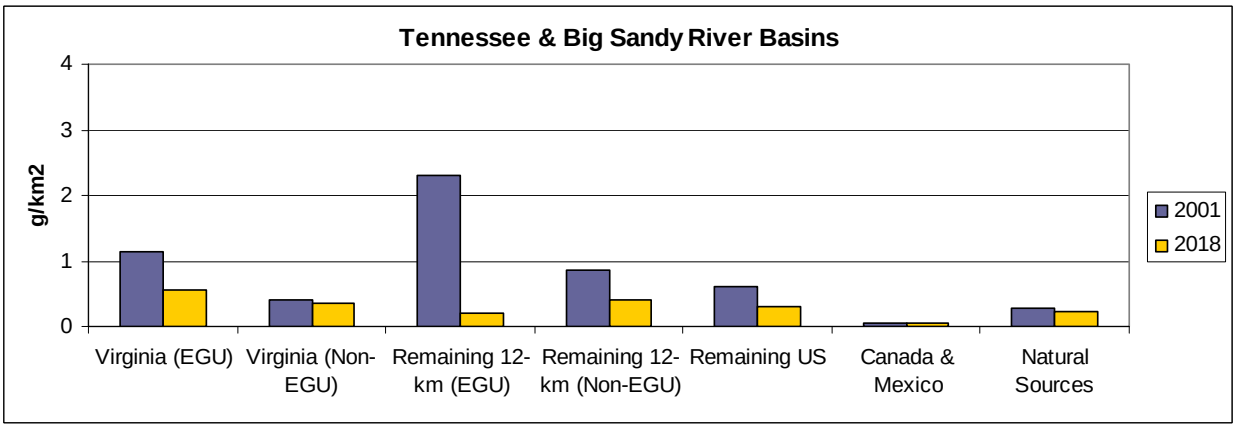
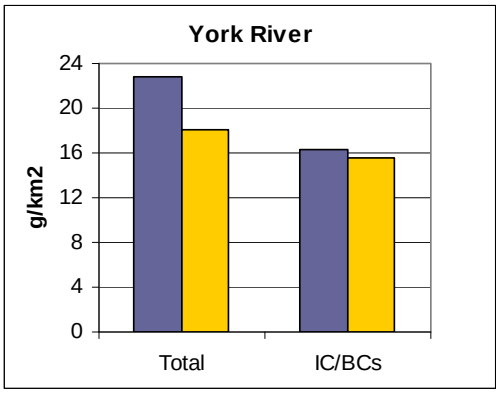


Figure 5-23j. Summary of CMAQ/PPTM 12-km Mercury Tagging Results for the York River Basin for 2001/2002 and 2018.



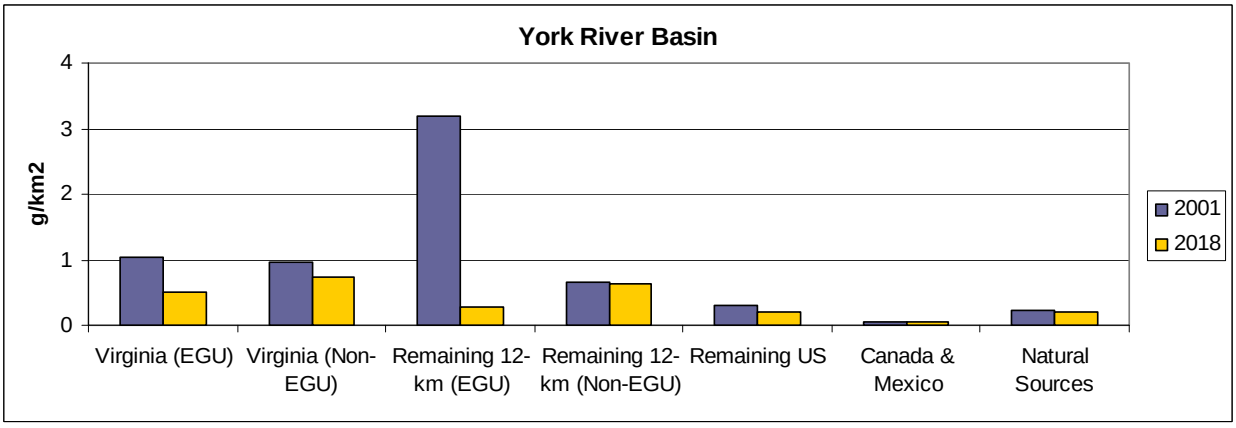


Figure 5-23 shows that, for all of the Virginia river basins, lower mercury deposition in 2018 is primarily driven by the reduction in emissions from EGU sources in the surrounding states between the base year and 2018. The other tagged source categories and regions vary in importance among the river basins. For example, reductions in emissions from the Virginia EGU and non-EGU sources as well as the non-EGU sources in the surrounding states also play a significant role in lowering simulated mercury deposition for the Chowan River Basin and Dismal Swamp between the base year and 2018. Reductions in emissions from the Virginia EGU and non-EGU sources (but not the non-EGU sources in the surrounding states) result in lower simulated mercury deposition for the James River and York River Basins. Additional analysis of these results is presented in Section 7.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6. AERMOD Modeling Results

AERMOD was applied for the 15 sources in Virginia with the greatest mercury emissions, ranked according to the VDEQ 2002 emissions inventory data. As noted in Section 4, AERMOD was applied separately for each source and for elemental, reactive gaseous, and particulate-bound mercury. The results of the AERMOD application are presented in this section of the report.

6.1. AERMOD Metrics

In this section, two key metrics are used for the presentation of the AERMOD results. The first is the average annual mercury deposition, averaged over all receptors in the 3-km area surrounding each source. The second is the maximum annual mercury deposition for any receptor. Both metrics were calculated for wet, dry and total deposition and for HG0, HG2 and HGP.

In addition to these metrics, graphs displaying the spatial distribution of mercury deposition for each source-receptor area and bar charts comparing the deposition amounts for the various facilities were also prepared. These were prepared for wet, dry and total deposition and for HG0, HG2 and HGP.

6.2. Sensitivity Simulations

Following the initial application of AERMOD, the annual deposition plots for each facility and corresponding receptor area were reviewed. As discussed in Section 4, the plots of wet, dry, and total deposition were also reviewed and the deposition of HG0, HG2 and HGP were compared to the speciation of the emissions. Three key findings emerged from this review: 1) dry deposition is greater than wet deposition for all facilities, 2) maximum wet deposition tends to occur in the receptor cells closest to the facility, and 3) maximum dry deposition tends to occur further away from the facility location. The finding related to wet deposition is consistent with wash out of the emissions near the facility when precipitation is occurring. The finding related to dry deposition is consistent with expected plume behavior under a variety of meteorological conditions and transport of the emissions to a downwind location before deposition occurs.

The initial AERMOD results also indicated that deposition amount is not directly proportional to the emissions totals for the top 15 sources, which are listed together with their base-year emissions in Table 4-1 (presented earlier). The units for deposition are micrograms per square meter ($\mu g\ m^{-2}$). The ranking of the facilities with respect to emissions totals is different from the ranking based on total (wet plus dry) deposition amount. As an example, the annual emissions and simulated deposition amounts for the top two facilities are provided in Table 6-1. The average stack height and exit velocity of the emissions for each facility are also provided in the table; the averages are taken over all stacks that comprise the facility.

Table 6-1. AERMOD Mercury Emissions Rates, Average Stack Parameters, and Simulated Total Deposition Amounts for Two Facilities.

Facility Name	Rank	Total Hg Emissions (lbs/yr)	Average Stack Height (m)	Average Exit Velocity ($m\ s^{-1}$)	Average Annual Hg Dep ($ug\ m^{-2}$)	Maximum Annual Hg Dep ($ug\ m^{-2}$)	EGU?
Dominion - Chesterfield Power Station	1	358.83	93.7	22.1	0.7	1.8	EGU
Chaparral Steel	2	292.30	23.2	6.1	3.6	49.5	Non-EGU

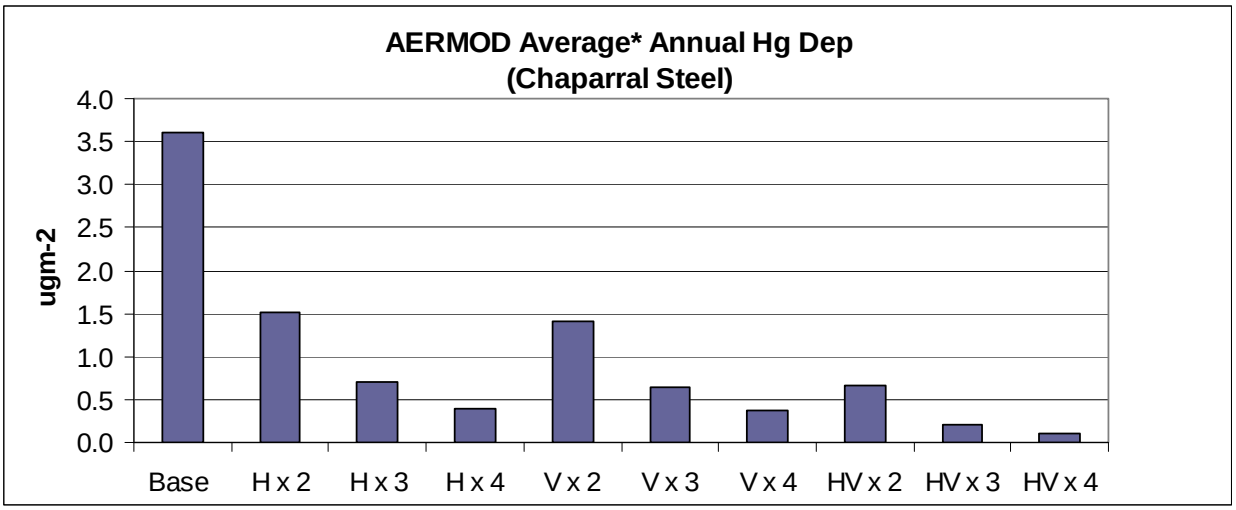
Even though the emissions are greater for the Chesterfield Power Station, the local deposition amounts are greater for Chaparral Steel. The maximum deposition for the Chesterfield Power Station is simulated to occur approximately 750 m away from the source, while that for Chaparral Steel occurs within 100 m of the source. The meteorological inputs for these two facilities are based on the same surface and upper-air meteorological data. Thus, it was concluded that the differences in deposition are not due to differences in meteorology. Some sensitivity simulations were conducted to examine the relationship of the stack parameters to the simulated deposition for the Chaparral Steel source under the meteorological conditions represented in this study. The goal was to examine and explain the modeling results, and not to conduct a rigorous test of the sensitivity of AERMOD to various parameters.

In series of simulations, the stack heights for Chaparral Steel were increased by factors of 2, 3 and 4. In a second series of simulations, the exit velocities for Chaparral Steel were increased by factors of 2, 3 and 4. Finally, both the stack heights and exit velocities were increased by these same factors. The results are presented in Table 6-2 and plotted in Figure 6-1 (annual average only). In presenting the results of the sensitivity tests, the deposition amounts are total (wet plus dry) deposition.

Table 6-2. AERMOD Annual Average and Maximum Simulated Total Mercury Deposition (μg m^{-2}) for the Chaparral Steel Facility for a Variety of Alternative Stack Parameters.

Scenario	Average Stack Height (m)	Average Exit Velocity (m s^{-1})	Average Annual Hg Dep (ug m^{-2})	Maximum Annual Hg Dep (ug m^{-2})
Base (Actual Stack Parameters)	23.2	6.1	3.6	49.5
Stack Height x 2	46.4	6.1	1.5	6.1
Stack Height x 3	69.6	6.1	0.7	2.3
Stack Height x 4	92.8	6.1	0.4	1.1
Exit Velocity x 2	23.2	12.2	1.4	12.6
Exit Velocity x 3	23.2	18.3	0.6	2.3
Exit Velocity x 4	23.2	24.4	0.4	1.2
Stack Height & Exit Velocity x 2	46.4	12.2	0.6	2.3
Stack Height & Exit Velocity x 3	69.6	18.3	0.2	0.6
Stack Height & Exit Velocity x 4	92.8	24.4	0.1	0.3

Figure 6-1. AERMOD Annual Average Simulated Mercury Deposition (μg m^{-2}) for the Chaparral Steel Facility for a Variety of Alternative Stack Parameters.



** Average over 3km sq. area surrounding facility.*

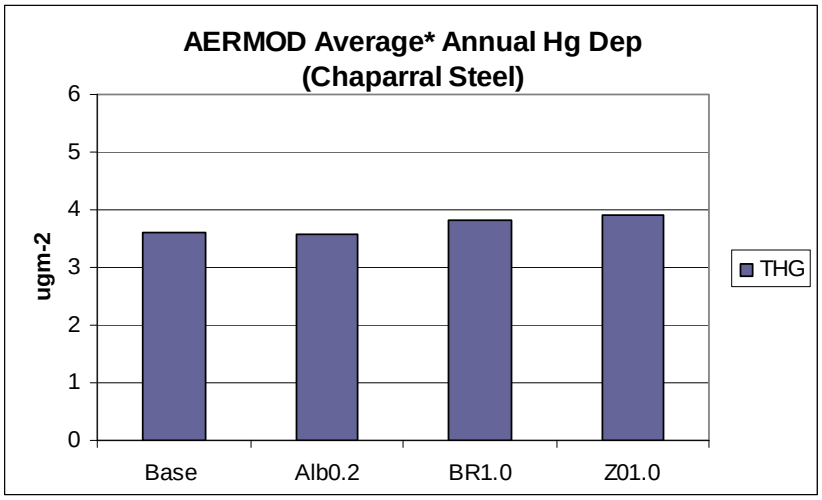
The simulated deposition is very sensitive to the stack parameters. Increasing stack height and exit velocity, both separately and in combination, reduces the amount of deposition in the receptor area. For several of the scenarios (including Stack Height x 3, Exit Velocity x 3, and Stack Height & Exit Velocity x 4) the simulation results for Chaparral Steel are comparable to the results for the Dominion Chesterfield Power Station. The last scenario, in which both the stack heights and the exit velocities are multiplied by a factor of 4, results in comparable stack parameters but lower deposition amounts compared to the Dominion facility. This may be due in part to the lower emissions, but also could be influenced by other factors (such as number of stacks, emissions rates, temperatures and speciation), that are not examined here.

We also examined the sensitivity of the AERMOD results to the surface characteristics. In another series of simulations, a uniform albedo, Bowen ratio, and roughness length were applied in preparing the meteorological input files for this same Chaparral Steel facility. The albedo specifies the reflectivity of the surface, the Bowen ratio is an indicator of surface moisture, and the roughness length is related to the height of obstacles that might affect wind flow. The values applied are 0.2 for albedo, 1.0 for the Bowen ratio, and 1.0 for roughness length. These values are within the range of typical values for a variety of land-use types and seasons. In the base AERMOD run, these parameters were specified for the four land-use sectors that surround the facility (comprised mostly of mixed forest, pasture, wooded wetland, evergreen forest, and residential land) and for each season. The albedo values range from 0.13 to 0.17 with an average value of 0.15. The Bowen ratios range from 0.31 to 0.86 and average to 0.65. The roughness lengths range from 0.56 to 1.2, with an average of 0.93. Both AERMET and AERMOD were rerun for this test. The results are presented in Table 6-3 and Figure 6-2 (annual average only).

Table 6-3. AERMOD Annual Average and Maximum Simulated Mercury Deposition (μg m^{-2}) for the Chaparral Steel Facility Assuming Uniform Surface Characteristics.

Scenario	Average Annual Hg Dep (ug m^{-2})	Maximum Annual Hg Dep (ug m^{-2})
Base (Variable Surface Characteristics)	3.6	49.5
Uniform Albedo = 0.2	3.6	49.1
Uniform Bowen Ratio = 1.0	3.8	51.2
Uniform Roughness Length = 1.0	3.9	52.6

Figure 6-2. AERMOD Annual Average Simulated Mercury Deposition (μg m^{-2}) for the Chaparral Steel Facility Assuming Uniform Surface Characteristics.



** Average over 3km sq. area surrounding facility.*

The AERMOD results are not very sensitive to variability in the surface characteristics for the ranges examined here.

Finally, the use of alternative deposition parameters was examined. Small changes in the air and water diffusivity values for HG0 and HG2 resulted in very slight changes in simulated deposition. Use of an alternative particle size distribution for HGP, however, did have an effect on the simulated deposition of particulate-bound mercury. Wesely et al. (2002) gives several alternatives to specifying the fine particle fraction and mass mean diameter for HGP. In the base run, the recommended values, which are 0.8 micron for the fine particle fraction and 0.4 micron for the mean particle diameter, were used. There is little variation among the alternative estimates of fine particle fraction, and, therefore, the use of different values for this parameter was not tested. An alternative value for the diameter is given as 0.8 micron and since this is quite different from the recommended value, a sensitivity test was conducted using this alternate value. This test was also of interest because of the importance of HGP deposition in the AERMOD results. The results are presented in Table 6-4.

Table 6-4. AERMOD Annual Average and Maximum Simulated Particulate Mercury Deposition (μg m^{-2}) for the Chaparral Steel Facility for an Alternate Particle Size Parameter.

Scenario	Average Annual Hg Dep (ug m^{-2})	Maximum Annual Hg Dep (ug m^{-2})
Base (Particle Diameter = 0.4mm)	3.6	49.5
Particle Diameter = 0.8 mm	4.1	55.4

The AERMOD results are sensitive to the specification of particle diameter and deposition increases with particle size.

From this analysis it is concluded that the AERMOD-based high deposition for Chaparral Steel is influenced by the stack parameters for that facility. Increasing stack height and exit velocity, both separately and in combination, reduces the amount of deposition in the receptor area. For several of the sensitivity scenarios, the simulation results for Chaparral Steel are comparable to the results for the Dominion Chesterfield Power Station. Since both sites use the same meteorological data and have similar emissions (Chesterfield actually has greater emissions), the differences in deposition are likely attributable to the differences in stack parameters.

More generally, it was also found that the AERMOD results are not very sensitive to variability in the surface characteristics for the ranges examined here and that they are sensitive to the specification of particle size.

6.3. Base- and Future-year Modeling Results

The base-year emissions for the top 15 sources and the corresponding base-year simulation results for all facilities are listed in Table 6-5. The table gives total modeled deposition which includes both wet and dry deposition from elemental (HG0), reactive gaseous (HG2) and particulate mercury (HGP). Note that the average deposition is averaged over a three square kilometer area surrounding the source and the maximum is at one of the defined receptor cells in this area.

Table 6-5. AERMOD Annual Average and Maximum Simulated Mercury Deposition (μg m^{-2}) for the Base Year (2001/2002).

Facility Name (Abbreviation)	Rank	2002 Total Hg (lbs/yr)	Average Annual Hg Dep (ug m^{-2})	Maximum Annual Hg Dep (ug m^{-2})
Dominion - Chesterfield Power Station (CHST)	1	358.83	0.71	1.79
Chaparral Steel (CHAP)	2	292.30	3.61	49.46
Dominion—Bremo (BRMO)	3	167.73	0.51	1.07
American Electric Power- Clinch River (CLCH)	4	159.21	0.02	0.09
Dominion - Chesapeake Energy Center (CHSP)	5	157.38	0.42	1.47
Potomac River Generating Station (POTO)	6	118.26	0.31	1.37
Dominion - Yorktown Power Station (YORK)	7	107.64	0.08	0.29
Jewel Coke Company LLP (JEWL)	8	105.62	0.71	5.02
Dominion-Possum Point Power Station (POSS)	9	100.19	0.51	1.72
Stone Container Enterprises (Smurfit) (SMUR)	10	77.76	0.18	0.53
Stone Container Corporation –Hopewell (HOPE)	11	69.69	0.34	0.89
American Electric Power (Glen Lyn) (GLEN)	12	65.14	0.03	0.11
Intermet Foundry Archer Creek (ARCH)	13	65.01	1.12	10.07
RES dba Steel Dynamics (RES)	14	60.80	0.56	2.98
Spruance Genco LLC (SPRU)	15	55.50	0.39	1.10

Both the base-year emissions and the AERMOD-derived deposition values (annual average only) are displayed in Figure 6-3. The relative contributions of HG0, HG2 and HGP are shown in the bar charts.

Figure 6-3a. 2002 Baseline Emissions for the Top 15 Virginia Facilities.

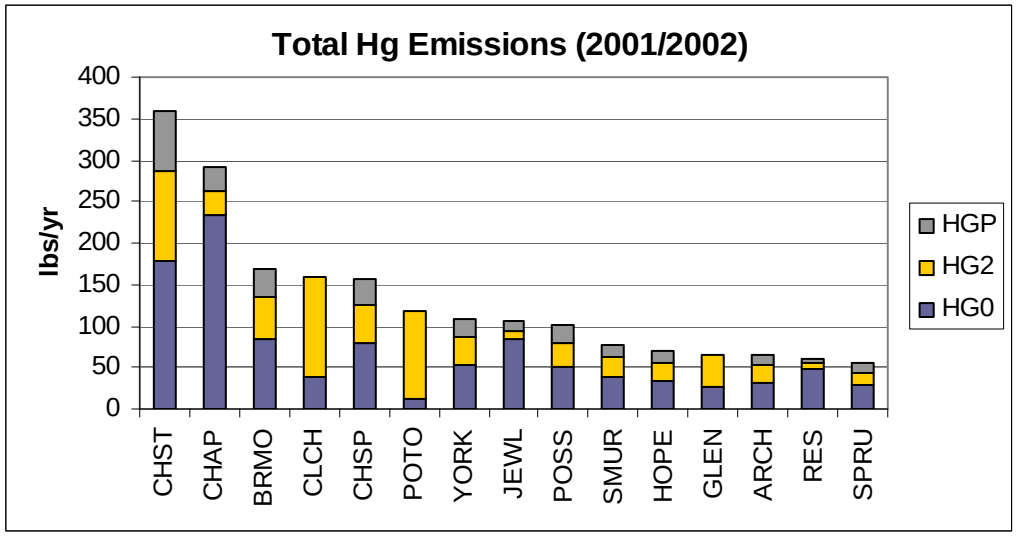
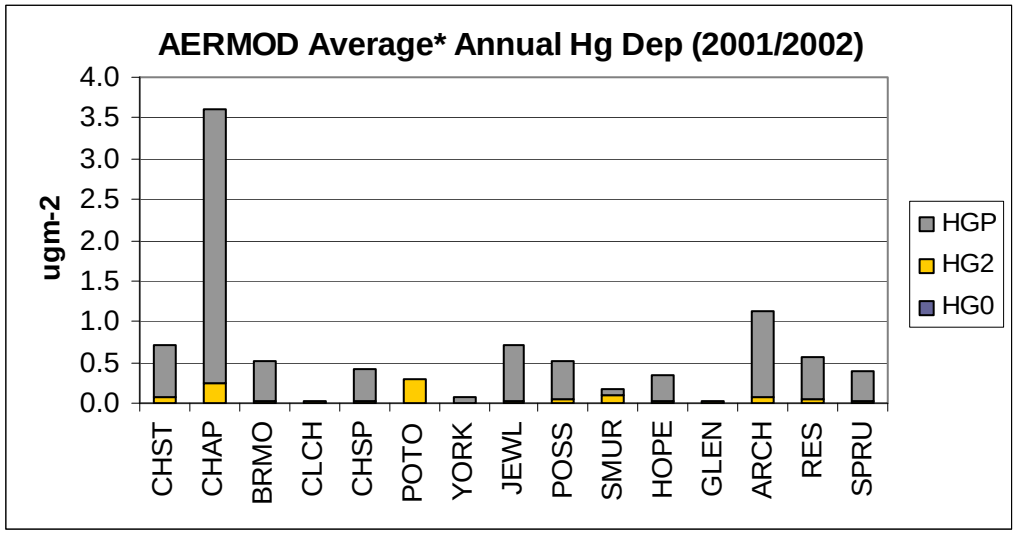


Figure 6-3b. AERMOD Annual Average Simulated Mercury Deposition (μg m^{-2}) for the Base Year (2001/2002) for the Top 15 Virginia Facilities.



** Average over 3-km sq. area surrounding facility.*

For reference, the base- and future-year emissions for the top 15 sources are listed in Table 4-4 (presented earlier). The corresponding future-year AERMOD simulation results for all facilities are listed in Tables 6-6a through c. The tables give total simulated deposition which includes both wet and dry deposition from HG0, HG2, and HGP.

Table 6-6a. AERMOD Annual Average and Maximum Simulated Mercury Deposition (μg/m^2) for 2010.

Facility Name (Abbreviation)	Rank	2010 Total Hg (lbs/yr)	Average Annual Hg Dep (ug m^{-2})	Maximum Annual Hg Dep (ug m^{-2})
Dominion - Chesterfield Power Station (CHST)	1	183.15	0.62	1.69
Chaparral Steel (CHAP)	2	100.50	1.25	17.03
Dominion—Bremo (BRMO)	3	172.74	0.53	1.11
American Electric Power- Clinch River (CLCH)	4	80.00	0.01	0.04
Dominion - Chesapeake Energy Center (CHSP)	5	81.05	0.22	0.78
Potomac River Generating Station (POTO)	6	72.37	0.19	0.83
Dominion - Yorktown Power Station (YORK)	7	105.85	0.08	0.30
Jewel Coke Company LLP (JEWL)	8	106.91	0.72	5.07
Dominion-Possum Point Power Station (POSS)	9	1.99	0.00	0.01
Stone Container Enterprises (Smurfit) (SMUR)	10	80.57	0.19	0.54
Stone Container Corporation –Hopewell (HOPE)	11	9.66	0.04	0.10
American Electric Power (Glen Lyn) (GLEN)	12	67.09	0.03	0.12
Intermet Foundry Archer Creek (ARCH)	13	21.77	0.38	3.53
RES dba Steel Dynamics (RES)	14	21.57	0.20	1.06
Spruance Genco LLC (SPRU)	15	25.95	0.18	0.51

Table 6-6b. AERMOD Annual Average and Maximum Simulated Mercury Deposition ($\mu g/m^2$) for 2015.

Facility Name (Abbreviation)	Rank	2015 Total Hg (lbs/yr)	Average Annual Hg Dep (ug m^{-2})	Maximum Annual Hg Dep (ug m^{-2})
Dominion - Chesterfield Power Station (CHST)	1	151.47	0.54	1.46
Chaparral Steel (CHAP)	2	50.50	0.63	8.55
Dominion—Bremo (BRMO)	3	189.88	0.58	1.22
American Electric Power- Clinch River (CLCH)	4	81.00	0.01	0.04
Dominion - Chesapeake Energy Center (CHSP)	5	89.09	0.24	0.85
Potomac River Generating Station (POTO)	6	72.37	0.19	0.83
Dominion - Yorktown Power Station (YORK)	7	73.46	0.06	0.21
Jewel Coke Company LLP (JEWL)	8	106.91	0.72	5.07
Dominion-Possum Point Power Station (POSS)	9	1.49	0.00	0.01
Stone Container Enterprises (Smurfit) (SMUR)	10	82.36	0.19	0.56
Stone Container Corporation –Hopewell (HOPE)	11	9.79	0.04	0.10
American Electric Power (Glen Lyn) (GLEN)	12	73.74	0.03	0.13
Intermet Foundry Archer Creek (ARCH)	13	12.87	0.23	2.21
RES dba Steel Dynamics (RES)	14	12.65	0.12	0.62
Spruance Genco LLC (SPRU)	15	28.53	0.20	0.56

Table 6-6c. AERMOD Annual Average and Maximum Simulated Mercury Deposition ($\mu g/m^2$) for 2018.

Facility Name (Abbreviation)	Rank	2018 Total Hg (lbs/yr)	Average Annual Hg Dep (ug m^{-2})	Maximum Annual Hg Dep (ug m^{-2})
Dominion - Chesterfield Power Station (CHST)	1	159.39	0.67	1.66
Chaparral Steel (CHAP)	2	50.50	0.63	8.55
Dominion—Bremo (BRMO)	3	200.38	0.61	1.28
American Electric Power- Clinch River (CLCH)	4	81.00	0.01	0.04
Dominion - Chesapeake Energy Center (CHSP)	5	94.01	0.26	0.90
Potomac River Generating Station (POTO)	6	29.77	0.08	0.34
Dominion - Yorktown Power Station (YORK)	7	31.19	0.03	0.12
Jewel Coke Company LLP (JEWL)	8	106.91	0.72	5.07
Dominion-Possum Point Power Station (POSS)	9	1.25	0.00	0.01
Stone Container Enterprises (Smurfit) (SMUR)	10	83.41	0.20	0.56
Stone Container Corporation –Hopewell (HOPE)	11	9.87	0.04	0.10

Facility Name (Abbreviation)	Rank	2018 Total Hg (lbs/yr)	Average Annual Hg Dep (ug m^{-2})	Maximum Annual Hg Dep (ug m^{-2})
American Electric Power (Glen Lyn) (GLEN)	12	77.82	0.03	0.13
Intermet Foundry Archer Creek (ARCH)	13	13.89	0.25	2.38
RES dba Steel Dynamics (RES)	14	13.65	0.13	0.67
Spruance Genco LLC (SPRU)	15	30.11	0.21	0.60

Finally, the base- and future-year emissions and corresponding AERMOD results (annual average only) by facility are presented in Figures 6-4 through 6-18. Each figure has two parts, one for emissions and one for annual average deposition over the receptor area. Emissions and deposition are displayed as a stacked bar chart that shows the contributions from HG0, HG2 and HGP. The total deposition amount (which includes wet and dry deposition) is given for each simulation year in units of micrograms per square meter (μg m^{-2}). Note that the scales differ among the facilities, appropriate to the emissions and deposition amounts. Maximum deposition (not shown) responds to the emissions changes in a qualitatively similar way.

Figure 6-4. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Dominion—Chesterfield Power Station.

(a) (b)

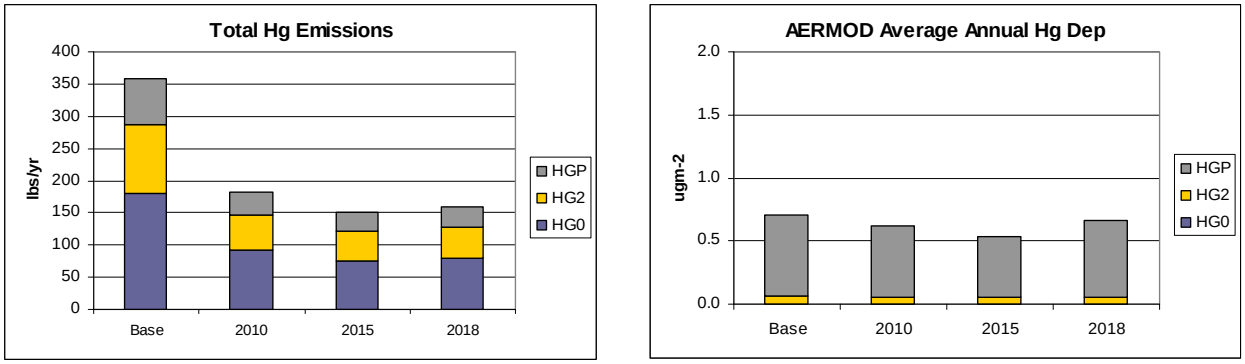


Figure 6-5. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Chaparral Steel.

(a) (b)

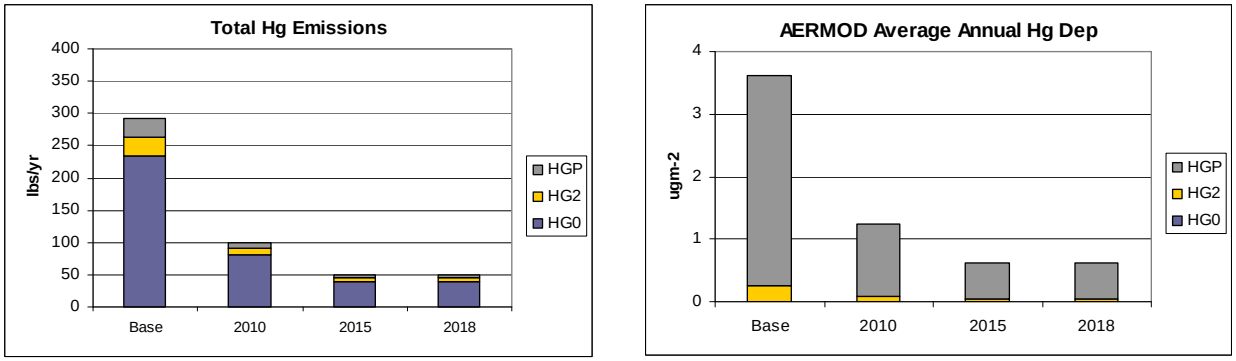


Figure 6-6. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Dominion—Bremo.

(a) (b)

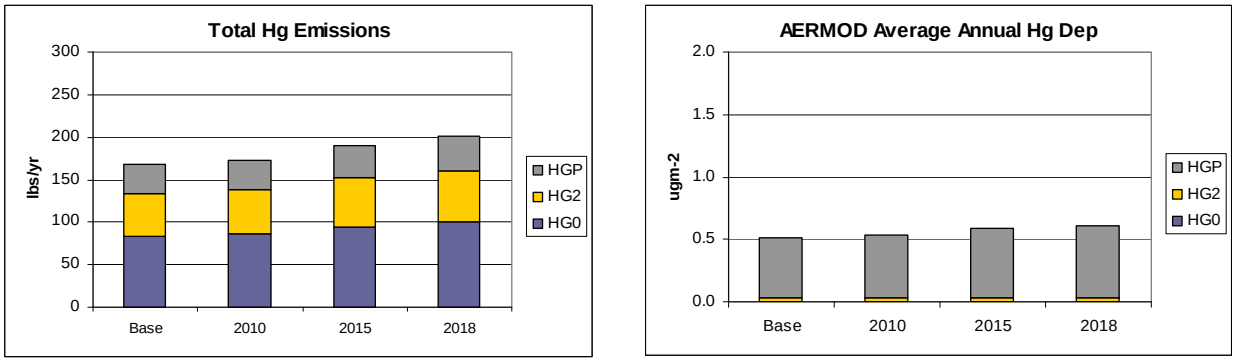


Figure 6-7. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: American Electric Power—Clinch River.

(a) (b)

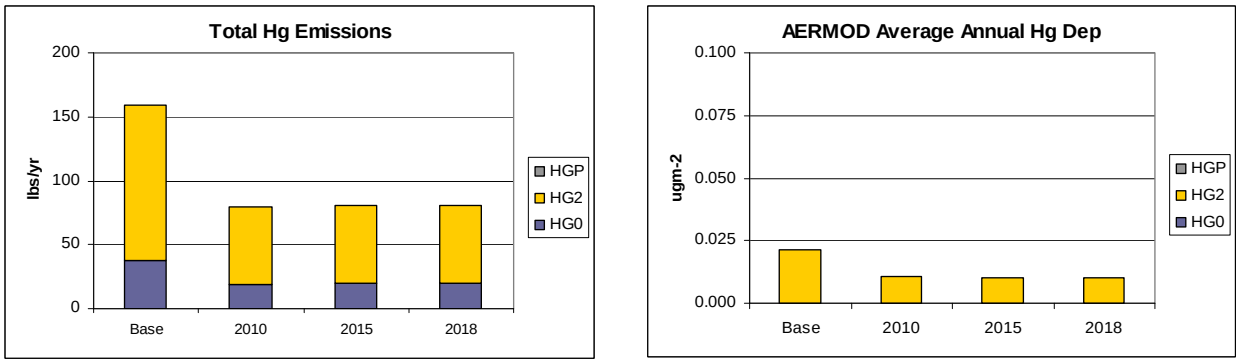


Figure 6-8. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Dominion—Chesapeake Energy Center.

(a) (b)

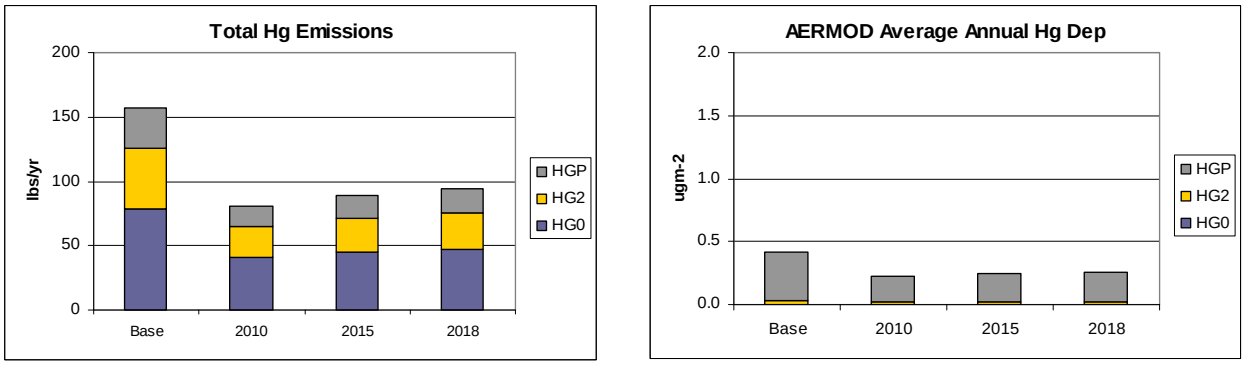


Figure 6-9. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Potomac River Generating Station.

(a) (b)

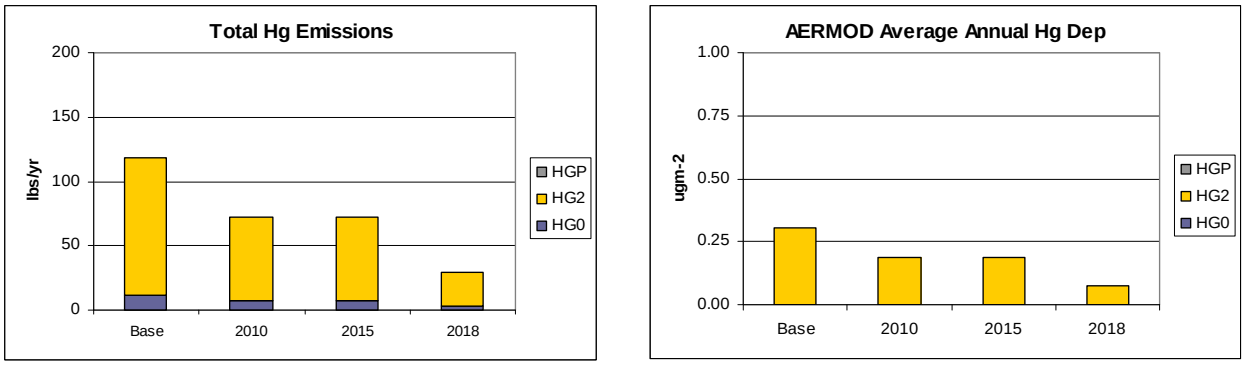


Figure 6-10. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Dominion—Yorktown Power Station.

(a) (b)

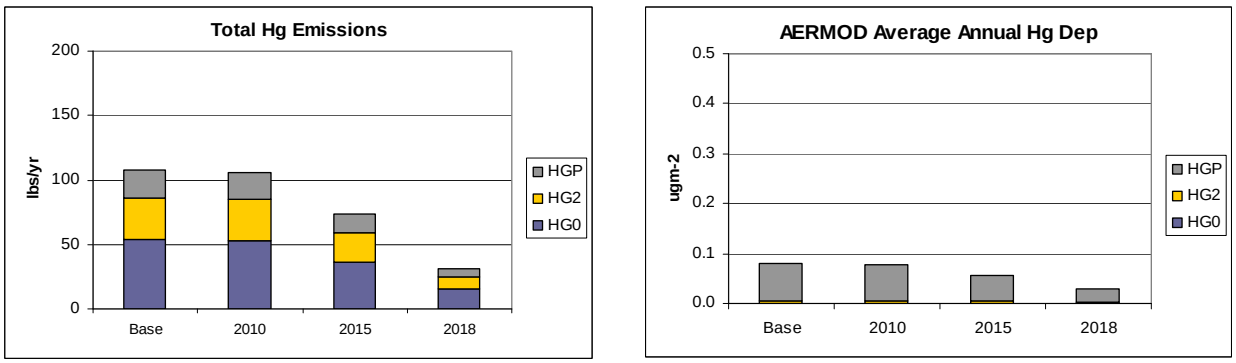


Figure 6-11. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Jewell Coke Company.

(a) (b)

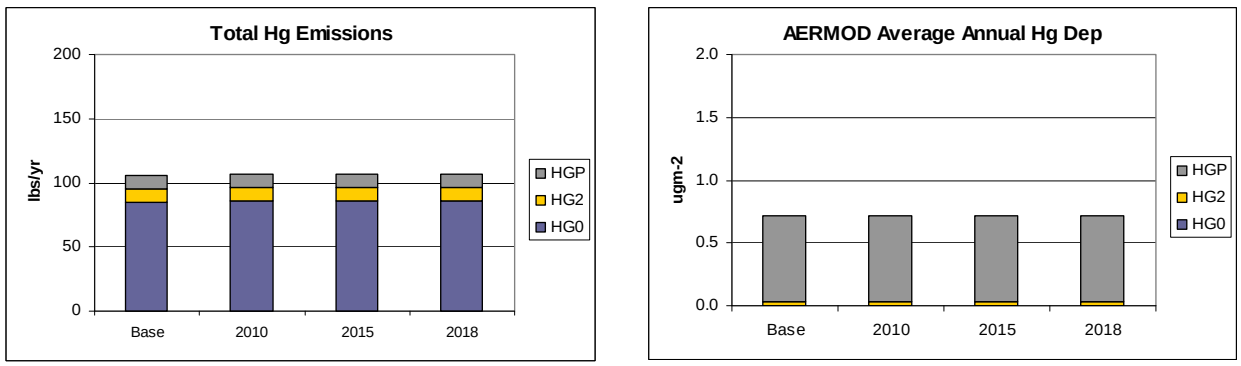


Figure 6-12. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Dominion—Possum Point Power Station.

(a) (b)

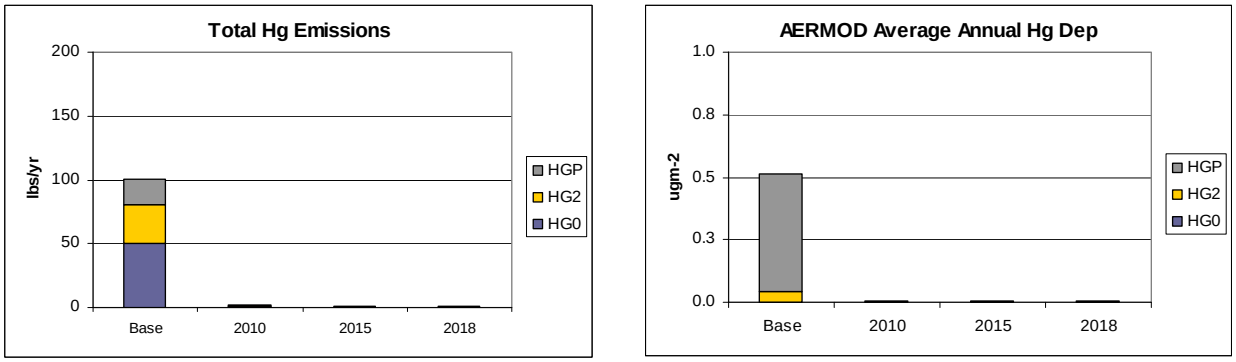


Figure 6-13. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Stone Container Enterprises (Smurfit).

(a) (b)

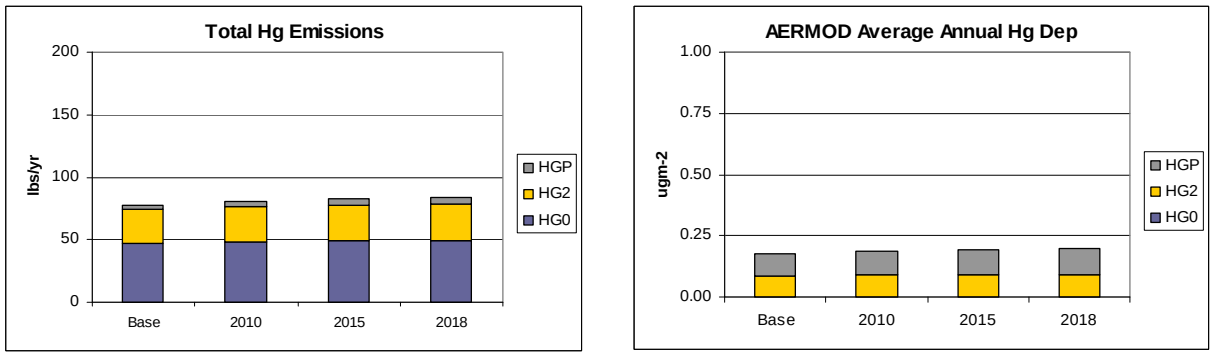


Figure 6-14. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Stone Container Corporation—Hopewell.

(a) (b)

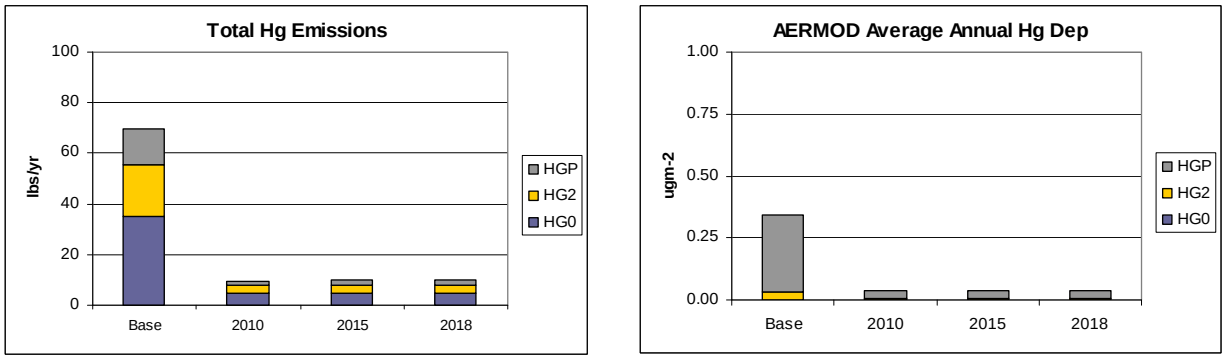
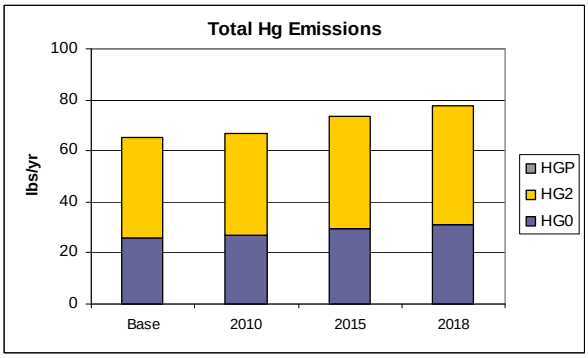


Figure 6-15. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: American Electric Power—Glen Lyn.

(a)



(b)

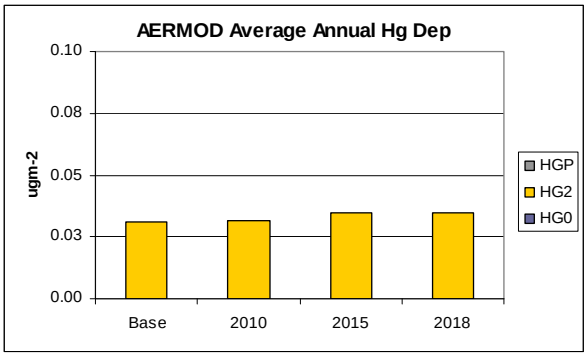
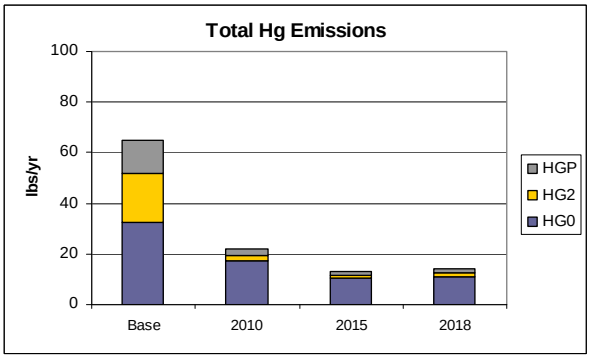


Figure 6-16. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Intermet Foundry Archer Creek.

(a)



(b)

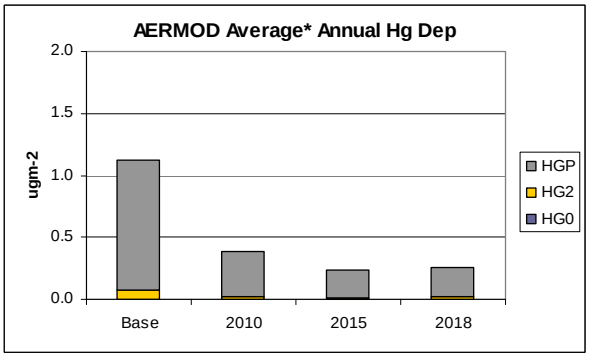
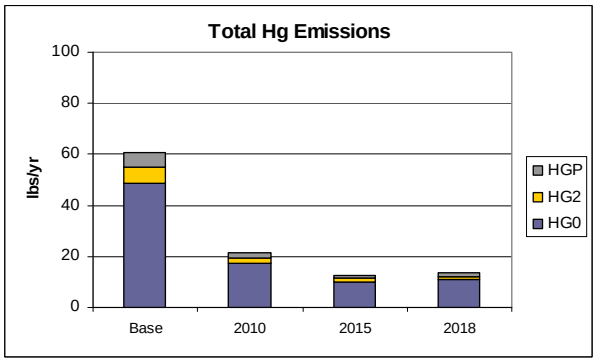


Figure 6-17. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: RES dba Steel Dynamics.

(a)



(b)

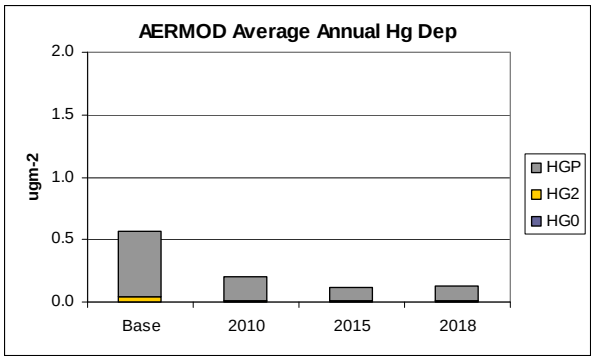
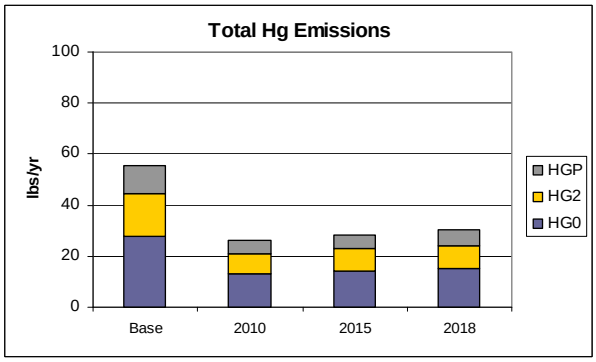
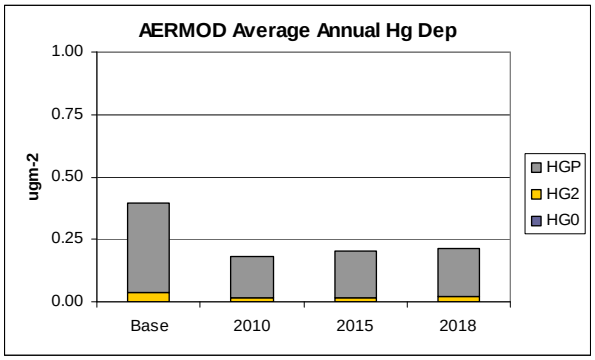


Figure 6-18. AERMOD Emissions (a) and Annual Average Simulated Mercury Deposition (μg m^{-2}) (b) for the Base Year (2001/2002), 2010, 2015 and 2018: Spruance Genco LLC.

(a)



(b)



The results for all facilities cannot be compared directly since the scales vary among the facilities.

For all facilities, the changes in simulated deposition track the changes in emissions quite closely, especially for HG2 and HGP. Since deposition of HG0 is small, changes in the HG0 emissions do not noticeably affect the deposition.

The largest reductions in both emissions and deposition tend to occur between the base year and 2010, but this varies by facility. Emission increases are associated with some of the facilities in 2015 and 2018 and these result in local deposition increases for the future years.

The growth and control assumptions were provided for each facility by the owner/operators and these vary by facility. A few examples follow. The changes in emissions for the Dominion Chesterfield Power Station (Figure 6-4) represent the effects of a combination of controls (scrubbers, flue gas desulfurization (FGD), and fabric filters (FF)) on the four units that comprise the power station. The emission reductions are offset by growth (apparent between 2015 and 2020). The emissions reductions for Chaparral Steel (Figure 6-5) are based on clean scrap requirements from the Electric Arc Furnace Area Source Maximum Available Control Technology (MACT) (40 CFR 63) and the permit limits for the facility. Emissions from the Dominion Bremo plant (Figure 6-6) are projected to increase due to growth and no planned controls.[3] Non-specific planned controls account for the reductions for the AEP Clinch River facility (Figure 6-7).

Most of the local mercury deposition is in the form of HGP, with some contribution from HG2. A key conclusion of this analysis is that emissions reductions of HG2 and HGP (especially HGP) at the top 15 facilities will reduce mercury deposition in the vicinity of the facilities. Additional analysis of these results is presented in Section 7.

[3] Note, however, that the Dominion Bremo plant is expected to eventually be converted to use natural gas fuel.

7. Summary Mercury Deposition Assessment

The mercury deposition modeling results are summarized in this section. Given the uncertainties associated with the modeling, the relative changes in both emissions and deposition are emphasized in this summary. Tables 7-1 and 7-2 summarize the emissions and mercury deposition changes simulated by CMAQ. The areas included in this summary are the CMAQ modeling domains, Virginia and the major water basins.

Table 7-1 displays the base- and future-year emissions for the 36-km grid, the 12-km grid, and Virginia. Emissions totals are given in Table 7-1a and percent reductions are given in Table 7-1b. Emissions are provided for EGU sources, non-EGU sources, non-point (area) sources, and all sources (total).

Table 7-1a. Mercury Emissions Totals (tons/year) for the CMAQ Modeling Domains and the Commonwealth of Virginia.

Region	EGU				Non-EGU				Non-Point				Total Emissions			
	2001/ 2002 *(tpy)*	2010 *(tpy)*	2015 *(tpy)*	2018 *(tpy)*	2001/ 2002 *(tpy)*	2010 *(tpy)*	2015 *(tpy)*	2018 *(tpy)*	2001/ 2002 *(tpy)*	2010 *(tpy)*	2015 *(tpy)*	2018 *(tpy)*	2001/ 2002 *(tpy)*	2010 *(tpy)*	2015 *(tpy)*	2018 *(tpy)*
36-km domain	54.8	32.1	28.7	25.6	53.4	38.6	41.5	44.8	7.9	6.9	7.3	7.8	116.1	77.5	77.6	78.1
12-km domain	22.6	9.5	8.0	7.3	15.5	10.4	11.0	11.6	2.2	2.1	2.2	2.2	40.3	22.0	21.1	21.2
Virginia	0.69	0.43	0.42	0.39	0.49	0.33	0.30	0.31	0.19	0.14	0.15	0.15	1.37	0.90	0.87	0.85

Notes:

(1) Emissions included in the 36-km and 12-km domains are for the U.S. only

(2) Point Source: 2002 emissions for Virginia are based on VDEQ 2002/EPA NEI 2002 Version 3 and the emissions for other state are based on the EPA 2002 NEI Version 3; 2010, 2015 and 2018 emissions for State of Virginia are based on VDEQ data, the emissions for other state are based on the EPA Clear Sky data

(3) Non-Point Source: 2002 Emissions are based on EPA 2002 NEI Version 3; 2010, 2015 and 2018 Emissions are based on the EPA Clear Skies data

Table 7-1b. Percent Change in Mercury Emissions Totals Compared to 2001/2002 for the CMAQ Modeling Domains and the Commonwealth of Virginia.

Region	EGU			Non-EGU			Non-Point			Total Emissions		
	2010 (%)	2015 (%)	2018 (%)	2010 (%)	2015 (%)	2018 (%)	2010 (%)	2015 (%)	2018 (%)	2010 (%)	2015 (%)	2018 (%)
36-km domain	-41.4	-47.6	-53.2	-27.7	-22.3	-16.1	-12.6	-7.6	-1.3	-33.2	-33.2	-32.7
12-km domain	-57.9	-64.6	-67.7	-32.9	-29.0	-25.2	-4.5	0	0	-45.4	-47.6	-47.4
Virginia	-37.7	-39.1	-43.5	-32.6	-38.8	-36.7	-26.3	-21.1	-21.1	-34.3	-36.5	-37.9

The majority of the emissions reductions are expected by 2010. These reflect expected reductions due to the Phase I CAIR controls and the original CAMR control provisions for the EGU sector and for those non-EGU units that are subject to CAIR. For the U.S. portion of the 36-km domain, compared to 2002, mercury emissions from EGUs are expected to drop by 41 percent in 2010 and by over 50 percent by 2018. For non-EGUs across the U.S., the mercury emissions are expected to be reduced by 28 percent in 2010, but increase slightly in 2015 and 2018 due to expected growth in the industrial sector. The non-point sector, which includes such

sources as residential/industrial fuel combustion, fluorescent lamp breakage, health services, agricultural production, waste disposal, landfills, and other combustion sources, are expected to decrease slightly (13.5 percent) in 2010, but increase slightly in 2015 and 2018 due to expected increases in population. Given the expected changes in the various sectors, total mercury emissions across the U.S. are expected to decrease by about 33 percent in 2010 and beyond compared to 2002. For the 12-km resolution domain, the mercury emissions from EGUs are expected to drop by a larger percentage in 2010 (~58 percent) due to the proximity of a large number of EGU sources in the Ohio River valley. In 2015 and 2018, further reductions are expected from the EGU sector. Similar to what is expected across the U.S., the non-EGU sector shows a substantial reduction in mercury emissions in 2010 (~33 percent), but a slight increase in 2015 and 2018, reflecting expected industrial growth. The total mercury emissions in the 12-km grid show about a 46 percent reduction in 2010 and beyond, compared to 2002. For Virginia, mercury emissions from EGUs are expected to be reduced by ~40 percent by 2010, with additional reductions in 2015 and 2018. For the non-EGU sector in Virginia, mercury emissions are expected to be reduced by about 32 percent in 2010, decrease further in 2015, but slightly increase in 2018. For the non-point sector in Virginia, mercury emissions are expected to decrease by about 24 percent in 2010 and basically stay the same beyond that. For Virginia, total mercury emissions are expected to decrease by about 34 percent in 2010, and slight decrease in 2015 and 2018.

Table 7-2 summarizes CMAQ-simulated base and future-year mercury deposition for Virginia and each of the major river basins. Deposition amounts (per unit area) are given in Table 7-2a and percent reductions are given in Table 7-2b. The values for Virginia and each river basin are calculated separately based on the simulated deposition within each region and the area encompassed by the region.

Table 7-2a. Mercury Deposition Totals (g km^{-2}) for Virginia and the Ten Major River Basins.

Region	2001/2002 (g km^{-2})	2010 (g km^{-2})	2015 (g km^{-2})	2018 (g km^{-2})
Virginia	22.7	18.6	18.2	18.1
Chesapeake Bay	15.0	12.8	12.6	12.5
Chowan River Basin & Dismal Swamp	22.7	18.5	18.0	18.0
James River Basin	22.5	18.9	18.5	18.4
New River Basin	24.4	21.4	21.0	20.9
Potomac River Basin	27.1	19.7	19.3	18.9
Rappahannock River Basin	21.9	17.6	17.2	17.1
Roanoke River Basin	22.3	18.1	17.5	17.4
Shenandoah River Basin	23.9	19.1	18.7	18.6
Tennessee & Big Sandy River Basins	25.1	21.2	20.7	20.4
York River Basin	22.8	18.7	18.3	18.1

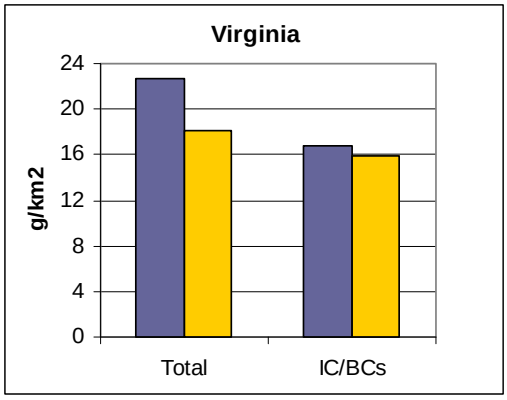
Table 7-2b. Percent Change in Mercury Deposition Totals (g km^{-2}) Compared to the 2001/2002 Base Scenario for Virginia and the Ten Major River Basins.

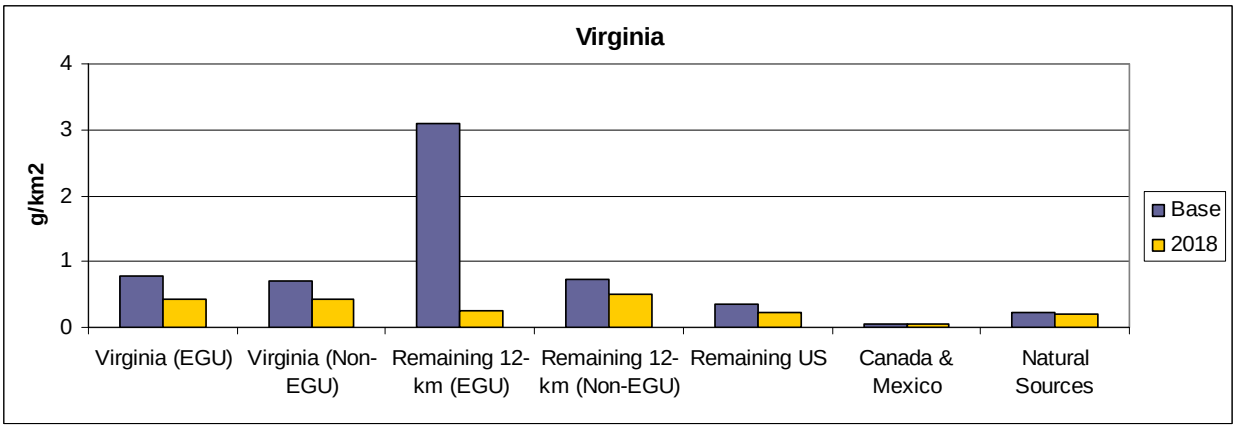
Region	2010 (%)	2015 (%)	2018 (%)
Virginia	-18.0	-19.9	-20.5
Chesapeake Bay	-14.8	-16.4	-16.7
Chowan River Basin & Dismal Swamp	-18.6	-20.6	-20.8
James River Basin	-16.3	-17.9	-18.2
New River Basin	-12.4	-13.9	-14.4
Potomac River Basin	-27.2	-28.8	-30.1
Rappahannock River Basin	-19.8	-21.6	-22.0
Roanoke River Basin	-18.5	-21.3	-21.7
Shenandoah River Basin	-20.0	-21.8	-22.0
Tennessee & Big Sandy River Basins	-15.7	-17.6	-18.7
York River Basin	-18.0	-19.9	-20.5

On a percentage basis, the greatest amount of reduction is simulated for the Potomac River Basin and the least amount is simulated for the New River Basin. In keeping with the emissions changes, the largest reductions in deposition occur between the base year and 2010.

In Section 5, the CMAQ/PPTM results showed the relative contribution from each of the tagged source regions and source categories to mercury deposition within each river basin for both 2001/2002 and 2018. Figure 7-1 presents this same information for the entire state. Again this shows that global background (IC/BC tag) is a primary contributor to simulated mercury deposition. The second largest contribution is from EGU sources in the surrounding states. This is followed by EGU sources in Virginia, non-EGU sources in Virginia, non-EGU sources in the surrounding states, sources in the remainder of the U.S., and natural sources.

Figure 7-1. CMAQ/PPTM 12-km Mercury Tagging Results for Virginia for 2001/2002 and 2018.





The contributions from all sources are lower for 2018. Although the IC/BC and natural emissions inputs are the same for both years, their contributions are lower for 2018 due to lower regional-scale ozone concentrations in the future year. Of primary interest is for this analysis is the change in contribution from the non-background/anthropogenic sources.

Table 7-3 summarizes the percent reduction for each tagged source region or category for 2018, relative to the contribution for that same category for the base scenario.

Table 7-3. Percent Change in Mercury Deposition Totals and Contributions (g km^{-2}) for 2018 Compared to the 2001/2002 Base Scenario, for Virginia and the Ten Major River Basins.

Region	Total (%)	Virginia (EGU) (%)	Virginia (Non-EGU) (%)	Remaining 12-km (EGU) (%)	Remaining 12-km (Non-EGU) (%)	Remaining US (%)	Canada & Mexico (%)	IC/BCs (%)	Natural Sources (%)
Virginia	-20.4	-43.3	-38.1	-91.6	-29.7	-37.0	-4.0	-5.0	-15.1
Chesapeake Bay	-16.7	-55.4	-9.6	-88.2	-12.4	-29.7	-3.6	-4.4	-11.0
Chowan River Basin & Dismal Swamp	-20.8	-46.2	-50.9	-89.5	-52.9	-33.8	-3.5	-4.8	-14.0
James River Basin	-18.2	-30.7	-37.9	-91.2	-27.2	-34.8	-4.3	-4.9	-15.2
New River Basin	-14.4	-5.0	-26.7	-89.9	-39.9	-41.6	-5.3	-5.0	-16.3
Potomac River Basin	-30.1	-68.6	-37.0	-93.0	-4.0	-28.3	-2.8	-4.6	-14.6
Rappahannock River Basin	-22.0	-48.4	-37.5	-92.3	-8.1	-30.5	-2.9	-4.6	-14.6
Roanoke River Basin	-21.7	-12.9	-44.1	-90.6	-24.8	-38.5	-5.8	-5.4	-16.0
Shenandoah River Basin	-22.0	-38.2	-56.3	-93.1	-29.8	-33.0	-3.6	-4.4	-16.0
Tennessee & Big Sandy River Basins	-18.7	-50.5	-13.9	-91.0	-53.8	-49.1	-5.8	-5.8	-16.5
York River Basin	-20.5	-50.4	-24.7	-91.5	-7.1	-30.7	-3.1	-4.8	-14.5

These results show that the 20.4 percent reduction in mercury deposition for Virginia is associated with a 43.3 percent reduction in deposition from EGU sources in the state, a 38.1 percent reduction in deposition from non-EGU sources in the state, a 91.6 percent reduction in deposition from EGU sources in the surrounding states, etc.

Since each of the source regions and categories contribute different amounts to the total mercury deposition, it is also of interest to attribute the overall change in total deposition to the change in contribution from each tagged region or category. This information is summarized in Table 7-4. Since the emissions changes are similar for all three future-years, it is expected that the attribution of the changes for 2018 can be applied for all years.

Table 7-4. Portion of Overall Percent Reduction in Mercury Deposition for 2018 Attributable to Each Tagged Source Region and Category, for Virginia and the Ten Major River Basins.

Region	Virginia (EGU) (%)	Virginia (Non-EGU) (%)	Remaining 12-km (EGU) (%)	Remaining 12-km (Non-EGU) (%)	Remaining US (%)	Canada & Mexico (%)	IC/BCs (%)	Natural Sources (%)
Virginia	7.2	5.7	61.0	4.6	2.8	0.0	18.0	0.8
Chesapeake Bay	7.4	1.4	62.7	3.1	2.6	0.1	20.0	0.7
Chowan River Basin & Dismal Swamp	9.2	13.9	45.1	10.4	2.3	0.0	16.6	0.7
James River Basin	8.4	8.5	54.9	3.5	2.7	0.1	20.4	0.8
New River Basin	0.6	2.4	55.6	5.0	5.4	0.1	28.9	1.2
Potomac River Basin	14.8	4.2	68.8	0.8	1.1	0.0	9.0	0.4
Rappahannock River Basin	5.1	3.3	72.1	1.2	1.9	0.0	15.1	0.7
Roanoke River Basin	0.6	5.2	68.7	2.5	2.8	0.0	18.8	0.8
Shenandoah River Basin	0.9	3.4	73.6	3.7	2.0	0.0	15.2	0.7
Tennessee & Big Sandy River Basins	12.2	1.2	44.3	9.9	6.4	0.1	23.8	1.0
York River Basin	11.1	5.1	62.3	1.0	2.0	0.0	16.6	0.7

Rather than summarizing the percent change in deposition for each individual tag, Table 7-4 gives the percent change in overall total deposition that is attributed to each tag. Based on this method of summarizing the reduction in mercury deposition, 7.2 percent of the overall simulated mercury reduction for Virginia is attributable to reductions in the emissions from EGU sources in the state, 5.7 percent is attributable to reductions in the emissions from non-EGU sources in the state, 61 percent is attributable to reductions in emissions from EGU sources in the surrounding states, etc. The results are different for each of the major river basins, but in all cases reductions in the emissions from EGU sources in the surrounding states are important to the overall reduction in mercury deposition.

In this study, AERMOD was used to examine the effects of emissions changes on local deposition. Tables 7-5 and 7-6 summarize these results in terms of the changes in emissions and simulated deposition amounts, on average, for the fifteen facilities in Virginia with the most mercury emissions in 2002. In addition, the average over the EGU and non-EGU facilities was also examined. Eight of the top fifteen facilities are EGUs and seven are in the non-EGU category.

Table 7-5 displays the average base and future emissions for the AERMOD sources (refer to Table 4-4 for more detail). Average emissions by category are given in Table 7-5a and percent reductions are given in Table 7-5b.

Table 7-5a. Average Mercury Emissions (lbs/yr) for the Top 15 Mercury Emitters in the Commonwealth of Virginia, Based on Emissions for 2002.

Grouping	2001/2002 (lbs/yr)	2010 (lbs/ yr)	2015 (lbs/yr)	2018 (lbs/yr)
EGU Sources (8)	154.3	95.5	91.6	84.4
Non-EGU Sources (7)	103.8	52.4	43.4	44.0
All 15 Sources	130.7	75.4	69.1	65.5

Table 7-5b. Percent Change in Mercury Emissions (lbs per year) for the Top 15 Mercury Emitters in the Commonwealth of Virginia, Based on Emissions for 2002.

Grouping	2010 (%)	2015 (%)	2018 (%)
EGU Sources (8)	-35.0	-36.6	-43.8
Non-EGU Sources (7)	-47.3	-52.8	-51.7
All 15 Sources	-40.7	-44.2	-47.5

Both EGU and non-EGU emissions are substantially reduced in all three future years. The largest reductions in both emissions and deposition tend to occur between the base year and 2010.

Table 7-6 summarizes the AERMOD-simulated deposition for the future-year scenarios, in terms of percent reduction for each grouping of sites.

Table 7-6. Percent Change in AERMOD Mercury Deposition Totals (μg m^{-2}) Compared to the 2001/2002 Base Scenario.

Grouping	2010 (%)	2015 (%)	2018 (%)
EGU Sources (8)	-30.4	-32.1	-37.4
Non-EGU Sources (7)	-47.4	-52.6	-51.4
All 15 Sources	-38.3	-41.7	-43.9

For this subset of sources, the local reduction in mercury deposition from non-EGU sources is, on average, greater than that for EGU sources. This is consistent with a greater reduction in emissions for the non-EGU sources.

We can qualitatively compare these results to the CMAQ modeling results. The CMAQ/PPTM results indicate that a 53 percent reduction in EGU mercury emissions for Virginia sources between 2002 and 2018 reduces the contribution of these EGU emissions to statewide mercury deposition by about 43 percent. The AERMOD results indicate that a 44 percent reduction in EGU emissions from the highest emitting sources reduces local mercury deposition by about 37 percent. For non-EGU sources, a 27 percent reduction in non-EGU mercury emissions for all Virginia sources between 2002 and 2018 reduces the contribution of these emissions to statewide mercury deposition by about 38 percent. The AERMOD results indicate that a 52 percent reduction in non-EGU emissions from the selected sources reduces local mercury deposition in the vicinity of these sources by about 52 percent. When compared in a relative sense, the CMAQ and AERMOD modeling results agree very well. The AERMOD results indicate that mercury reductions from a given facility within the state will reduce local mercury deposition by a percentage that is similar to the emissions reductions. On a statewide basis, the CMAQ results indicate that the average reduction in mercury deposition from facilities within the state is comparable, on a percentage basis, to the average emissions reduction. Both models indicate that in-state controls are effective in reducing the in-state contribution to mercury deposition.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8. References

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Appendix A: Modeling Protocol

Virginia Department of Environmental Quality

Protocol for Mercury Deposition Modeling for the Virginia Mercury Study

Last Updated: February 28, 2008

07-027

Passion. Expertise. Results.

Virginia Department of Environmental Quality

Protocol for Mercury Deposition Modeling for the Virginia Mercury Study

Prepared for
Michael Kiss
Virginia Department of Environmental Quality
629 East Main Street
Richmond, VA 23219
(804) 698-4460
mfkiss@deq.virginia.gov

Prepared by:
ICF International
101 Lucas Valley Road, Suite 260
San Rafael, CA 94903
(415) 507-7164

07-027

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1. Introduction and Modeling Study Design

This protocol document outlines the methods and procedures followed in conducting mercury deposition modeling for the Commonwealth of Virginia. The initial version of this protocol document was prepared at the beginning of the study and was intended to provide a basis for study participants to review and comment on all aspects of the modeling analysis including the modeling tools and databases, modeling domain and simulation period, modeling procedures, quality assurance procedures, schedule, and communication structures. The protocol was used throughout the study to guide the progress of the modeling analysis and decisions made as the work progressed. This final version of the protocol document reflects the changes to the modeling approach and schedule that were incorporated throughout the study, such that all aspects of the modeling project are now accurately documented and the protocol can serve as a reference for future work and other studies. Although there are no current EPA guidelines for mercury deposition modeling, the modeling protocol and the modeling practices were designed to be consistent, wherever applicable, with current EPA guidelines for ozone and fine particulate modeling (EPA, 2006a).

This section of the protocol document summarizes the background and objectives of the study and provides an overview of the modeling study, including the modeling approach, project management and communication structures, schedule and deliverables for the study.

1.1. Background and Objectives

Human exposure to mercury is most commonly associated with the consumption of contaminated fish. Due to measured high levels of mercury in fish, at least 44 U.S. states have, in recent years, issued fish consumption advisories. These advisories typically suggest limits on the consumption of certain types of fish or recommend limiting or not eating fish from certain bodies of water because of unsafe levels of mercury contamination. States have identified more than 6,000 individual bodies of water as mercury impaired and have issued mercury fish advisories for more than 2,000 individual bodies of water.

Until 2002, significant mercury contamination in Virginia surface waters was known only in three rivers (the North Fork of the Holston River, the South River, and the South Fork of the Shenandoah River) and was associated with historical industrial releases. Since then, however, state monitoring efforts have identified mercury contamination in a number of surface waters without readily identifiable sources.

The Virginia Department of Environmental Quality (VDEQ) expanded its mercury monitoring in 2002 based on an increasing scientific understanding of mercury's environmental chemistry and discoveries in other states (e.g., Florida, Maryland) of mercury pollution in water bodies without direct sources. The 2002 monitoring effort focused on rivers of the coastal plain, mostly to the east of Interstate 95. As a result of this effort, Virginia found elevated mercury levels in some fish in the Blackwater River, the Great Dismal Swamp Canal, the Dragon Run Swamp, and the Piankatank River. Consistent with findings from Florida and elsewhere, these water bodies in Virginia possess characteristics favorable for the formation of the highly bio-accumulative form of mercury, methyl mercury. These characteristics include low dissolved oxygen, high organic matter, and low pH, and are most prevalent in the "backwaters" of the southeastern portion of the state.

The primary source of mercury to these water bodies is suspected to be atmospheric deposition. Until recently, there were three Mercury Deposition Network (MDN) sites located in Virginia, in Shenandoah National Park, Culpeper, and Harcum (the Culpeper site was discontinued in 2006). Data from these sites have contributed to the regional characterization of mercury transport and

wet mercury deposition in the Commonwealth. Additional monitoring at the Harcum site in 2005 revealed that dry deposition of reactive gaseous (divalent) mercury along the Piankatank River (near the Chesapeake Bay) and in upstream areas is an important contributor to the high mercury levels observed in the water and fish in the area.

Global, regional, and local sources of air mercury emissions contribute to the deposition, and understanding these contributions is an important step toward identifying measures that will effectively reduce mercury deposition and environmental mercury levels.

A key objective of the mercury deposition modeling analysis was to examine and quantify the contribution of regional and local emissions sources to mercury deposition throughout the Commonwealth, and to provide information to support the further analysis of the impact of mercury deposition on the environment.

For each of the bodies of water listed as impaired by Virginia, the Clean Water Act calls for the calculation of a Total Maximum Daily Load (TMDL). TMDLs identify the pollutant reductions or limits that are needed in order to achieve water quality standards. TMDLs must also allocate the reductions to the different sources of pollution, including air sources. Thus another key objective of the data and modeling analyses was to provide information that will enable VDEQ to conduct future TMDL studies.

Finally, the results of this study will also be used to support VDEQ's evaluation of potential measures needed to reduce mercury emissions in Virginia. Specifically, the data and modeling analysis results will allow VDEQ to evaluate the effectiveness of planned control measures and support the development of management strategies for meeting water quality criteria and protecting human health. A detailed analysis of mercury emissions inventory data was also conducted to supplement and enhance the overall reliability of the modeling study.

1.2. Conceptual Description of the Mercury Deposition Problem

A separate conceptual description report was prepared as part of the mercury deposition modeling study. This separate report includes an overview of mercury deposition, a summary of observed mercury deposition for Virginia and the surrounding states, and an analysis of meteorological and emissions related influences. The conceptual description has improved the overall understanding of the mercury problem and the relationships between meteorology and mercury deposition. The development of the conceptual model included the use of the Classification and Regression Tree (CART) analysis method (Brieman, 1984; Steinberg & Colla, 1997) to probe the relationships between meteorology and mercury deposition.

Mercury deposition data are available for three Mercury Deposition Network (MDN) sites in Virginia: Culpeper, Shenandoah National Park, and Harcum. The period of record for the MDN data is late 2002 through 2006 for Culpeper, late 2002 to present for Shenandoah, and approximately 2005 to present for the Harcum site. The Culpeper site is located in central Virginia, the Shendandoah site is located in mountainous northwestern Virginia, and the Harcum site is located along the southern portion of the inner coast of the Chesapeake Bay. Each measurement of wet deposition represents an approximate seven-day period. The conceptual model was developed based on data through 2005 and a portion of 2006 (based on the availability of the MDN data). Annual mercury wet deposition for these sites and for this period is summarized in Table 1-1.

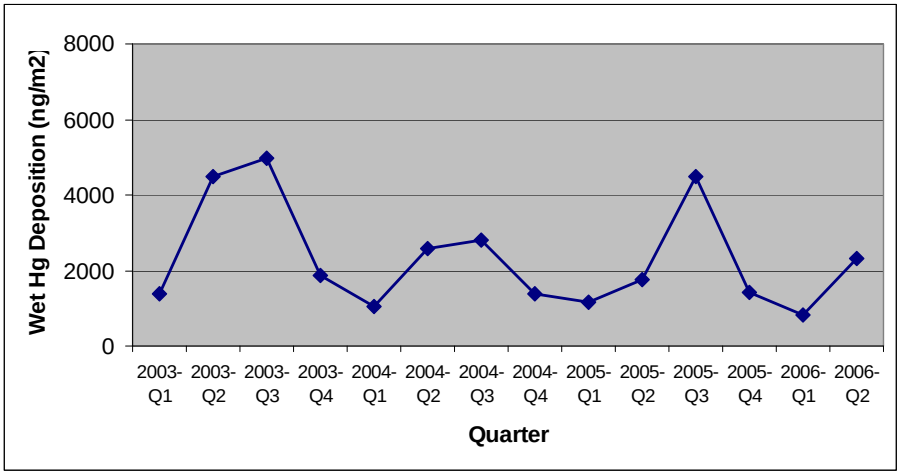
Table 1-1. Summary of Annual Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia.

Site Name (MDN ID)	Annual Observed Mercury Wet Deposition (ng m^{-2})		
	2003	2004	2005
Culpeper (VA08)	13,097	7,784	8,811
Shenandoah National Park (VA28)	11,922	9,727	7,074
Harcum (VA98)	—	—	8,218

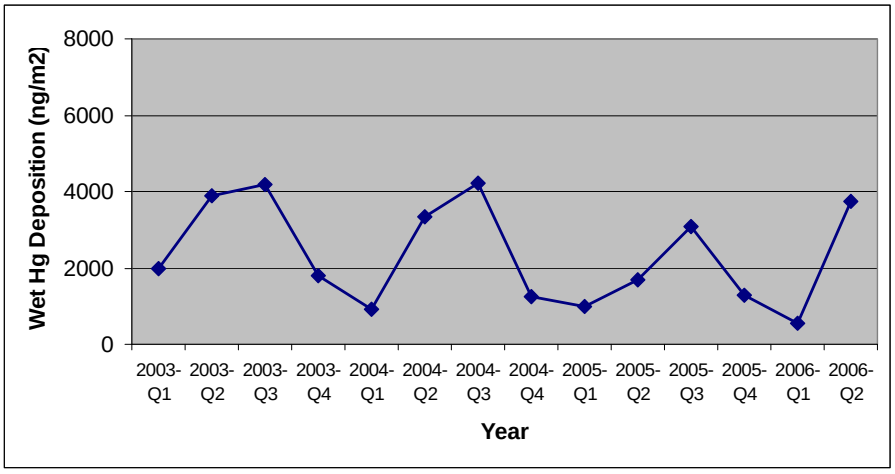
Within each calendar year, there are variations in deposition by week, month and quarter, primarily in accordance with variations in rainfall amount. Figure 1-1 suggests that mercury deposition (and thus rainfall amounts) appear to have an annual cycle, with higher deposition amounts during the second and third quarters (April through June and July through September, respectively).

Figure 1-1. Quarterly Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia.

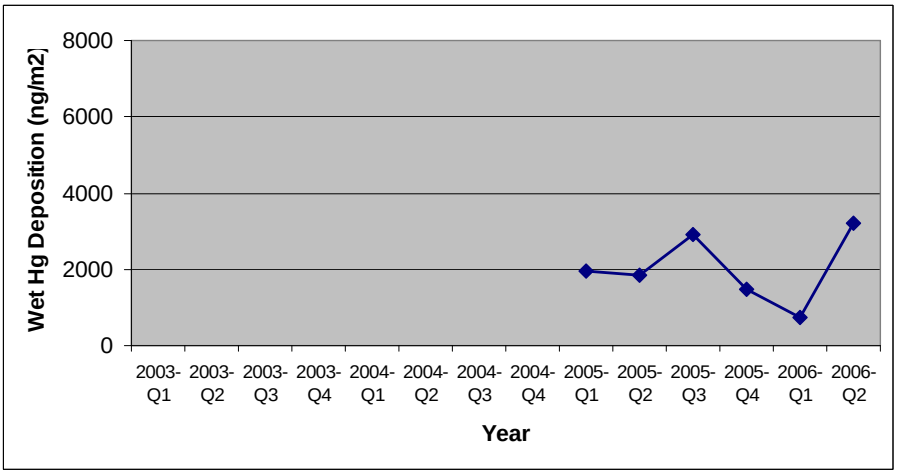
(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



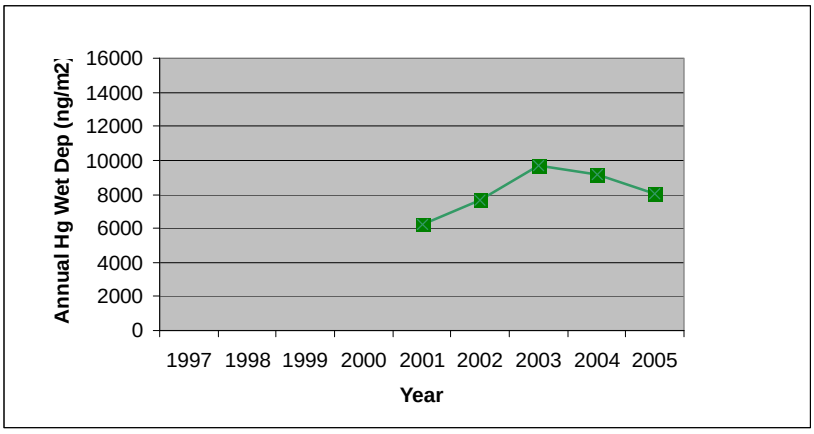
(c) Harcum (VA98)



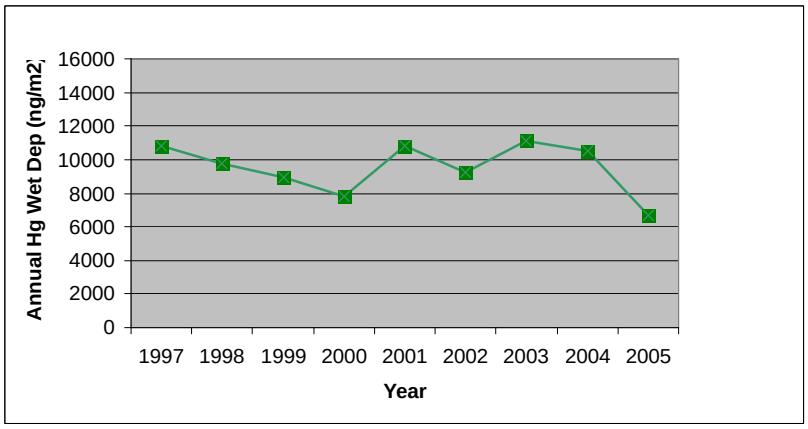
With only three full calendar years of data, it is difficult to assess annual variations and trends. Several MDN sites in nearby Pennsylvania and North Carolina have a somewhat longer period of record. These include Arendtsville, Pennsylvania (near Gettysburg, along the PA/MD border), Allegheny Portage Railroad National Historic Park in the southern Allegheny Mountains of Pennsylvania, and Pettigrew State Park in coastal, northeastern North Carolina. In addition to having longer data records, these sites also have some geographical similarities (with respect to location, elevation, and proximity to the coastline) to the three Virginia sites (Culpeper, Shenandoah, and Harcum, respectively). The observed annual variations in wet mercury deposition for these three neighboring sites are displayed in Figure 1-2.

Figure 1-2. Annual Observed Mercury Wet Deposition (ng m^{-2}) for Selected MDN Monitoring Sites in Pennsylvania and North Carolina.

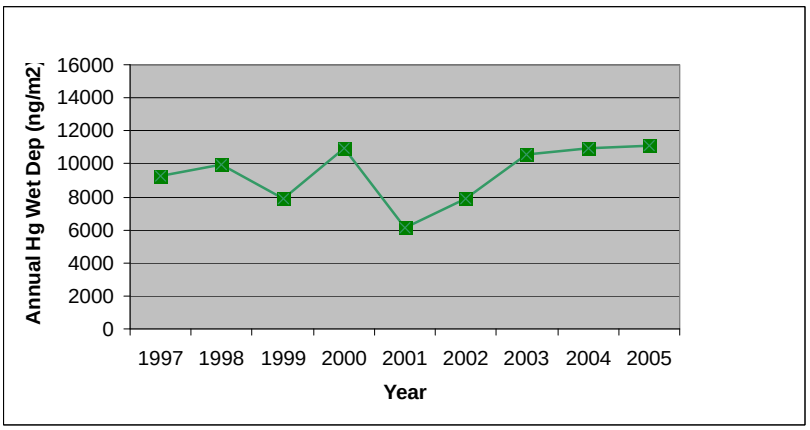
(a) Arendtsville, PA (PA00)



(b) Allegheny Portage Railroad National Historic Site, PA (PA13)



(c) Pettigrew State Park, NC (NC42)



For all three neighboring sites, there is significant year-to-year variation in mercury wet deposition and this most likely reflects year-to-year variability in the meteorological conditions, particularly rainfall. Additional analysis of the meteorology and emissions data, including the calculation of meteorologically adjusted mercury deposition trends is summarized in the conceptual model report.

1.3. Overview of the Modeling Approach

The modeling approach accounts for the different scales and chemical interactions important to mercury deposition through the combined use of a state-of-the-science regional modeling system with source-contribution-assessment capabilities, boundary conditions for the regional model based on global modeling, and Gaussian modeling for the detailed assessment of local contributions.

At the regional scale, we applied the latest version (version 4.6) of the Community Multiscale Air Quality (CMAQ) modeling system. The CMAQ model is a state-of-the-science, regional air quality modeling system that is designed to simulate the physical and chemical processes that govern the formation, transport, and deposition of gaseous and particulate species in the atmosphere. The CMAQ modeling system supports the detailed simulation of mercury (Hg), including the emission, chemical transformation, transport, and wet and dry deposition of elemental, divalent, and particulate forms of mercury.

The CMAQ Particle and Precursor Tagging Methodology (PPTM) for mercury was used in this study to provide detailed, quantitative information about the contribution of selected sources, source categories, and/or source regions to simulated mercury concentrations and (wet and dry) deposition. Mercury emissions from selected sources, source categories, or source regions are (numerically) tagged and then tracked throughout a simulation, and the contribution from each tag to the resulting simulated concentration or deposition for any given location can be quantified. By tracking the emissions from selected sources or source locations, the methodology also provides information on the fate of the emissions from these sources.

Boundary concentrations for the regional-scale modeling were extracted from global model simulation results.

At the local scale, the EPA Gaussian model AERMOD was applied for the 15 highest emitting point sources in Virginia, based on the 2002 emissions inventory. AERMOD was used to screen the top mercury emissions sources and to determine which have the potential to impact areas outside the vicinity of the source. AERMOD was then used to simulate the effects of future-year emission changes for the selected sources and their local areas.

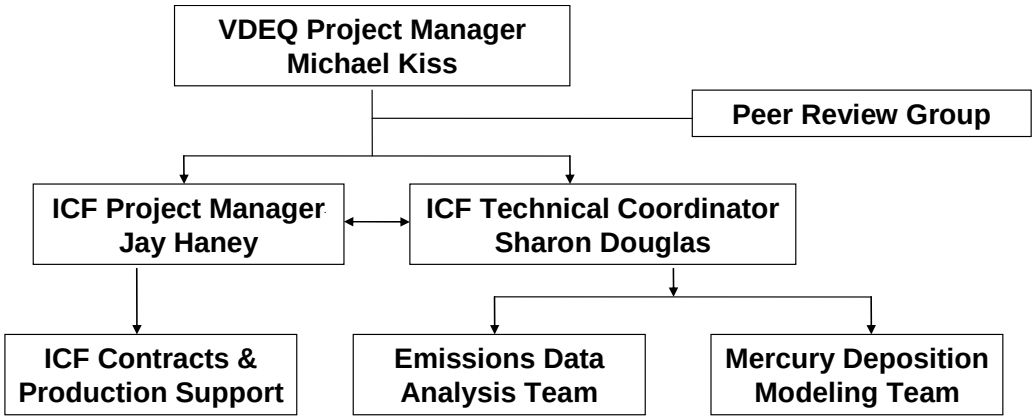
This combination of modeling tools has allowed us to address the variety of factors influencing mercury deposition in Virginia. Additional details regarding model selection, input preparation, and application and analysis procedures are provided later in the protocol document.

The modeling results provide a basis for quantifying the contribution of emissions sources to mercury deposition and examining the fate of mercury emissions from selected sources. For environmental planning purposes, the modeling results will be used by VDEQ to examine the effectiveness of control measures in reducing mercury concentrations in contaminated bodies of water and improving or maintaining water quality within the designated areas of interest in Virginia. By quantifying deposition, the modeling results will also provide a link between the analysis of mercury emissions and the assessment of the impacts of airborne mercury on fish tissue and human health.

1.4. Project Management and Communication Structures

This project was funded and managed by the Virginia Department of Environmental Quality (VDEQ). The mercury deposition modeling was conducted by ICF International. Note that the project also included a detailed analysis of mercury emissions inventory data to supplement and enhance the overall reliability of the modeling study. The overall project organization and communication structure is presented in Figure 1-3.

Figure 1-3. Project Organization Chart for the Virginia Mercury Study.



The majority of the technical work was conducted by ICF with VDEQ providing assessment and oversight. Ms. Diane Shotynski of Thruput and Mr. Tim Lavallee of LPES, Inc., both Virginia based consultants, assisted with the emission inventory review and literature search tasks.

Conference calls were held throughout the project to review project status, discuss technical issues and/or the resolution of technical difficulties. As problems were identified and corrective actions were required, ICF made the corrections to the approach or work product and documented the corrections.

ICF provided VDEQ with monthly progress reports summarizing work accomplished during each reporting period, problems encountered and how they were resolved, planned activities for the next reporting period, and status of deliverables. The monthly progress reports also included a summary of expenditures for the period and cumulative expenditures for the project.

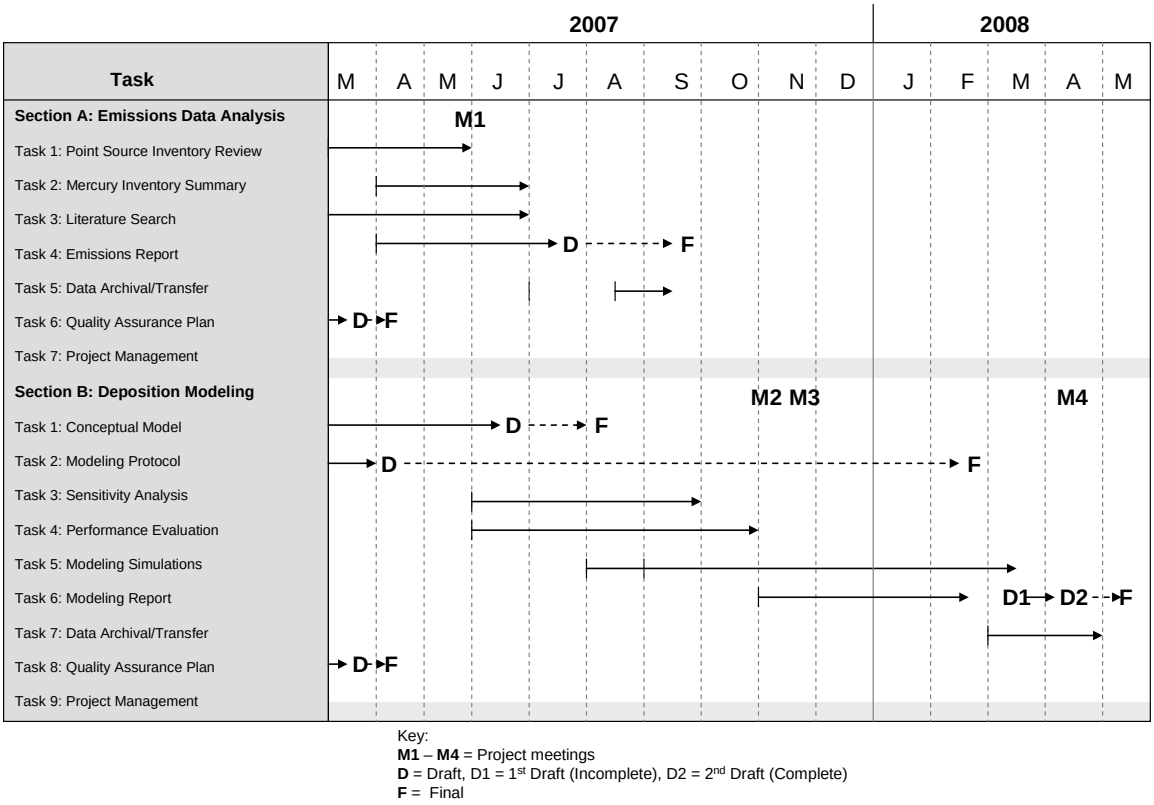
Peer review of the technical analysis, results, and reports was conducted as requested by VDEQ.

1.5. Schedule and Deliverables

The schedule for conducting the mercury deposition modeling is provided in Figure 1-4. The schedule for completing the emissions data analysis tasks is also included in this figure, since the results of this analysis were used in the modeling study.

Figure 1-4. Schedule for the Virginia Mercury Study.

(shading represents ongoing activity).



Key:
M1 – **M4** = Project meetings
D = Draft, D1 = 1st Draft (Incomplete), D2 = 2nd Draft (Complete)
F = Final

Major deliverables for work conducted under the emissions data analysis and deposition modeling components of the Virginia Mercury Study are listed and the completion dates are provided in Table 1-2.

Table 1-2a. Milestones and Deliverables for the Emissions Analysis Component of the Virginia Mercury Study.

Milestone/Deliverable	Completion Date
Tasks 1 & 2: Emissions Review & Summary	
Draft memorandum	4/4/2007
Task 3: Literature Search	
Draft memorandum	7/19/2007
Task 4: Emissions Report	
Draft emissions data analysis report	7/19/2007
Final emissions data analysis report	9/27/2007
Task 5: Data Archival/Transfer	
Transfer inventory files to VDEQ	9/29/2007
Task 6: Quality Assurance Plan	
Draft quality assurance plan	3/16/2007
Final quality assurance plan	4/6/2007
Task 7: Project Management	
Conduct 1st technical meeting	5/31/2007

Table 1-2b. Milestones and Deliverables for the Deposition Modeling Component of the Virginia Mercury Study.

Milestone/Deliverable	Completion Date
Task 1: Conceptual Model	
Draft conceptual model report	6/21/2007
Final conceptual mode report	8/2/2007
Task 2: Modeling Protocol	
Draft modeling protocol	4/6/2007
Updated modeling protocol	2/22/2008
Tasks 3: Sensitivity Analysis	
Draft report section on sensitivity analysis	3/15/2008
Task 4: Performance Evaluation	
Draft report section on model performance	3/15/2008
Tasks 5 & 6: Modeling Simulations & Report	
First draft mercury deposition modeling report	3/15/2008
Second draft mercury deposition modeling report	4/15/2008
Final mercury deposition modeling report	5/15/2008
Task 7: Data Archival/Transfer	
Transfer modeling files to VDEQ	4/30/2008
Task 8: Quality Assurance Plan	
Prepare draft quality assurance plan	3/16/2007
Prepare final quality assurance plan	4/6/2007
Task 9: Project Management	
Conduct 2nd technical meeting	11/8/2007
Conduct 3rd technical meeting	11/27-11/29/2007
Conduct 4th technical meeting	4/15/2008

2. Model Selection and Application Procedures

The modeling platform for the Virginia mercury deposition modeling study consists of three primary components: a grid-based air quality/deposition model, an emissions preprocessing system, and a Gaussian air quality model. The Community Multiscale Air Quality (CMAQ) model was used to simulate mercury deposition at the regional scale. The Sparse-Matrix Operator Kernel Emissions (SMOKE) emissions processing system was used to process the emissions for input to the CMAQ model. The EPA Gaussian model AERMOD was used to examine mercury deposition at the local scale for selected areas and sources.

The selection of modeling tools considered 1) technical formulation, capabilities, and features, 2) comprehensiveness of testing, and 3) demonstrated successful use in previous applications The rationale for selecting each of these modeling tools (in keeping with EPA guidance) is discussed in this section; an overview of each modeling tool and a brief discussion of the input requirements and application procedures are also provided. The meteorological and boundary condition inputs for this study will be obtained from prior studies and the tools used to prepare these inputs are discussed in the database section of the protocol (Section 3).

2.1. Selection and Overview of the Grid-based Mercury Deposition Model

2.1.1. Overview of CMAQ Version 4.6

The CMAQ model is a state-of-the-science, regional air quality modeling system that is designed to simulate the physical and chemical processes that govern the formation, transport, and deposition of gaseous and particulate species in the atmosphere (Byun and Ching, 1999). The CMAQ model was designed as a “one-atmosphere” model and can be used to simulate ozone, particulate matter, and mercury. For mercury, CMAQ supports the detailed simulation of the emission, chemical transformation, transport, and wet and dry deposition of elemental, divalent, and particulate forms of mercury. The latest version of CMAQ, version 4.6, was used for this study.

According to Bullock et al. (2007), the CMAQ model reflects the current state-of-the-science in simulating the atmospheric processes that influence the dispersion, advection, chemical transformation and deposition of mercury. The CMAQ model includes three mercury (Hg) species; elemental mercury (Hg^0), reactive gaseous mercury (RGM), and particulate mercury (PHg). RGM is known to be comprised almost entirely of divalent mercury (Hg^{2+}), since Hg compounds at other valence states tend to be chemically unstable in the atmosphere. PHg is also primarily comprised of divalent mercury, but may also include elemental mercury.

Mercury simulation capabilities were first incorporated into the CMAQ model by adding gaseous and aqueous chemical reactions involving mercury to the CMAQ chemical mechanism (Bullock and Brehme, 2002). Since that time, the chemical mechanism has been further updated to include additional reactions and updated information on reaction rates. The most recent changes to CMAQ for mercury include an improved dry deposition algorithm and the incorporation of natural mercury emissions. The CMAQ modeling system, including the mercury modeling component, has been peer reviewed (e.g., Amar et al., 2005).

In addition to the state-of-the science chemical mechanism for mercury, other key features of the CMAQ model in simulating mercury deposition include state-of-the-science advection, dispersion and deposition algorithms, the latest version of the Carbon Bond chemical mechanism (CB05), and the CMAQ Particle and Precursor Tagging Methodology (PPTM).

PPTM for mercury (Douglas et al., 2006) provides detailed, quantitative information about the contribution of selected sources, source categories, and/or source regions to simulated mercury concentrations and (wet and dry) deposition. Mercury emissions from selected sources, source categories, or source regions are (numerically) tagged and then tracked throughout a simulation, and the contribution from each tag to the resulting simulated concentration or deposition for any given location can be quantified. By tracking the emissions from selected sources or source locations, the methodology also provides information on the fate of the emissions from these sources.

The CMAQ model has been used by EPA to support the development of the Clean Air Mercury Rule (CAMR) (EPA, 2005a). This study included the evaluation of global modeling results to prescribe boundary conditions for CMAQ, evaluation of mercury deposition using MDN data, and assessment of the contribution of mercury emissions from coal-fired power plants on mercury deposition in the U.S.

CMAQ was also included in the North American Mercury Model Intercomparison Study (NAMMIS) for mercury (Bullock et al., 2008) and the performance and response of CMAQ was found to be reasonable and also consistent with that for the Regional Modeling System for Aerosols and Deposition (REMSAD), which has been widely applied and tested for mercury (e.g., Myers et al., 2006).

In summary, EPA (2006a) lists five factors to be considered in selecting a model for use air quality (and deposition) modeling studies. The selection of CMAQ, version 4.6, with PPTM capabilities addressed each of these factors.

- ***Documentation and past performance should be satisfactory.*** The CMAQ modeling system is well documented and comparisons with other models (e.g., Bullock et al., 2008) have demonstrated that CMAQ performance is reasonable and consistent with that for other models.
- ***The selected model should reflect the current state-of-the-science and include advanced features (e.g. source apportionment tools) as needed to support the model application.*** CMAQ version 4.6 reflects the current state-of-the-science in mercury chemistry and the PPTM feature supports the analysis of source contributions.
- ***Relevant experience of available staff and contractors should be consistent with choice of a model.*** ICF and VDEQ scientists are experienced in the use of CMAQ, including the PPTM capabilities.
- ***Time and resource constraints may be considered.*** The time and resource requirements for CMAQ are consistent with the schedule and budget for the mercury deposition analysis.
- **Consistency of the model with what was used in adjacent regional applications should be considered.** CMAQ was used by EPA for the CAMR modeling.

2.1.2. Input Requirements

The CMAQ model requires hourly, gridded input fields of several meteorological parameters including wind, temperature, water-vapor concentration, pressure, vertical exchange coefficients (K_v), cloud cover, and rainfall rate. The model also requires hourly, gridded, speciated precursor emissions as required for the simulation of ozone, particulates and mercury. In addition, the CMAQ modeling system requires specification of initial and boundary values for each species, topographic and land-use data, and photolysis rates. Several preprocessor programs are

available to aid the preparation of these input files. For this study, we used a combination of existing (from EPA) and newly derived datasets and these are described in some detail later in this section and in Section 3.

2.1.3. Application Procedures for the Virginia Mercury Deposition Modeling Study

CMAQ was applied for all gaseous, particulate, and mercury species and for the domain and simulation period discussed in Section 3 of this document. The modeling system was configured as follows:

Horizontal grid spacing:	36 & 12 km
Number of vertical layers:	14
Plume-in-grid treatment:	None
Gas phase chemical mechanism:	Carbon-Bond 05 (CB05)
Aerosol treatment:	AERO4/ISOROPIA
Mercury options	Gas and aqueous phase chemistry as implemented in CMAQ4.6; natural and reemission estimates included.
Source attribution method:	PPTM

2.2. Selection and Overview of the Emissions Preprocessing System

2.2.1. Overview of SMOKE

Model-ready mercury emissions for the application of CMAQ were prepared using the Sparse Matrix Operator Kernel Emissions (SMOKE) emissions processing system (CEP, 2004 and 2006). The SMOKE tool has been paired with CMAQ for most applications of the CMAQ modeling system to date. SMOKE is designed to convert emissions inventory data as well as calculated emissions estimates (e.g., mobile-source and biogenic emissions) into the formatted emission files required by CMAQ. Operations that are performed by SMOKE include spatial and temporal allocation of emissions, chemical speciation, and application of emissions controls.

SMOKE accounts for point-source, area-source, on-road mobile, non-road mobile, and natural (e.g., biogenic and geogenic) emissions—although not all of these are required for mercury deposition modeling. These emission components are processed separately and merged together in the final, model ready emissions inventory.

Key features of SMOKE that make it well suited for this project include 1) compatibility with CMAQ and PPTM and 2) compatibility with regional-scale mercury modeling conducted by EPA, such as the CAMR modeling (EPA, 2005b). The quality assurance and reporting features of SMOKE were used in this study. Version 2.3 of SMOKE was applied.

For this study, we used a combination of existing (EPA) and newly derived emissions datasets and these are described in some detail in this section and Section 3.

2.2.2. Input Requirements

SMOKE will accept mercury emissions data from point, area, mobile and natural/geogenic sources—as available. For this study, the input data consisted of point- and area source emissions data from version 3 of the 2002 National Emissions Inventory (NEI) for mercury and point-source data for sources in Virginia (provided by VDEQ and quality assured and updated for use in this study). Emissions for on-road and non-road mobile sources were not included since they were not available from the NEI in time for this study.

2.2.3. Application Procedures for the Virginia Mercury Deposition Modeling Study

SMOKE was used to generate hourly, gridded, speciated mercury emissions files for the domain and simulation period discussed in Section 3.

The reporting and quality assurance tools available in SMOKE were used to summarize and review the emissions and ensure the successful completion of each processing step.

SMOKE was also used to prepare the mercury tagging emissions for CMAQ PPTM using the procedures outlined by Douglas et al. (2006).

2.3. Selection and Overview of the Gaussian Plume Model

2.3.1. Overview of AERMOD

AERMOD is a steady-state Gaussian dispersion model designed to simulate the local-scale dispersion of pollutants from low-level or elevated sources in simple or complex terrain. It is an EPA “preferred” model (40 CFR Part 51, Appendix W, *Guideline on Air Quality Models*). Recent versions of AERMOD (EPA, 2006b) include algorithms for simulating deposition of gaseous and particulate pollutants. In this study, AERMOD was applied for selected point sources in the Virginia emissions inventory and was used to screen the mercury emissions sources and to determine whether they have the potential to impact areas outside the vicinity of the source. AERMOD was also used to simulate the effects of local emission changes for selected areas and sources.

The AERMOD modeling system consists of three components: the AERMOD dispersion model, the AERMET meteorological data preprocessor, and the AERMET terrain preprocessor. The dispersion algorithms are based on the fundamental concepts of planetary boundary layer meteorology. The airflow and stability characteristics (e.g., convective versus stable) as well as the vertical structure of the boundary layer are accounted for in simulating dispersion. Numerous features and options accommodate a variety of source types, pollutants, and land-use and topographical features.

Wet and dry deposition can be estimated using AERMOD. The wet deposition algorithms use a washout ratio that is dependent on precipitation rate and the properties of the pollutant being simulated. Dry deposition is based on aerodynamic resistance calculations, and the deposition velocities are calculated based on surface type and local meteorological conditions.

2.3.2. Input Requirements

AERMOD requires several input files:

The simulation control file specifies which options and features of AERMOD are to be applied, and contains information about the emissions sources (location, emissions rate, stack parameters, etc.) as well as the receptor locations (essentially the gridded geographical area over which the estimated concentrations and deposition amounts are calculated).

Two meteorological input files provide detailed information about 1) the characteristics of the boundary layer (wind, temperature, stability parameters) and 2) the vertical structure of temperature and wind near the source location. For deposition analyses, the boundary layer meteorological file includes information about pressure, relative humidity, cloud cover and precipitation.

Preparation of these inputs for the Virginia mercury study is discussed in Section 3 of this document.

2.3.3. Application Procedures for the Virginia Mercury Deposition Modeling Study

AERMOD was applied for the 15 sources in Virginia with the greatest mercury emissions and for the full annual simulation period.

The sources reflect several different types of facilities and a variety of species distributions, stack parameters, locations relative to sensitive watershed areas, and designated potentials for future control.

The receptor area for each source was defined following EPA guidance and consists of a 10 by 10 grid with grid cells of 100 x 100 m near the source that increase to 200 x 200 m and then to 500 x 500 m. The receptor area extends approximately 3000 m (3 km) in any direction of the source.

Meteorological inputs were prepared using available surface and upper-air meteorological data from nearby, geographically representative monitoring sites. The meteorological monitoring sites were paired with the source locations based on proximity, and similarities in geographical and land-use characteristics. Surface characteristics for processing of the meteorological inputs were defined based on 100 m resolutions U.S. Geological Survey (USGS) land-use data.

All other inputs to the modeling system were specified in accordance with EPA guidance on the use of AERMOD (using the EPA default parameters) (EPA, 2004). The default reactivity factor for divalent mercury was applied and the output includes information on wet, dry and total mercury deposition (EPA, 2006b).

As part of this study, sensitivity simulations were conducted to examine the sensitivity of the AERMOD results to selected input parameter specifications.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3. Simulation Period, Domain and Database Issues

3.1. Selection of the Simulation Period

Selection of the simulation period considered meteorological and emissions database availability and meteorological representativeness. The availability of meteorological inputs for CMAQ was an important factor in selecting the simulation period. Comprehensive, tested meteorological inputs for the modeling domain are available for two calendar years: 2001 and 2002. For both years, the meteorological inputs were prepared by EPA and were generated using the Fifth Generation Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (MM5). The MM5-derived meteorological fields are available for both 36- and 12-km resolution.

Meteorological representativeness was also considered in selecting the modeling period. The representativeness of the two candidate periods varies seasonally. For example, 2001 is characterized by normal precipitation amounts during the summer months, for Virginia and most of the surrounding areas. This is offset, however, by less than normal precipitation during the fall period. Figure 3-1 shows the deviation from normal rainfall (based on 40 years of data) for the summer and fall of 2001. In contrast, 2002 is characterized by less than normal rainfall during the summer months followed by greater than normal rainfall toward the end of the year. This is displayed in Figure 3-2. Note that these plots were obtained from the NOAA web site. The precipitation plots for spring were comparable and one of the plots for winter was not available. Figures 3-3 and 3-44 show that temperatures during the summer months were normal for 2001 and higher than normal for 2002.

From this information, we concluded that 2001 is (meteorologically) a more suitable year for mercury deposition modeling, primarily because the summer of 2002 was characterized by lower than normal rainfall amounts in Virginia and surrounding states. We gave somewhat more weight to the summer months in making this assessment, since precipitation is highest, on average, during the summer months compared to the other seasons (by as much as 40 to 50 percent). Since summer can be an important time for mercury wet deposition, 2002 is not an ideal meteorological base year for the modeling exercise.

Consequently, the annual simulation period for the mercury deposition modeling was selected to be 2001. Sensitivity testing was conducted to examine the differences in the CMAQ results due to the use of the 2002 versus 2001 meteorological inputs.

Figure 3-1a. Deviation from Normal Precipitation for Summer 2001.

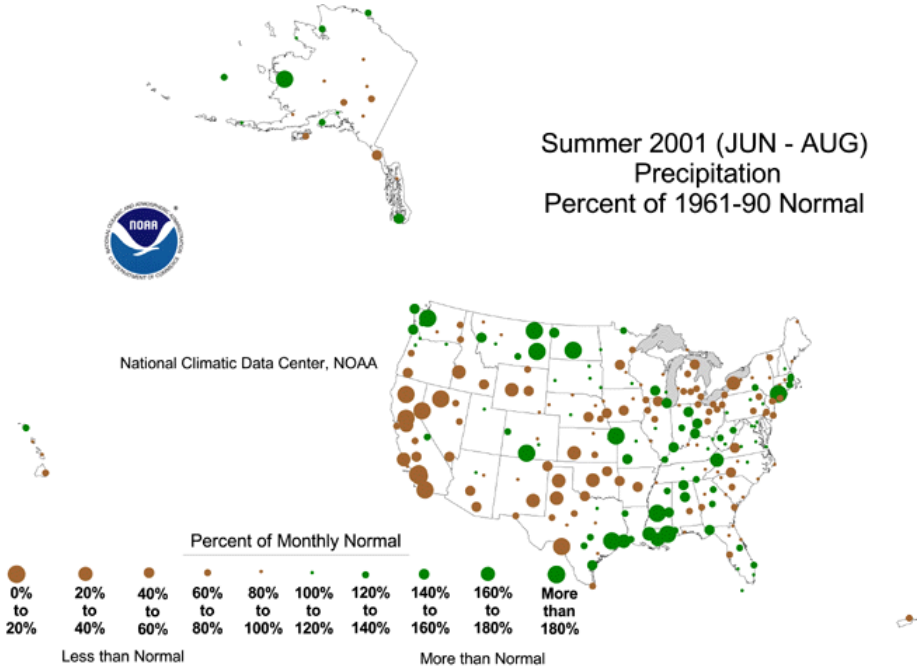


Figure 3-1b. Deviation from Normal Precipitation for Fall 2001.

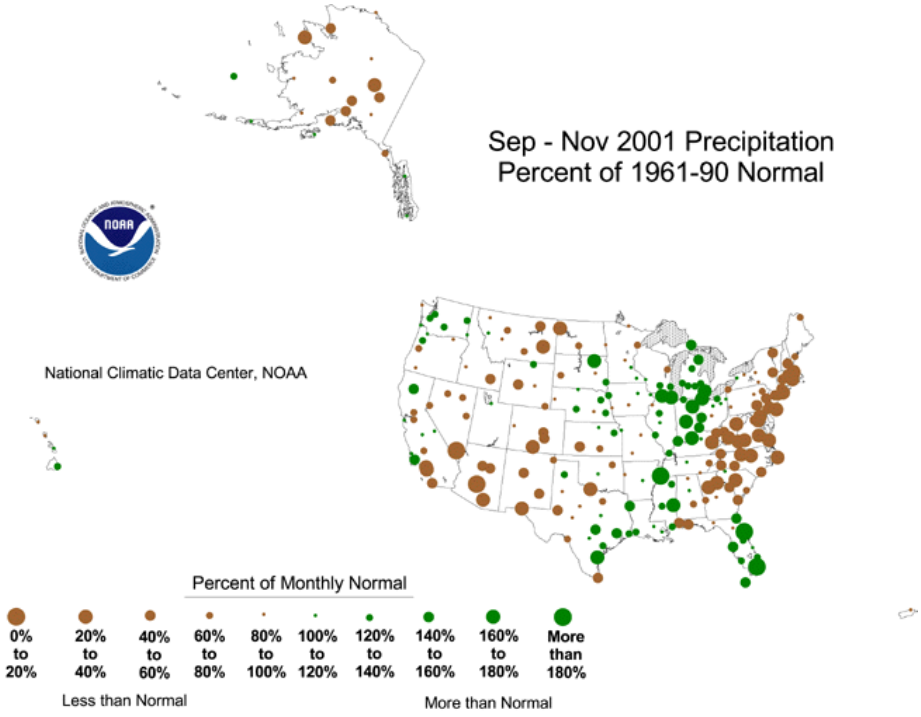


Figure 3-2a. Deviation from Normal Precipitation for Summer 2002.

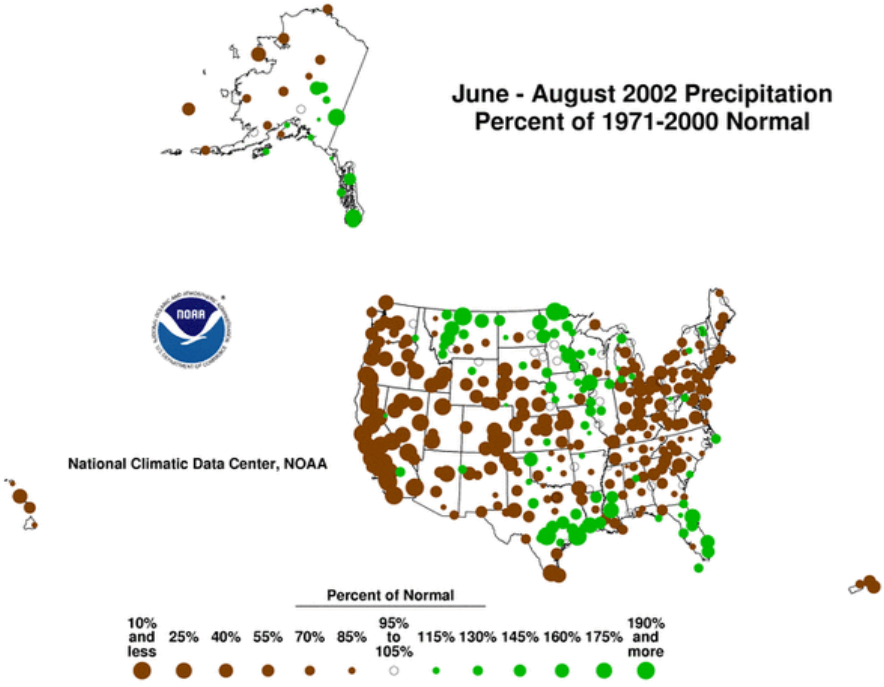


Figure 3-2b. Deviation from Normal Precipitation for Fall 2002.

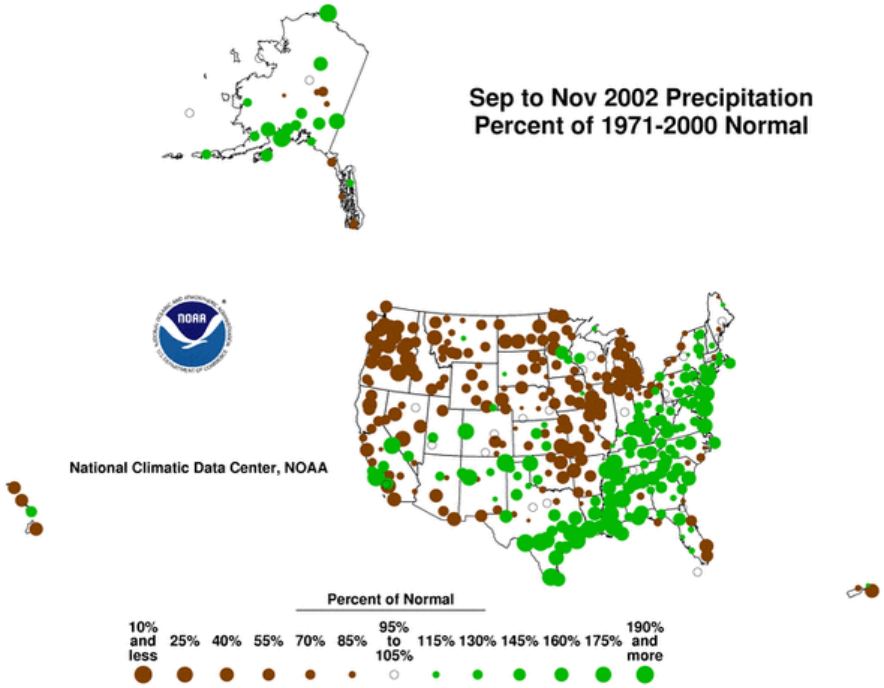


Figure 3-3. Deviation from Normal Temperature for Summer 2001.

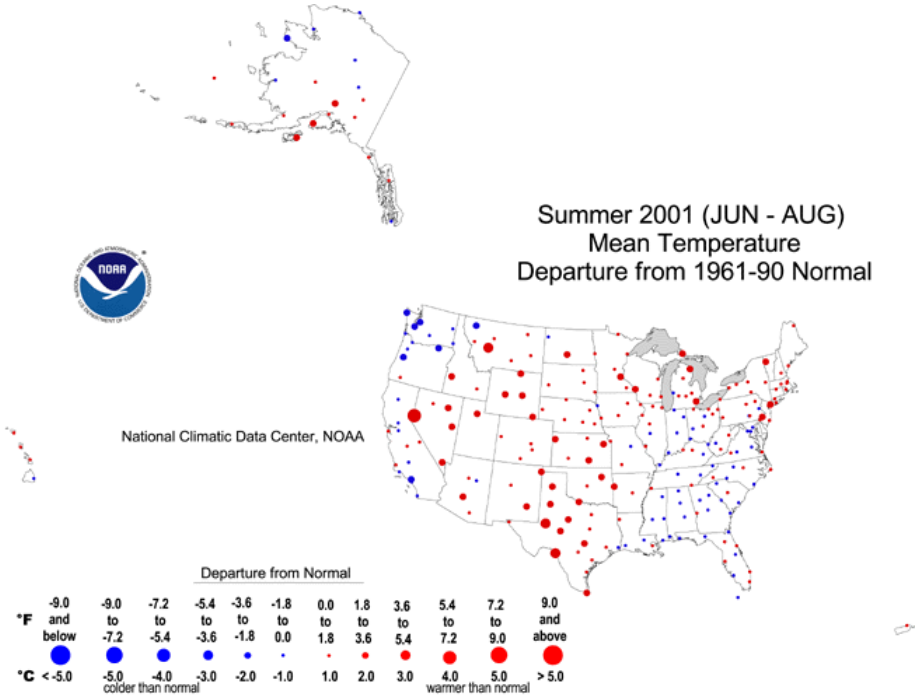
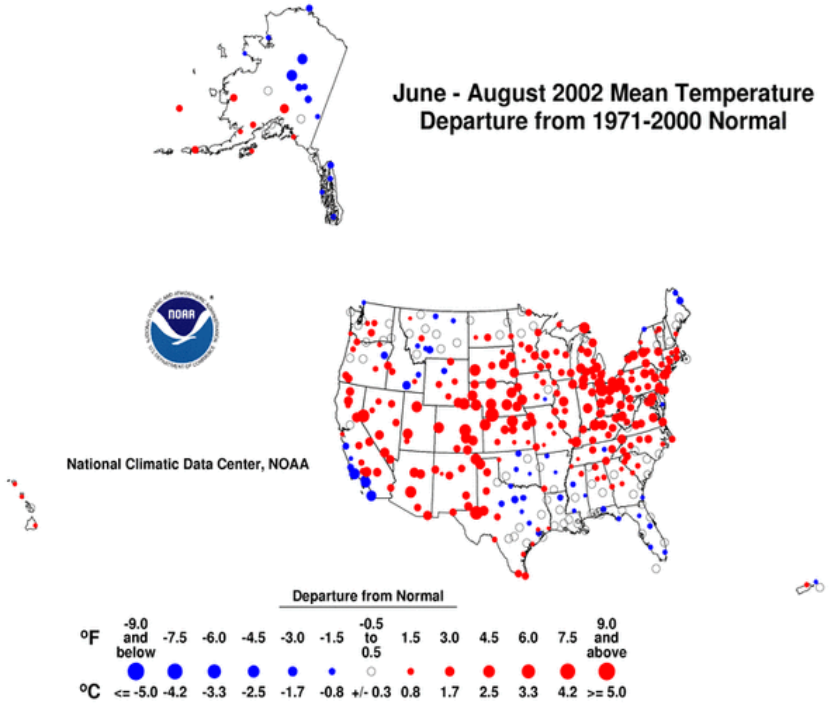


Figure 3-4. Deviation from Normal Temperature for Summer 2002.

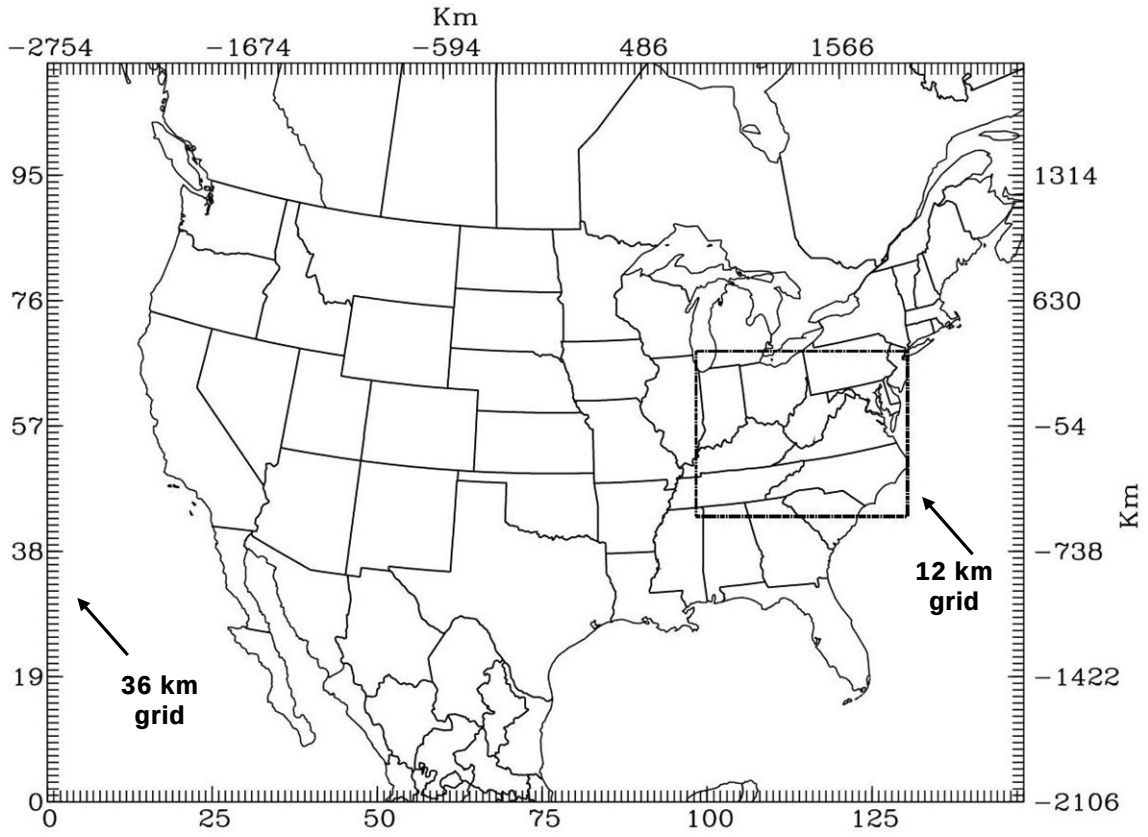


3.2. CMAQ Modeling Domain

3.2.1. Horizontal Extent and Grid Spacing

The CMAQ modeling domain is illustrated in Figure 3-5. The outer domain is the regional-scale modeling domain that has been established by EPA for regulatory applications (e.g. CAMR modeling). The outer grid encompasses the entire contiguous U.S. as well as portions of Canada and Mexico and, therefore, all or nearly all mercury emissions sources in North America. The horizontal resolution of the outer, coarse grid is 36 km. The inner grid focuses on Virginia and the surrounding states and has a horizontal grid resolution of 12 km.

Figure 3-5. CMAQ 36- and 12-km Nested-Grid Modeling Domain.



3.2.2. Vertical Structure

The CMAQ domain includes 14 vertical layers. CMAQ uses a sigma vertical coordinate system, which is a terrain-following vertical coordinate system with numerous numerical advantages. The vertical structure of the modeling domain is such that the highest resolution is achieved near the surface. The top of the modeling domain is approximately 17,000 m. The sigma layers and their approximate heights (under standard pressure conditions) are provided in Table 3-1.

Table 3-1. Vertical Levels that Define the CMAQ Modeling Domain.

Layer Number	Sigma	Height (m)
1	0.995	0
2	0.99	36
3	0.98	72
4	0.96	145
5	0.94	293
6	0.91	444
7	0.86	674
8	0.8	1074
9	0.74	1579
10	0.65	2115
11	0.55	2989
12	0.4	4078
13	0.2	6037
14	0	9733

3.3. AERMOD Spatial Configuration

3.3.1. Selection of Sources for Application of AERMOD

AERMOD was applied for the 15 sources in Virginia with the greatest mercury emissions and for the full annual simulation period. The sources reflect several different types of facilities and a variety of species distributions, stack parameters, locations relative to sensitive watershed areas, and designated potentials for future control.

3.3.2. Specification of Receptor Grids

The receptor area for each source was defined following EPA guidance and consists of a 10 by 10 grid with grid cells of 100 x 100 m near the source that increase to 200 x 200 m and then to 500 x 500 m. The receptor area extends approximately 3000 m (3 km) in any direction of the source.

3.4. Emissions Data and Databases

3.4.1. Baseline Emissions

The mercury emissions inventory incorporates the latest mercury emission data for point sources in Virginia (for 2002 and 2005). The mercury emissions inventory for point sources in Virginia were reviewed and updated as part of this study to ensure that the methods used to calculate the emissions are valid, the data are complete, and that the emissions totals, locations, and stack parameters are correct.

Baseline mercury emissions for all other areas and source categories were based on the latest version (version 3) of the 2002 National Emissions Inventory (NEI). Currently the NEI inventory does not include mercury emissions for motor vehicle or non-road sources.

We prepared the model-ready emissions for CMAQ using the SMOKE emissions processing program and applied our standard quality assurance procedures (as outlined in the quality assurance plan for the project) to the emissions processing.

CMAQ also requires hourly, gridded emissions for other criteria pollutants and related precursor emissions. For this study we used 36- and 12-km model-ready criteria-pollutant emissions prepared by EPA for the 2001 annual simulation period. The 36-km criteria pollutant emissions were used directly, since the VDEQ 36-km domain is the same as that used by EPA. The 12-km emissions for the VDEQ subdomain were extracted from a larger 12-km domain used by EPA. The criteria pollutant emissions were re-speciated for use with the CB05 chemical mechanism. We used SMOKE to merge the criteria pollutant and mercury emissions into a model-ready emissions inventory for CMAQ.

3.4.2. Future-Year Emissions

Future-year emission inventories were prepared for 2010, 2015, and 2018. Emissions projections were based on information available from EPA (e.g., CAMR) and from VDEQ (primarily through surveys). The future-year emission inventories were prepared using the SMOKE emissions processing system.

For all states, the future-year mercury emissions estimates take into account the provisions of CAMR. The CAMR, promulgated on May 18, 2005, includes two mechanisms to reduce mercury emissions from electric power plants. First, it sets standards of performance for new and existing coal-fired power plants. Second, it establishes a two-phase, national cap-and-trade program. In the initial phase of the cap-and-trade program, the national mercury emissions will be capped at 38 tons and emissions reductions will occur as a "co-benefit" of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions under the Clean Air Interstate Rule (CAIR) issued on March 10, 2005. In the second phase, due in 2018, coal-fired power plants will be subject to a second cap, which will reduce emissions to 15 tons upon full implementation.

For Virginia, HB1055 was also accounted for in the future emissions projections. To participate in the cap-and-trade program, states must submit to EPA a State Implementation Plan revision that describes how the state will meet its mercury reduction budget. States may adopt a "model rule" or a rule(s) with comparable provisions. Legislation enacted by Virginia in April 2006 authorized the Air Pollution Control Board to adopt and submit to EPA the model rule. As described below, the Virginia legislation also provided authority for state-specific rules to further control mercury emissions from sources regulated under CAMR. These are summarized by the following amendments to the Code of Virginia:

- § 10.1-1328 C—This section directs the Air Pollution Control Board to adopt and submit to EPA the CAMR "model rule" for participation in the federal mercury cap-and-trade trading program. The rule will include a set-aside of mercury allowances for new sources not to exceed 5 percent of the total state budget during the first five years and 2 percent thereafter.
- § 10.1-1328 D—This section is a state-specific (i.e., that exceeds the requirements of the CAMR rule) rule. Its requirements are similar to the CAMR cap-and-trade program, but it applies to additional (smaller) sources and includes additional restrictions on compliance options.
- § 10.1-1328 E—This section directs the Air Pollution Control Board to adopt regulations governing mercury emissions that meet, but do not exceed, the requirements and implementation timetables for (i) any coke oven batteries for which the EPA has promulgated standards under § 112(d) of the

Clean Air Act, and (ii) facilities subject to review under § 112(k) of the Clean Air Act and that receive scrap metal from persons subject to § 46.2-635 of the Code of Virginia.

- § 10.1-1328 F—This section is a state-specific rule that prohibits electric generating facilities in nonattainment areas from meeting mercury compliance obligations by purchasing credits from other facilities. An exception applies when the facility owner can demonstrate compliance using allowances at another of its facilities within 200 kilometers of the Virginia boarder.

These rules and provisions have been incorporated into the emissions estimates and the future-year emission inventories, staged them as appropriate, for each future year. The future-year emissions estimates also reflect the implementation timing and effects of the CAIR and CAMR emission reduction provisions (using the best available information at the time the work was conducted).

Preparation of the future-year mercury emissions included an analysis of expected emissions reductions, future-year trends for all source categories, and a comparison of Virginia emissions with neighboring states, regions, and national sources affecting Virginia.

The future-year criteria pollutant emissions inventories were based on EPA's 2010, 1015 and 2020 Clear Skies emission inventories (ref). The emissions for the 36-km domain were extracted directly from the inventories listed above. For the 12-km domain, the future-year emissions from the above inventories were allocated to the 12-km grid using spatial allocation factors. These factors were developed using the base-year (2001)12-km emission inventory. By applying these factors, the spatial distribution of emissions within each 36-km grid cell is the same for the base and future years but the amount of emissions reflects the future year. For all three future-years the criteria pollutant emissions were re-speciated for use with the CB05 chemical mechanism.

3.4.3. Emissions for AERMOD

Source-specific emissions estimates for input to AERMOD for both the baseline year and each future year were extracted from the CMAQ point-source emission inventory. Stack parameter, exit velocity, and stack diameter information for use by AERMOD was also extracted from the CMAQ emissions inventory.

3.5. Meteorological Data and Databases

As noted earlier, we made use of existing meteorological input files for this study. These were prepared by EPA for use in CMAQ modeling for the selected modeling domain using the MM5 meteorological model (EPA, 2005a; McNally, 2003). The MM5 outputs were postprocessed by EPA for input to CMAQ using the Meteorology-Chemistry Interface Processor (MCIP) program. The 2001 MM5-derived meteorological fields are available for both 36- and 12-km resolution. The 36-km meteorological fields were used directly, since the VDEQ 36-km domain is the same as that used by EPA. The 12-km meteorological fields for the VDEQ subdomain were extracted from a larger 12-km domain used by EPA.

The 2002 meteorological inputs used for sensitivity testing were also prepared by EPA (using MM5 and MCIP), for both 36- and 12-km resolution.

Corresponding meteorological inputs for AERMOD for 2001 were developed using observed data. For each source included in the AERMOD analysis, meteorological inputs were prepared using

available surface and upper-air meteorological data from nearby, geographically representative monitoring sites. The meteorological monitoring sites were paired with the source locations based on proximity, and similarities in geographical and land-use characteristics. Table 3-1 lists the AERMOD sources along with the matched surface and upper-air sites. The elevation of each location is given in the table. The distance between the facility and each of the paired meteorological monitoring sites is also listed.

Table 3-1. AERMOD Facilities and Paired Meteorological Monitoring Sites. Locations are in Virginia, Except Where Noted.

Facility Name	Facility Elevation (m)	Met Site Type	WBAN or CASTNet #	WBAN or CASTNet Name	Met Site Elevation (m)	Distance (km)
Dominion - Chesterfield Power Station	10.1	SFC	13740	Richmond	50	16.0
		UPR	93734	Sterling (Washington Dulles)	85	177.9
Chaparral Steel	50.3	SFC	13740	Richmond	50	38.7
		UPR	93734	Sterling (Washington Dulles)	85	199.9
Dominion - Bremo	67.1	SFC	93736	Charlottesville	190	49.2
		UPR	93734	Sterling (Washington Dulles)	85	158.0
American Electric Power-Clinch River	452.5	SFC	13877	Bristol-Johnson City-Kingsport, TN	465	53.4
		UPR	53829	Roanoke/Blacksburg	648	161.4
Dominion - Chesapeake Energy Center	4.0	SFC	13737	Norfolk	7	17.8
		UPR	93739	Wallops Island	13	147.8
Potomac River Generating Station	10.4	SFC	13743	Washington, DC	3	5.2
		UPR	93734	Sterling (Washington Dulles)	85	41.1
Dominion - Yorktown Power Station	4.0	SFC	93741	Newport News	13	9.7
		UPR	93739	Wallops Island	13	117.3
Jewel Coke Company LLP	365.9	SFC	13877	Bristol-Johnson City-Kingsport, TN	457	89.5
		UPR	53829	Roanoke/Blacksburg	648	144.6
Dominion-Possum Point Power Station	11.0	SFC	13773	Quantico	4	5.2
		UPR	93734	Sterling (Washington Dulles)	85	41.1
Stone Container Enterprises (Smurfit)	3.0	SFC	13740	Richmond	50	45.3
		UPR	93734	Sterling (Washington Dulles)	85	170.5

Stone Container Corporation - Hopewell	14.3	SFC	13740	Richmond	50	24.6
		UPR	93734	Sterling (Washington Dulles)	85	187.9
American Electric Power (Glen Lyn)	464.5	SFC	VPI120	Horton Station	920	27.4
		UPR	53829	Roanoke/Blacksburg	648	44.4
Intermet Foundry Archer Creek	167.6	SFC	13733	Lynchburg	287	16.2
		UPR	53829	Roanoke/Blacksburg	648	122.0
RES dba Steel Dynamics	301.8	SFC	13741	Roanoke	350	5.7
		UPR	53829	Roanoke/Blacksburg	648	37.3
Spruance Genco LLC	16.5	SFC	13740	Richmond	50	12.2
		UPR	93734	Sterling (Washington Dulles)	85	169.8

The meteorological inputs for AERMOD were generated using the AERMET program (EPA, 1998). For each location/site pair we needed to specify the roughness length, albedo and Bowen ratio based on the land-use characteristics of the area in which the surface meteorological monitoring site is located. This was accomplished by first assessing the land-use for each 100 by 100 m grid cell in a 3 km area surrounding the site. The land-use was plotted and divided in to sectors of similar land use based on visual inspection. For each sector the fractional land use was calculated. Each land-use value was assigned a value of roughness length, albedo and Bowen ratio based on tables provided in EPA (2007). (EPA. 2007 . "AERSURFACE User's Guide." Draft Version.) A weighted value for each parameter was calculated for each sector based on the fractional land use.

The remaining steps included: extraction of hourly surface and twice-daily upper-air data from the National Weather Surface (NWS) database, quality assurance of the data, merging of the surface and upper-air data, and application of AERMET to calculate the planetary boundary layer parameters required by AERMOD.

The meteorological inputs are contained in two files. The first file includes surface wind, temperature, pressure, relative humidity, and stability information as well as cloud cover and precipitation values. The second file contains information on the vertical structure of temperature and wind near the source location.

3.6. IC/BC, Land Use and Other Geophysical Data

For this study, we used existing initial condition, boundary condition, land-use and photolysis rate input files prepared by EPA for use in CMAQ modeling for the selected modeling domain and simulation period (EPA, 2005a). For mercury, the boundary conditions were extracted from the output of a global model (the CTM model).

3.7. Air Quality and Deposition Data

Air concentration and deposition data for the evaluation of model performance for both non-mercury and mercury species are described in Section 4.

4. Model Performance Evaluation

The evaluation of model performance for CMAQ and AERMOD is discussed in this section.

4.1. Overview of Model Performance

A typical application of any air quality and deposition modeling system consists of several simulations, including an initial simulation and a series of diagnostic and sensitivity simulations (designed to examine the effects of uncertainties in the inputs on the simulation results, identify deficiencies in the inputs, and investigate the sensitivity of the modeling system to changes in the inputs). For each simulation, model performance is primarily assessed through graphical and statistical comparison of the simulated pollutant concentrations and deposition amounts with observed data. The results of this comparison are used to guide the modeling analysis (through the determination of additional diagnostic and sensitivity simulations) and to assess whether the model is able to adequately replicate the air quality and deposition characteristics of the simulation period. Model performance evaluation tests and procedures and diagnostic and sensitivity analyses that may be performed to understand and improve model performance are discussed in this section.

EPA guidance (EPA, 2006a) stresses the need to evaluate a model relative to how it will be used in simulating the response to changes in emissions. In this study, we have used emissions contribution analysis together with comparisons with air quality and emissions trends to evaluate the reliability of the modeled response. Use of different models for regional and local scale mercury deposition has also helped us to evaluate the reasonableness of the responses and bound the response to the changes in mercury emissions.

The evaluation of model performance for CMAQ considered concentration and deposition of both mercury and non-mercury species. The emphasis of the model performance evaluation, however, was mercury deposition for Virginia and the mid-Atlantic region. Following EPA guidance for evaluating model performance, we examined 1) whether the CMAQ model is able to replicate observed (and estimated) mercury deposition data, and 2) whether the response of the model to changes in mercury emissions is reasonable.

For AERMOD, the evaluation of model performance was aimed at assessing the reasonableness of the simulated deposition amounts and spatial patterns, as well as the response of the model to changes in emissions.

4.2. Model Evaluation Datasets

4.2.1. Non-Mercury Species Concentrations and Deposition Data

The assessment of CMAQ model performance for non-mercury species considered air concentrations for ozone and fine particulate matter ($PM_{2.5}$) species, and deposition for selected PM species on a monthly and/or annual basis, depending on the pollutant.

Model performance for ozone was evaluated against observations available from the EPA Air Quality System (AQS) network. For the national-scale modeling domain, the number of sites ranges from approximately 500 to 1000, depending on the time of year. The sites are primarily located in urban areas. The daily maximum simulated ozone concentration for each monitor for each day of the annual simulation period was compared to the corresponding maximum observed concentration.

Measurements of $PM_{2.5}$ were obtained from the AQS network, which includes more than 200 sites, and the Interagency Monitoring of Protected Visual Environments (IMPROVE) network,

which samples approximately 100 Class I national parks and wilderness areas throughout the U.S. For $PM_{2.5}$ and its component species, daily average values were compared.

Observed wet deposition amounts of sulfate, nitrate, and ammonia from the National Acid Deposition Program (NADP) were used to assess the model's ability to simulate the deposition for each of these species. The NADP network includes more than 200, typically rural, sites. Monthly average values were compared.

4.2.2. Mercury Deposition Data

For mercury, the CMAQ wet deposition values were compared to data from the Mercury Deposition Network (MDN), as available from the National Acid Deposition Program (NADP). There are a total of 53 MDN monitors with complete data for 2001 in the full modeling domain.

Emphasis was given to the evaluation of model performance for the mid-Atlantic region. Mercury deposition data are available for MDN sites in several surrounding states, within and adjacent to the Mid-Atlantic region. The period of record for these sites varies, and there are several sites in Pennsylvania, North Carolina, and South Carolina that have data for 2001. Sites at the Allegheny Portage Railroad National Historic Site, Pennsylvania; Arendtsville, Pennsylvania; and Pettigrew State Park, North Carolina all have data for 2001 and are likely most representative, based on proximity and/or similar geographical features, to the areas of interest in Virginia. In particular, Pettigrew State Park, near the Albemarle Sound, may be representative of coastal Virginia.

Mercury wet deposition data for Virginia are available for three MDN monitoring sites, Shenandoah National Park (beginning in October 2002), Culpeper (beginning in November 2002) and Harcum (beginning in December 2004). The Culpeper site is located in central Virginia (near Richmond) and the Harcum site is located in coastal Virginia. Although there are no actual data for these sites for the 2001 simulation period, we used the data for 2003-2005 for sites in Virginia and throughout region to estimate deposition for 2001 at the Virginia monitoring sites. The estimated deposition values were used in the evaluation of model performance, primarily for CMAQ.

4.2.3. Estimated Mercury Deposition "Data"

We used the results from the CART analysis (which was conducted to support the development of the conceptual model) to estimate deposition for 2001 for the Virginia monitoring sites. Specifically, we classified each seven-day period in 2001 according to the observed meteorological conditions and determined the corresponding CART-based classification group. We assigned the daily average mercury deposition for the grouping (the daily average for all other periods in the classification group) to the 2001 weekly period (multiplying by 7 to get the weekly deposition amount). We did this for each period for the entire year of 2001 and then used the weekly mercury deposition values to estimate seasonal and annual deposition amounts. The key assumption here is that by matching the meteorological conditions for 2001 on a weekly basis to those for later years, observed mercury deposition for the later years can be used to estimate deposition for 2001. Applying this assumption on a weekly basis allowed us to account for the variable effects of meteorology throughout the year. We used a similar approach for the EPA OW, in order to estimate annual mercury deposition for a ten-year period (Douglas et al., 2003). EPA then used these values for water quality modeling and estimating fish tissue concentrations.

In order to confirm the reasonableness of these results, we also applied this same method for several additional sites with longer term records: including the Allegheny Portage Railroad National Historic Site, Arendtsville, and Pettigrew State Park (and these results were mixed). In addition, we compared ratios of the annual average deposition (for example, 2003/2001) for the nearby sites with observed data with those for the Virginia sites using the estimated data to ensure that the CART-derived estimated values are reasonable.

4.3. Model Performance Evaluation for CMAQ

The evaluation of model performance for CMAQ considered concentration and deposition of both mercury and non-mercury species. The non-mercury species include ozone, $PM_{2.5}$ and related species. For mercury, we compared the simulated total wet deposition with actual and estimated data for the MDN monitoring sites. We compared simulated and observed values of concentration and deposition for each site and the average over all sites within 1) the full domain, 2) the 12-km inner grid of the modeling domain, and 3) Virginia.

4.3.1. Statistical Performance Metrics

A variety of statistical measures were used to quantify model performance. These include

- Mean observed concentration or deposition = $1/N \sum O_I$
- Mean simulated concentration or deposition = $1/N \sum S_I$
- Ratio of means = $1/N \sum S_I / 1/N \sum O_I$
- Mean bias = $1/N \sum (S_I - O_I)$
- Mean fractional bias (expressed as percent) = $200 \cdot 1/N \sum (S_I - O_I)/ (S_I + O_I)$
- Mean error = $1/N \sum |SI - OI|$
- Mean fractional error (expressed as percent) = $200 \cdot 1/N \sum |S_I - O_I|/ (S_I + O_I)$
- Coefficient of determination (R^2) =
  $(\sum S_I O_I - \sum S_I \sum O_I/N)^2 /[(\sum O_I^2 - (\sum O_I)^2/N) \cdot (\sum S_I^2 - (\sum S_I)^2/N)]$

Where S is the simulated value, O is the observed value, and N is the number of simulation-observation pairs used in the calculation. Statistical measures were calculated on a monthly, seasonal and annual basis, based on data availability.

4.3.2. Graphical Analysis

Plots and graphics were also be used to assess the reasonableness of the results. Spatial plots of the simulated and observed values were used to qualitatively assess the ability of the model to emulate the spatial deposition patterns. Monthly time-series plots comparing these same values at the monitoring sites were used to determine whether the timing and magnitude of the simulated values matches the observations. Scatter plots were used to graphically compare the simulated and observed deposition values.

4.3.3. Diagnostic and Sensitivity Testing

To a large extent, model configuration for CMAQ was determined by the selection of the meteorological and emissions databases. Some additional testing was conducted to which of

the parameter settings are best suited for mercury deposition. We also explored how to maximize consistency between the AERMOD and CMAQ models.

Following the establishment of the modeling platform, we identified potential weaknesses in the model input fields and conducted some limited sensitivity simulations to examine the effects of these weaknesses or uncertainties. We examined the different estimates of boundary concentrations that are currently available (from the application of global models) and selected the mid range conditions. While no simulation tests with CMAQ were done, we tagged the boundary conditions using PPTM and were able to use the different global model estimates to estimate some bounds for the simulated global contribution. We also explored the sensitivity of the modeling results to the selection of the simulation period, by substituting the 2002 meteorological inputs and re-running CMAQ for a three-month (summer) period. This simulation allowed us to assess the importance of the meteorology in determining the amount of simulated mercury deposition and to ensure that the model responded in a reasonable way (based on our understanding of the meteorological differences) to changes in the meteorological conditions. In addition, we also used PPTM as a probing tool and examined the PPTM results to verify that the contributions from selected emission sources are commensurate with the locations and emissions of the sources as well as the prescribed meteorological conditions.

4.4. Model Performance Evaluation for AERMOD

For AERMOD, we conducted a limited performance evaluation to assess whether the model is able to simulate the deposition distributions and maximum values represented by the observed and estimated data. Sensitivity simulations were conducted to determine which of the parameter settings are best suited for mercury deposition and how to maximize consistency between the AERMOD and CMAQ models. With regard to model performance, we examined the response of the model for the sensitivity simulations to ensure that the model responds in a reasonable way (based on our current knowledge of near-source mercury deposition) to changes in the meteorological and emissions inputs.

4.5. Performance Goals and Benchmarks

In keeping with current EPA guidance on model performance evaluation for other pollutants, we used a “weight-of-evidence” approach to determine whether model performance for both CMAQ and AERMOD is good enough for use in future-year modeling and control measure assessment.

For CMAQ, this was based on the statistical performance measures, the response of the model to changes in the inputs, and the reasonableness of the PPTM contribution results.

For AERMOD, this was based on the comparison of simulated and estimated data—particularly the distribution and maximum values. We also compared the CMAQ and AERMOD results to assure that the simulated local contributions from AERMOD bound the CMAQ results, as they are more likely to represent the maximum impact from directly emitted divalent forms of mercury from a source.

4.6. Use of Model Performance Results to Guide the Interpretation and Use of Modeling Results

Information obtained as part of the model performance evaluation was used throughout the analysis to guide the interpretation and use of the future-year simulation results. For example,

although overall model performance for mercury deposition was reasonable for the mid-Atlantic sites, it varied from season to season. For some sites, this included overestimation of wet deposition during the winter months and underestimation during the summer months. Consequently, we examined the response of the model to changes in emissions (for the future-year scenarios) for each season as well as on an annual basis.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5. Assessment of Mercury Deposition

In this study, we used both the CMAQ and AERMOD models to examine the contributions of a variety of sources to mercury deposition to Virginia's "impaired" water bodies. The modeling analysis consisted of baseline modeling for 2001/2002 and future-year modeling for 2010, 2015, and 2018.

5.1. Baseline Modeling

5.1.1. CMAQ PPTM Scenarios

Several CMAQ/PPTM simulations were conducted using the baseline 2001/2002 emissions inventory. These simulations were designed to assess the contributions of various source sectors to mercury deposition to water bodies in Virginia.

The first scenario examined and quantified the contributions from mercury air emissions sources in 1) Virginia, 2) the mid-Atlantic region (or selected neighboring states), 3) all other U.S. states, 4) Canada and Mexico, 5) global emissions sources, and 6) natural emissions. We used CMAQ version 4.6 with PPTM. We assigned tags to each of the six regions/categories listed above. An initial/boundary condition tag was used to represent the global impact on deposition. This set of tags provides estimates of Virginia, regional, national, and global impacts on deposition for any location (grid cell or group of grid cells) within the state or the modeling domain.

The second scenario quantified the contributions from Electric Generating Unit (EGU) and non-EGU facilities in Virginia and the surrounding states. We tagged 1) all of Virginia's EGU sources and separately 2) all of the non-EGU sources in the state, 3) all EGU sources in the surrounding states (remainder of the 12-km grid), and 4) all non-EGU sources in the surrounding states. The results allow us to quantify and compare the contributions from these two source sectors to mercury deposition for any location (grid cell or group of grid cells) within the state or the modeling domain.

5.1.2. AERMOD Application

At the local scale, we applied the most recent version of the EPA Gaussian model AERMOD. The AERMOD modeling was performed for selected point sources in the Virginia emissions inventory (the top 15 emitters). We used AERMOD to estimate the maximum expected impact from each source based on the directly emitted mercury and to identify individual sources with a potentially significant local impact. AERMOD was applied separately for HG0, HG2 and HGP.

5.2. Future-year Modeling and Contribution Assessment

CMAQ was applied for 2010, 2015 and 2018, using emissions projected to these years. For 2010 and 2015, PPTM was not applied. For 2018, the same CMAQ/PPTM runs that were done for the baseline were conducted.

For each future year, we examined the simulated change in mercury deposition, overall and from each tagged (as possible) or modeled source or source category. The PPTM results were used to attribute the future-year reductions in mercury deposition for 2018 for each area of interest to the specific tagged sources or source categories.

AERMOD was also applied for 2010, 2015 and 2018 and the change in deposition relative to the base year was calculated.

5.3. Display and Analysis of the Modeling Results

Graphical and tabular summaries of the results were prepared. Plots of the CMAQ results were prepared for each CMAQ modeling domain and for each of the major water basins in the Commonwealth of Virginia. Tabular summaries of the overall and PPTM results were also assembled. Similarly, plots of the AERMOD results were prepared for each facility, showing the changes in deposition resulting from each future-year scenario. Analysis of the results focused on the effectiveness of the various measures and emissions changes in reducing future-year mercury deposition both statewide and within the key areas of interest. Given the uncertainties associated with mercury deposition modeling, we emphasize the relative changes in deposition associated with the emissions changes for each source and source category in our analysis of the results.

6. Procedural Requirements

Documents, technical memoranda, and databases developed in this study were submitted to VDEQ for review and distribution.

6.1. Reporting

In addition to this protocol document, other project documents include: 1) project work plan, 2) quality assurance plan, 3) memorandum summarizing the emissions data review, 4) draft and final versions of an emissions data analysis report, 5) draft and final versions of a conceptual model report, and 6) draft and final versions of a mercury deposition report.

The deposition modeling report contains an executive summary, technical details of all aspects of the modeling analysis (including input preparation, model performance evaluation, and the CMAQ and AERMOD results), a discussion of the uncertainties and limitations of the results, and information on how to access and utilize the modeling datasets.

6.2. Data Archival and Transfer of Modeling Files

All of the data, data files, and software required to corroborate the results and findings of the study areavailable from VDEQ. Files can made available by ftp methods (for the transfer of smaller files) and using portable disk drives (for the transfer of larger files and/or the complete database).


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Appendix B: Conceptual Model Report

Virginia Department of Environmental Quality (VDEQ)

Conceptual Description of Mercury Deposition for Monitored Areas in Virginia

Technical Report

February 13, 2008

07-034

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Conceptual Description of Mercury Deposition for Monitored Areas in Virginia

Technical Report

February 13, 2008

Prepared for
Michael Kiss
Virginia Department of Environmental Quality (VDEQ)
629 E. Main Street
Richmond, VA 23219
(804) 698-4460

Prepared by:
Sharon Douglas
Belle Hudischewskyj
Jay Haney
YiHua Wei
ICF International
101 Lucas Valley Road, Suite 260
San Rafael, CA 94903
(415) 507-7164

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1. Overview of Mercury Deposition

This document provides a conceptual description of mercury deposition for several locations in Virginia and the surrounding states. It includes a summary of observed mercury deposition data and trends, an analysis of the relationships between mercury deposition and meteorology, an overview of mercury emissions, and an examination of available mercury modeling results. The key questions to be addressed in the conceptual description include:

1. Is mercury deposition primarily a local issue, or are regional, national, and global factors important?
2. Are there any characteristic temporal (seasonal) patterns of mercury deposition?
3. Are there any characteristic spatial patterns of mercury deposition?
4. What are the specific meteorological parameters that influence mercury deposition in Virginia, and how important are each of these parameters?
5. Are there discernable trends in mercury deposition, and have recent changes in deposition been accompanied by changes in emissions or primarily driven by meteorological variability?
6. What is the relative importance of wet versus dry deposition, and the various mercury species?

Before addressing these issues for Virginia, we begin with a brief review of the science of mercury deposition including a discussion of the sources of airborne mercury, mercury chemistry, global and regional transport, mercury deposition mechanisms, and effects.

1.1. Sources of Airborne Mercury

Mercury in the atmosphere can be attributed to both natural and anthropogenic sources. The global cycle of mercury must also account for deposition of mercury to the earth's surface through a variety of wet and dry deposition processes and re-emission of mercury that has been previously deposited to the earth's surface back into the atmosphere.

Certain soils, rocks, and other geologic structures naturally contain mercury and therefore represent natural or geogenic sources of mercury emissions. Volcanic activity is thought to be an important but variable source of naturally occurring airborne mercury (Niagru and Becker, 2003). Within North America, most natural mercury emissions are associated with land types found in the western part of the continent. In addition to the land masses, the oceans are also a source of natural mercury emissions. Emissions fluxes from the ocean are thought to be greatest near the equator and to decrease toward the poles (Seigneur et al., 2003; Kim and Fitzgerald, 1986).

Anthropogenic sources of mercury include coal-fired power plants and other industrial coal-burning facilities, municipal, medical, industrial and hazardous waste incinerators, chlor-alkali and other chemical manufacturing plants, taconite and other metallurgical processing facilities, pulp and paper manufacturing facilities, mining operations, cement plants, mobile sources, and a wide variety of other industrial and residential sources (EPA, 2005a).

Re-emission of both natural and anthropogenic emissions from both land and water areas is an important part of the global mercury budget. Over land, prescribed burning and wild fires can increase the rate of re-emission.

Currently, it is estimated that global mercury emissions are equally apportioned among natural emissions, direct anthropogenic emissions, and re-emission of previously deposited natural and anthropogenic emissions (Valente et al., 2007).

1.2. Mercury Chemistry

Airborne mercury (Hg) is comprised of three forms: elemental mercury (Hg(0)), reactive gaseous mercury (RGM), and particulate mercury (Hg(p)). RGM is known to be comprised almost entirely of divalent mercury (Hg^{2+} or Hg(II)), since mercury compounds at other valence states tend to be chemically unstable in the atmosphere (Bullock et al., 2007). Hg(p) is also primarily comprised of divalent mercury, but may also include elemental mercury.

Elemental mercury is the dominant atmospheric species and comprises about 99 percent of the total mercury in the atmosphere. Hg(0) is characterized by low reactivity and low solubility in water. The dry deposition velocity is believed to be relatively low. Hg(0) has a long atmospheric lifetime (perhaps on the order of months to years) and is therefore dispersed and transported/circulated globally.

RGM represents less than one percent of atmospheric mercury. It is highly reactive and highly soluble. It can be actively removed from the atmosphere through both wet and dry deposition processes. As a result, the atmospheric lifetime of RGM is expected to be on the order of one day to one week. Based on these properties, RGM likely contributes to mercury deposition near the source location (locally or regionally).

Hg(p) also represents less than one percent of atmospheric mercury. It is moderately reactive and highly soluble in water. It is likely removed from the atmosphere primarily through wet deposition, since the dry deposition velocity of Hg(p) is expected to be low (based on that for similar fine particles). The atmospheric lifetime of Hg(p) is estimated to be on the order of one day to one week, or longer in the absence of precipitation. Based on these properties, Hg(p) also likely contributes to mercury deposition near the source location (locally or regionally).

Chemical transformations transfer mercury mass from one of these states to another. Several gas phase and aqueous phase reactions and equilibrium processes are expected to be important in the transformation of mercury (Seigneur et al., 2003):

Equilibrium processes

$Hg(0)\ (g) \leftrightarrow Hg(0)\ (aq)$

$HgCl_{2\ (g)} \leftrightarrow HgCl_2\ (aq)$

$Hg(OH)_2\ (g) \leftrightarrow Hg(OH)_2\ (aq)$

$HgCl_2\ (aq) \leftrightarrow Hg^{2+} + 2Cl^-$

$Hg(OH)_2\ (aq) \leftrightarrow Hg^{2+} + 2OH^-$

$Hg^{2+} + SO_3^{2-} \leftrightarrow HgSO_3$

$HGSO_3 + SO_3^{2-} \leftrightarrow Hg(SO_3)_2^{2-}$

$Hg(II)\ (aq) \leftrightarrow Hg(II)\ (p)$

Gas phase transformations

$Hg(0)\ (g) + O_3\ (g) \rightarrow Hg(II)\ (g)$

$Hg(0)\ (g) + HCl\ (g) \rightarrow HgCl_2\ (g)$

$Hg(0)\ (g) + Cl_2\ (g) \rightarrow Hg\ Cl_2\ (g)$

$Hg(0)\ (g) + H_2O_2\ (g) \rightarrow Hg(OH)_2\ (g)$

$Hg(0)\ (g) + OH\ (g) \rightarrow Hg(OH)_2\ (g)$

Aqueous phase transformations

$Hg(0)\ (aq) + O_3\ (aq) \rightarrow Hg^{2+}$

$HgSO_3\ (aq) \rightarrow Hg(0)\ (aq)$

$Hg(II)\ (aq) + HO_2\ (aq) \rightarrow Hg(0)\ (aq)$

$Hg(0)\ (aq) + HOCl\ (aq) \rightarrow Hg^{2+}$

$Hg(0)\ (as) + OCl^- \rightarrow Hg^{2+}$

Aqueous phase reactions occur primarily in clouds and fog. The chlorine pathway is considered to be active only at night. In the above formulae Hg(II) (g) refers to divalent gaseous mercury (or RGM) and Hg (II) (p) refers to divalent particulate mercury (or Hg(p)). Hg(p) is assumed to be adsorbed onto fine particles (such as soot particles).

1.3. Global and Regional Transport

Various atmospheric processes influence the dispersion, advection, and transport of mercury. With an atmospheric lifetime that may be on the order of months to years, Hg(0) is dispersed and transported globally by atmospheric circulation systems and regionally by synoptic scale weather systems. Similarly, with atmospheric lifetimes on the order of a week, RGM and Hg(p) may also be subject to regional-scale transport. The global and regional transport of mercury is an important consideration in any analysis of mercury deposition. Recent modeling studies (e.g., Myers et al., 2006) have indicated that for most areas in the U.S., global background may account for as much as 25 to 50 percent or more of mercury deposition, with the greatest percent contribution from global background occurring along the west coast. According to these modeling studies, the contribution from upwind sources (the regional transport component) increases from west to east across the U.S., consistent with the presence of anthropogenic emissions sources, prevailing wind conditions, and the movement of synoptic scale weather systems (primarily from west to east).

1.4. Deposition Mechanisms

Various atmospheric processes also influence the wet and dry deposition of mercury onto land and water surfaces.

Wet deposition is the scavenging of gasses and particulates from the atmosphere by precipitation, and their subsequent deposition (via precipitation) to the surface. Dry deposition occurs upon contact with the surface and the deposition flux is proportional to the concentration of mercury in the atmosphere as well as the adsorption properties of the species and the uptake properties of the surface.

As noted earlier Hg(0) is not very soluble in water. In addition, dry deposition of Hg(0) is not expected to be rapid. RGM and HG(p) are highly soluble and therefore subject to wet deposition. Dry deposition of both RGM and Hg(p) is also expected, and determining their respective dry deposition velocities is an area of ongoing research.

A majority of measurements of mercury deposition are limited to wet deposition. Recent modeling studies (e.g., Myers, 2006) indicate that for most areas in the U.S. on an annual basis both wet and dry depositions are important to total mercury deposition. For many areas, the simulated annual wet and dry deposition amounts are about equal.

Once deposition occurs, mercury can be re-emitted from both land and water surfaces (e.g., Sofiev and Galperin (2000)). Prescribed burning and wild fires may account for some of the re-emissions. Other natural processes, including microbial activity, may also account for some of the re-emission (Syrakov, 1998). Re-emission of mercury is mainly in the form of Hg(0) (Schluter, 2000)

1.5. Impacts of Mercury Deposition on Aquatic Ecosystems

In the U.S., more than 8,500 individual bodies of water have been identified as mercury impaired and the primary source of mercury to these water bodies is believed to be atmospheric deposition. Mercury deposition affects the viability of aquatic ecosystems in a number of different ways. The sustainability of marine life, recreational and commercial fishing, and human health can be directly or indirectly affected by mercury deposition and the build up of mercury in lakes, streams, rivers, and wetland areas. In certain bodies of water such as those with low dissolved oxygen, high organic matter content, and low acidity, mercury deposition can lead to the formation and build up of the highly bio-accumulative form of mercury (methyl mercury).

Human exposure to mercury is most commonly associated with the consumption of contaminated fish. Due to measured high levels of mercury in fish, at least 44 U.S. states have, in recent years, issued fish consumption advisories. These advisories cover more than 2000 individual bodies of water and may suggest limits on the consumption of certain types of fish or recommend limiting or not eating fish from certain bodies of water because of unsafe levels of mercury contamination.

Within Virginia, fish consumption advisories have been issued for several bodies of water for which atmospheric deposition is thought to be the primary source of mercury. These are primarily located along the coastal plain, and have characteristics that are consistent with mercury methylation and bioaccumulation of mercury in fish. The “mercury sensitive waters” include: Lake Gordonsville (in Louisa Co.), Lake Whitehurst (in Norfolk), Lake Trashmore (in Virginia Beach), a portion of the Mattaponi River, a portion of Herring Creek, a portion of the Pamunkey River, Chickahominy Lake (in Charles City Co.), Harrison Lake (in Charles City Co.), portions of the Blackwater River, a portion of the Dismal Swamp Canal, and Dragon Run Swamp.

Other areas suspected of being “mercury sensitive waters” and undergoing monitoring in 2006-2007 include additional portions of the Blackwater River, the Nottoway River, and the Meherrin River.

2. Summary of Observed Mercury Deposition for Virginia and Surrounding States

In this section, we summarize the availability and characteristics of the observed mercury wet deposition data for monitoring sites located in Virginia and several surrounding states.

2.1. Site-Specific Mercury Deposition Amounts, Characteristics and Trends

Mercury wet deposition data are available for three Mercury Deposition Network (MDN) sites in Virginia: Culpeper, Shenandoah National Park, and Harcum (NADP, 2007). The period of record for the MDN data is late 2002 through 2006 for Culpeper, late 2002 to the present for Shenandoah, and approximately 2005 to the present for the Harcum site. The Culpeper site is located in north central Virginia. The Shenandoah site is a high elevation monitoring site located within the national park (in northwestern Virginia), while the Harcum site is located along the southern portion of the inner coast of the Chesapeake Bay. Each measurement of wet deposition represents an approximate seven-day period. Annual mercury wet deposition for these sites is summarized in Table 2-1. Figure 2-1a shows the location of these sites as well as other selected MDN sites in neighboring states. Figure 2-1b highlights the Virginia MDN sites and also shows the locations of nearby surface and upper-air meteorological monitoring sites that will be referred to later in the report.

Table 2-1. Summary of Annual Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia.

Site Name (MDN ID)	Annual Observed Mercury Wet Deposition (ng m^{-2})		
	2003	2004	2005
Culpeper (VA08)	13,097	7,784	8,811
Shenandoah National Park (VA28)	11,922	9,727	7,074
Harcum (VA98)	—	—	8,218

Figure 2-1a. Locations of MDN Monitoring Sites in Virginia and Neighboring States.

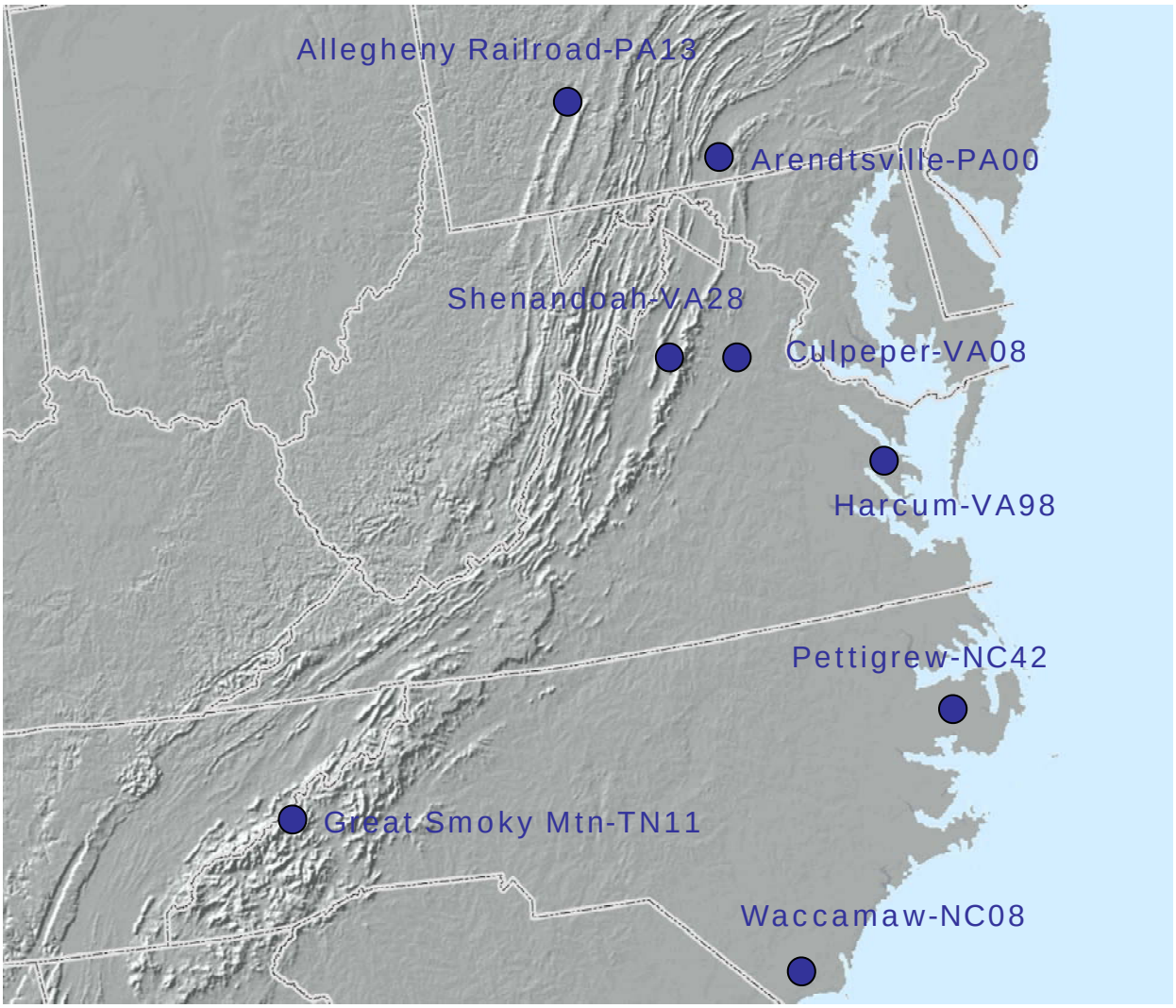
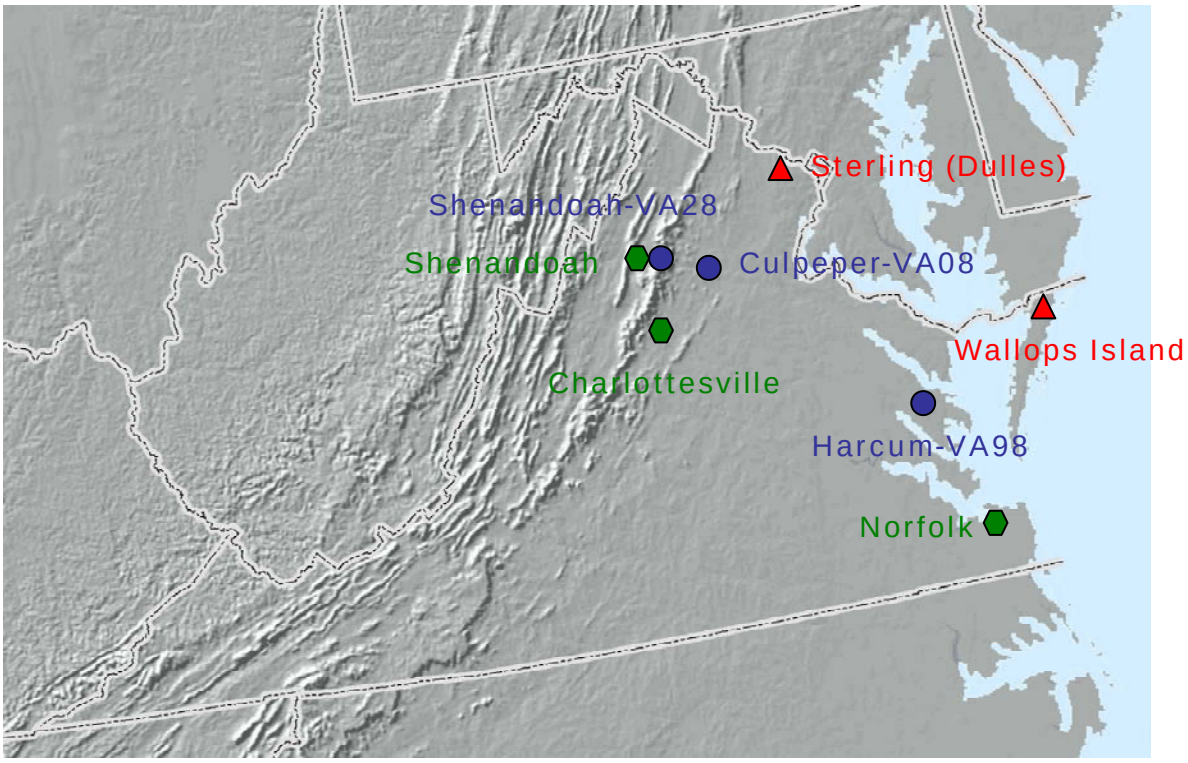


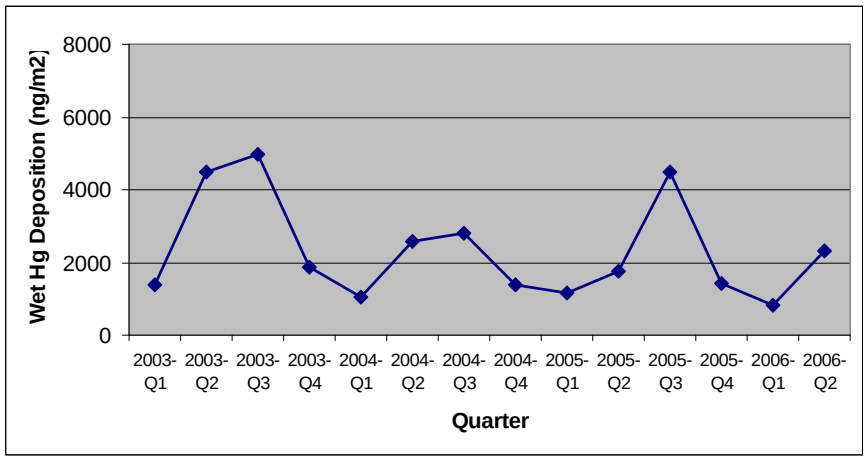
Figure 2-1b. Locations of MDN Monitoring Sites (Blue) and Nearby Surface (Green) and Upper-Air (Red) Meteorological Monitoring Sites in Virginia.



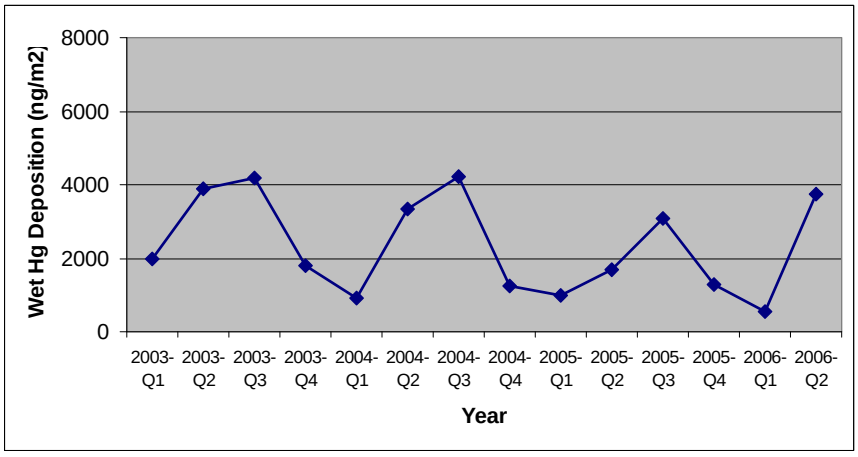
Within each calendar year, there are variations in deposition by week, month, and quarter, primarily in accordance with variations in rainfall amount. Figure 2-2, which displays quarterly deposition amounts, suggests that mercury deposition (and thus rainfall amounts) appear to have an annual cycle, with higher deposition amounts during the second and third quarters (April through June and July through September, respectively).

Figure 2-2. Quarterly Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia.

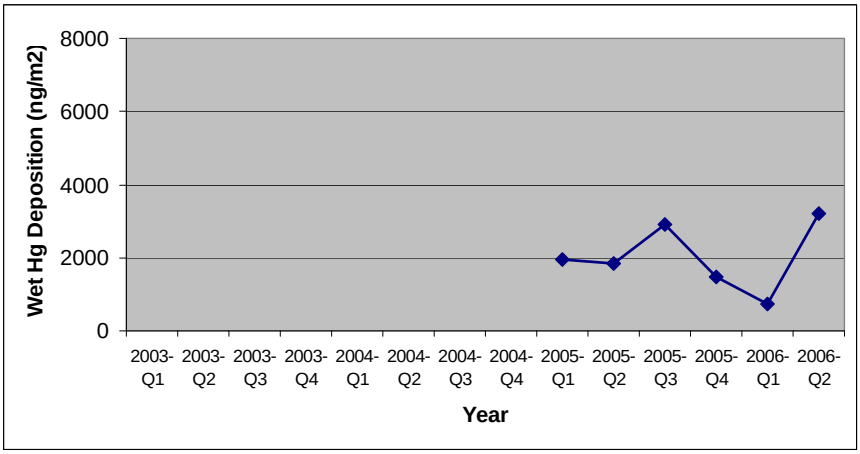
(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)

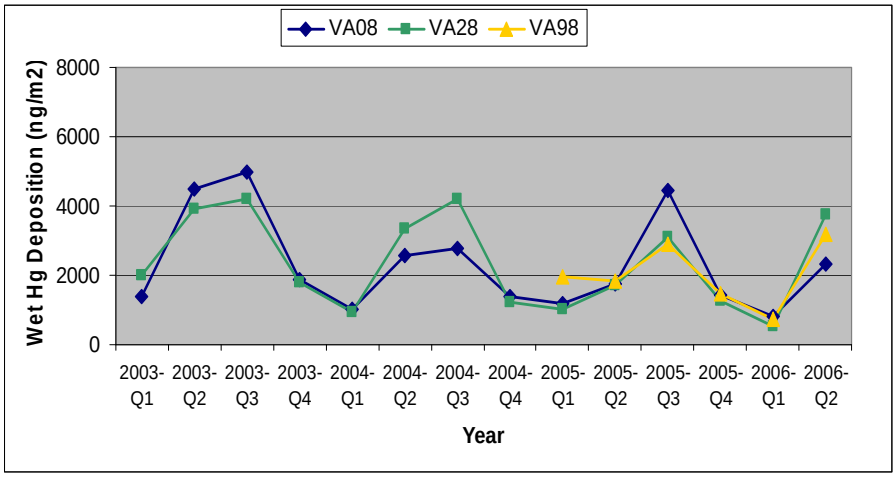


(c) Harcum (VA98)



When plotted together (Figure 2-3), the annual cycle shows up clearly and we see that the deposition amounts are generally similar among the three sites but that there are some differences.

Figure 2-3. Quarterly Observed Mercury Wet Deposition (ng m^{-2}) for the Three MDN Monitoring Sites in Virginia.



With only three full calendar years of data, it is difficult to assess annual variations and trends. Therefore, we also obtained and examined data for several other MDN sites located in neighboring states. For each site, the site ID, site name, location, elevation, and period for which data are currently available are listed in Table 2-2.

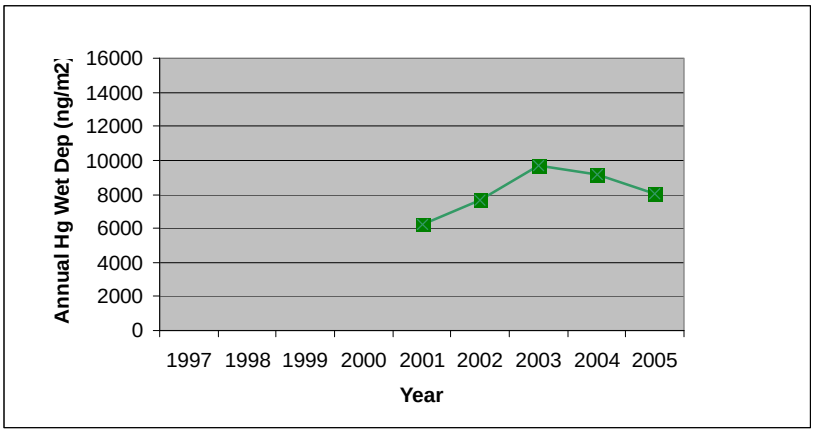
Table 2-2. List of MDN Monitoring Sites in Virginia and Several Surrounding States.

Site ID	Site Name	Latitude (degrees)	Longitude (degrees)	Elevation (m)	Period of Record
VA08	Culpeper	38.42	-78.10	163	11/19/02 - 6/30/06
VA28	Shenandoah National Park	38.52	-78.44	1074	10/22/02 - 6/30/06
VA98	Harcum	37.53	-76.49	13	12/17/04 - 6/30/06
NC08	Waccamaw State Park	34.26	-78.48	10	7/1/96 - 6/30/06
NC42	Pettigrew State Park	35.74	-76.51	2	7/1/96 - 6/30/06
PA00	Arendtsville	39.92	-77.31	269	11/14/00 - 6/30/06
PA13	Allegheny Portage Railroad National Historic Site	40.46	-78.56	739	1/9/97 - 6/30/06
TN11	Great Smoky Mountains National Park	35.66	-83.59	640	1/30/02 - 6/30/06

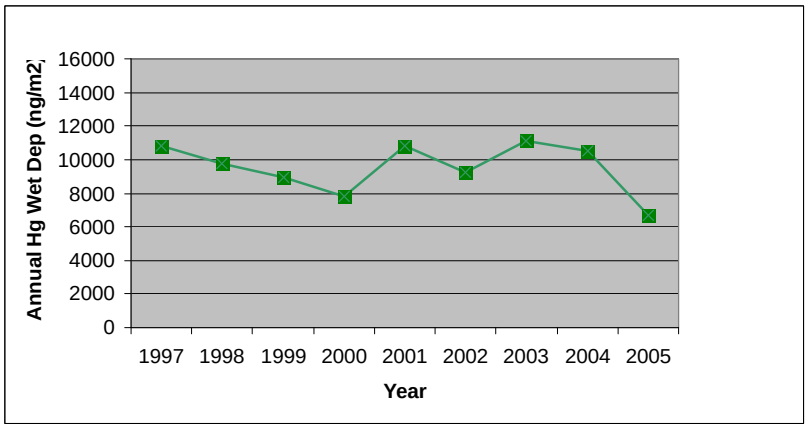
In addition to having longer data records, the sites in Arendtsville, Pennsylvania (near Gettysburg, along the PA/MD border), Allegheny Portage Railroad National Historic Park in the southern Allegheny Mountains of Pennsylvania, and Pettigrew State Park in coastal, northeastern North Carolina also have some geographical similarities (with respect to location, elevation, and proximity to the coastline) to the three Virginia sites (Culpeper, Shenandoah, and Harcum, respectively). The observed annual variations in mercury wet deposition for these three neighboring sites are displayed in Figure 2-4.

Figure 2-4. Annual Observed Mercury Wet Deposition (ng m^{-2}) for Selected MDN Monitoring Sites in Pennsylvania and North Carolina.

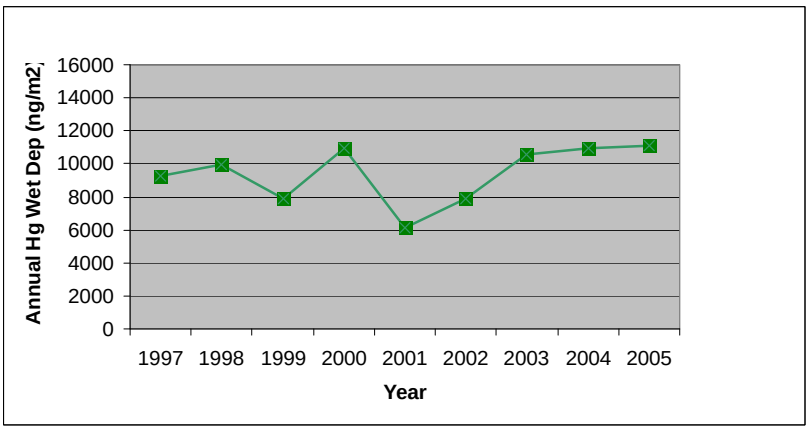
(a) Arendtsville, PA (PA00)



(b) Allegheny Portage Railroad National Historic Site, PA (PA13)



(c) Pettigrew State Park, NC (NC42)

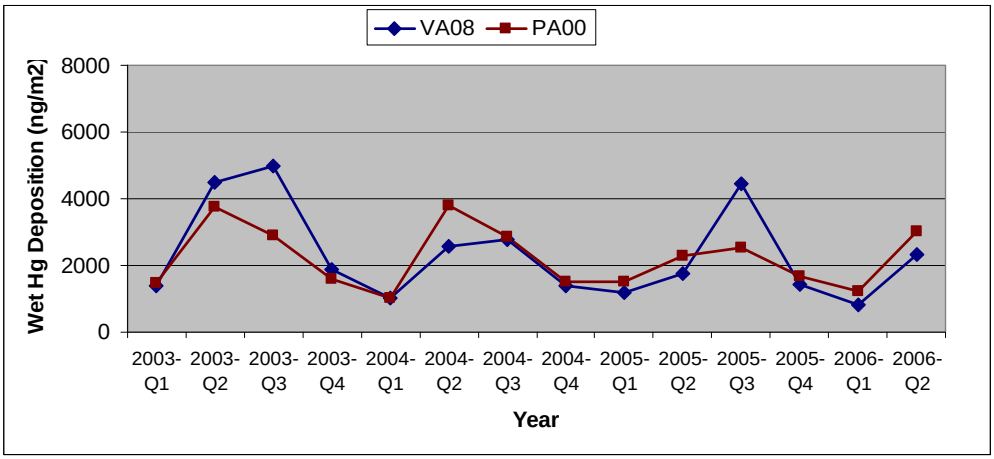


For all three neighboring sites, there is significant year-to-year variation in mercury wet deposition and this most likely reflects year-to-year variability in the meteorological conditions, particularly rainfall. The data do not reveal an obvious trend; however, more analysis of the meteorology and emissions is needed to ascertain any underlying trend in the data.

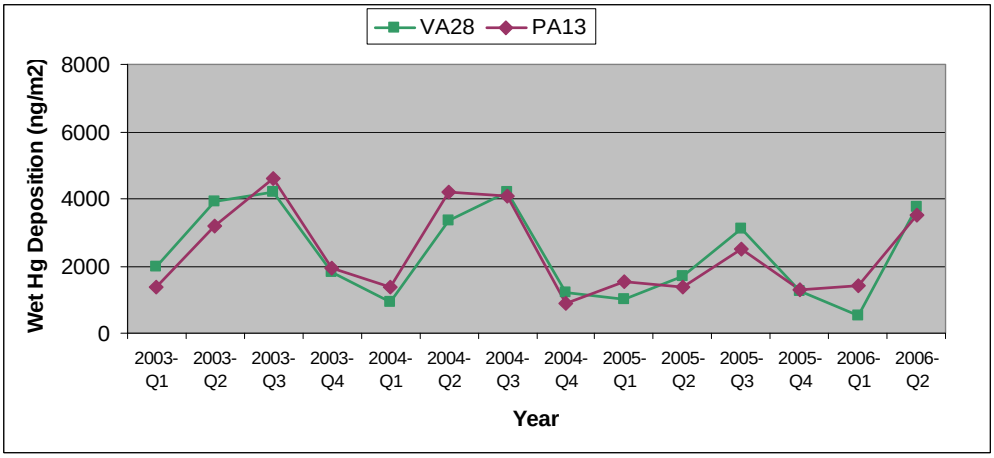
The corresponding quarterly deposition amounts are compared with the quarterly deposition amounts for the Virginia sites that are best matched to these sites in Figure 2-5.

Figure 2-5. Quarterly Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia and Selected Sites in Pennsylvania and North Carolina.

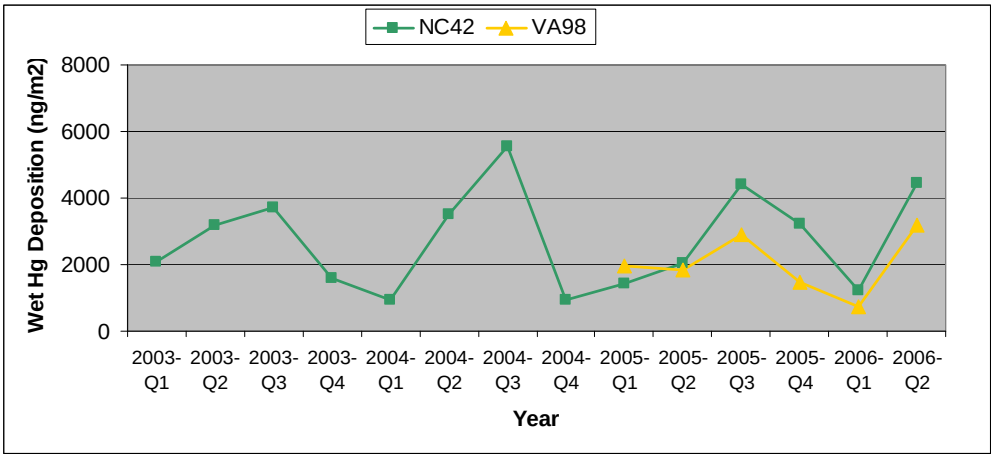
(a) Culpeper (VA08) and Arendtsville, PA (PA00)



(b) Shenandoah National Park (VA28) and Allegheny Portage Railroad National Historic Site, PA (PA13)



(c) Harcum (VA98) and Pettigrew State Park, NC (NC42)



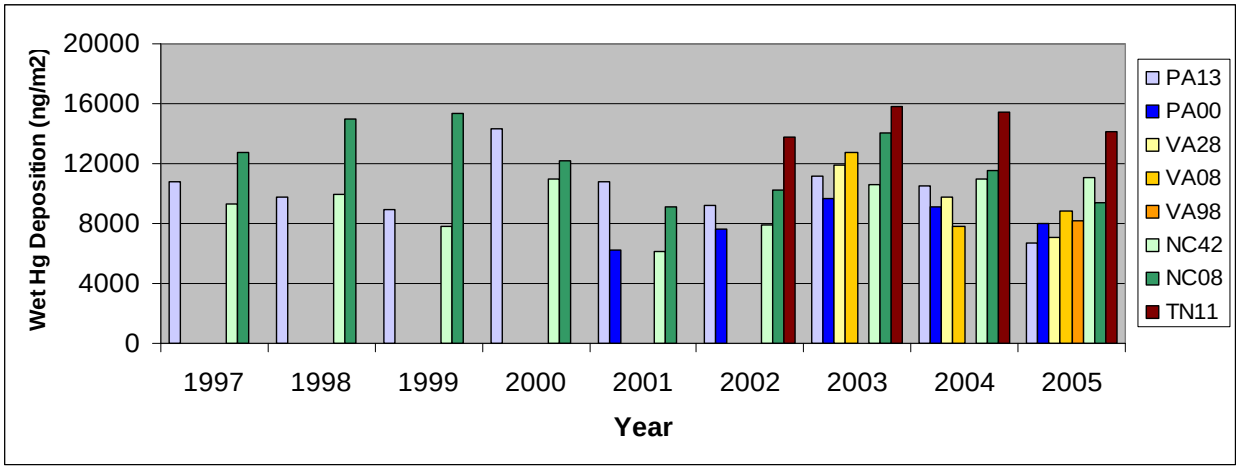
Culpeper has higher deposition than Arendtsville for two of the Q3 periods (2003 and 2005), while Arendtsville is higher for the 2004 Q2 period (Figure 2-4a). Otherwise, deposition at the two sites is similar. The deposition data for the two higher elevation sites (Figure 2-4b) is very similar. Along the coast, Harcum is characterized by lower deposition than Pettigrew State Park (Figure 2-4c).

2.2. Spatial Variations in Mercury Deposition

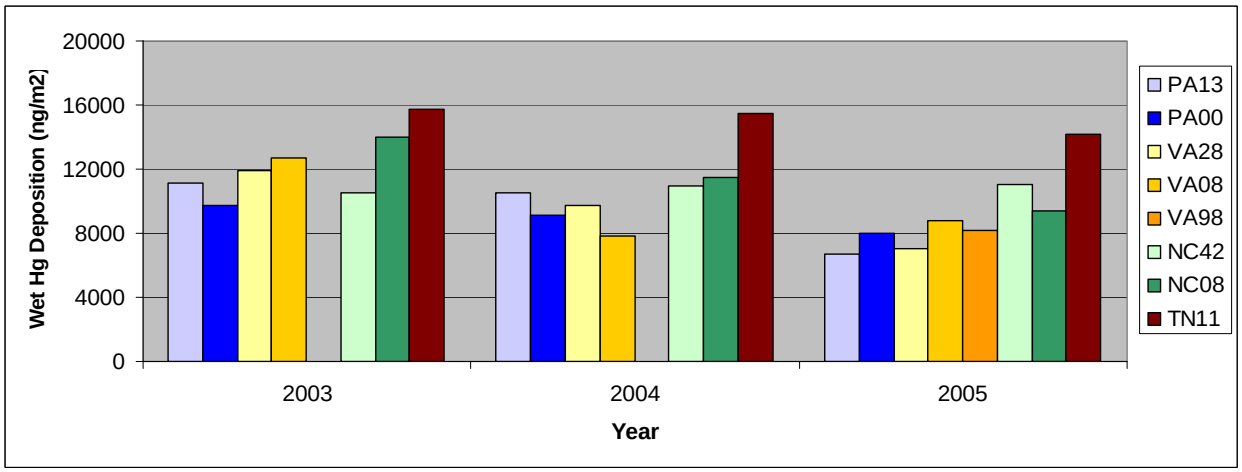
Spatial and temporal variations for all eight sites included in this analysis are further displayed in Figure 2-6. Figure 2-6a shows annual mercury wet deposition data for all sites for 1997-2005, as available. Figure 2-6b focuses on 2003 to 2005, when data are available for Virginia.

Figure 2-6. Annual Observed Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia and Neighboring States.

(a) 1997-2005



(b) 2003-2005



This display indicates that annual deposition amounts for sites in Pennsylvania and Virginia are similar for 2003 to 2005. Sites in North Carolina tend to have higher deposition amounts than sites in Virginia, with some exceptions. Deposition at the Great Smoky Mountains site in Tennessee is consistently higher than that at the other sites.

The mercury deposition data are coupled with meteorological and emissions data and examined further in the following sections.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3. Meteorological Influences

In this section, we examine the relationships between meteorological conditions and mercury wet deposition for monitoring sites in Virginia. Scavenging by precipitation is an important removal mechanism for mercury in the atmosphere. Thus, mercury wet deposition is clearly linked with precipitation. This analysis examines whether observed mercury wet deposition is more influenced by the amount or duration of precipitation (or both) and whether deposition is also influenced by other meteorological factors.

3.1. Overview of Meteorological Factors Influencing Mercury Deposition

As noted above, precipitation is an important mechanism for wet mercury deposition. All of the factors that contribute to precipitation events are therefore potentially important to mercury deposition. These include upper-level synoptic-scale airflow and pressure patterns that guide the movement of regional-scale weather patterns and features, including low pressure systems, associated frontal systems, and possibly other precipitation generating events (e.g., tropical storms and hurricanes), and cause precipitation to occur over Virginia. They also include local meteorological factors such as temperature, humidity, stability, and wind speed that control the development and severity of small-scale precipitation events, such as thunderstorms.

Wind directions, both near the surface and aloft, may influence the regional and local transport of mercury emissions from source regions or individual sources for subsequent deposition at the monitoring sites (and to bodies of water) in Virginia.

Although not considered in this analysis, dry deposition of mercury will be influenced by several meteorological factors including the stability of the atmosphere and the wind speed. These factors influence the near surface concentration of airborne mercury, determine the turbulence characteristics of the atmosphere, and consequently determine dry deposition velocities.

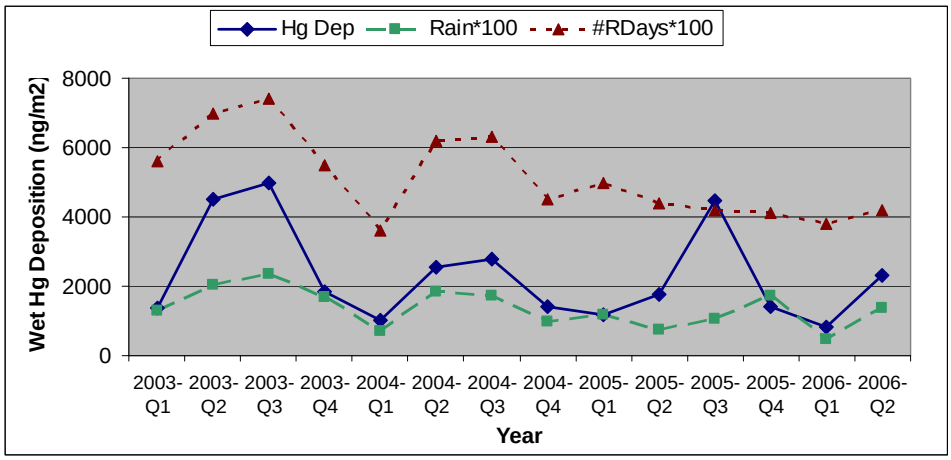
3.2. Precipitation Effects

Figure 3-1 compares quarterly mercury wet deposition with rainfall amount and number of days with measurable rainfall for the three MDN sites in Virginia. Precipitation data from nearby Class I National Weather Service (NWS) meteorological monitoring sites with complete data for the analysis period were used for this comparison. For the Culpeper site, the matched meteorological monitoring site is in Charlottesville, VA (about 44 km away). For the Harcum site, the matched meteorological monitoring site is in Norfolk, VA (about 69 km away). For Shenandoah, precipitation is measured at the MDN site. (Refer to Figure 2-1b.)

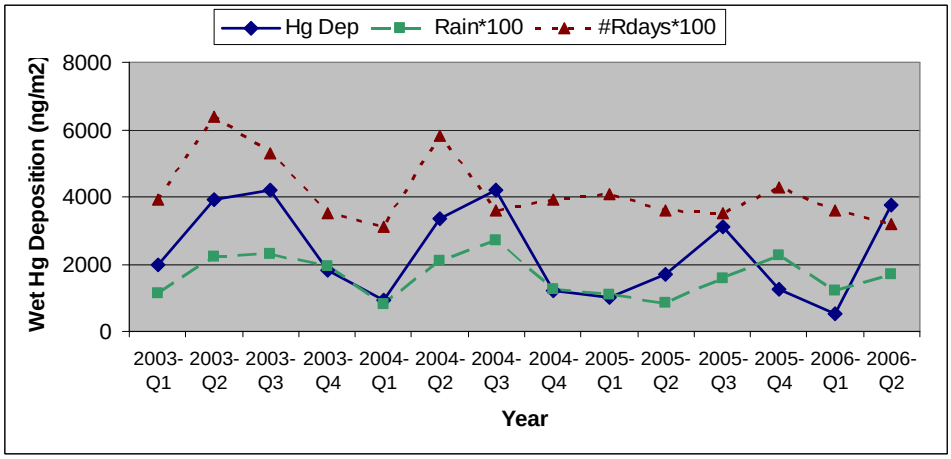
For all three site pairs, there appears to be a relationship between rainfall amount and mercury deposition, although mercury deposition is not fully explained by rainfall amount. Similarly, the number of rain days also appears to be well correlated with the deposition amount for all three sites, especially during 2005-2006. Note that for Culpeper and Harcum, the distance between the MDN and meteorological monitoring sites might contribute to the differences in timing between deposition and rainfall (especially in the event of localized rainfall that affects one but not both of the locations). Nevertheless, the agreement between mercury deposition and precipitation is no better for Shenandoah than for the other two sites. This simple analysis indicates that mercury deposition is affected by the amount and frequency of precipitation, but that there are also other factors that influence mercury deposition. These are explored further in the following sections.

Figure 3-1. Quarterly Observed Mercury Wet Deposition (ng m^{-2}), Total Rainfall (Scaled to Inches x 100), and Number of Days with Rainfall (Scaled by 100).

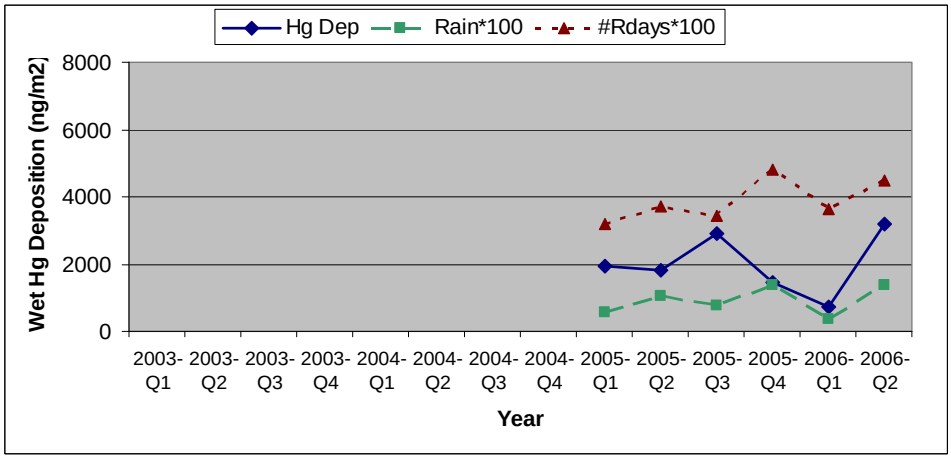
(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



(c) Harcum (VA98)



3.3. Regional-Scale Wind Patterns

As noted earlier, wind directions, both near the surface and aloft, may influence the regional and local transport of mercury emissions from source regions or individual sources for subsequent deposition at the monitoring sites (and to bodies of water) in Virginia.

Plots comparing the frequency of wind directions and speeds for all periods versus high mercury deposition periods are provided in Figure 3-2 through 3-10. The high mercury deposition periods are defined separately for each site and include the top 20 percent of the periods with the highest mercury deposition totals. The MDN sites were matched with surface and upper-air meteorological monitoring sites, based on location and data completeness. For the Culpeper site, the matched surface meteorological monitoring site is in Charlottesville, VA (about 44 km away) and the upper-air monitoring site is in Sterling, VA (Dulles Airport) (about 83 km away). For Shenandoah, surface winds are monitored at the location of the MDN site and the nearest upper-air site is Dulles Airport (about 98 km away). For the Harcum site, the selected surface meteorological monitoring site is in Norfolk, VA (about 69 km away) and the nearest upper-air site is at Wallops Island, VA (about 99 km away). (Refer to Figure 2-1b).

The upper-air data are from National Weather Service (NWS) radiosonde monitoring sites, and are available twice per day, at approximately 0700 and 1900 EST. In the plots, we examine data for 850 mb, which is approximately 1500 m above ground level (agl). The upper-air wind data are used here to represent the regional-scale wind patterns. The surface wind data are intended to represent local wind information.

We present the wind data as wind rose diagrams. In these diagrams, wind direction is defined as the direction from which the wind is blowing. The length of the bar within that wind-direction sector indicates the frequency of occurrence of a particular wind direction. The shading indicates the distribution of wind speeds. We specifically examine the distribution of wind direction for all periods and, separately, for high mercury wet deposition periods. Distinguishing features in the wind plots for the high deposition periods, when contrasted to those for all periods, may help to define the wind and/or transport patterns associated with high deposition events. Our qualitative discussion of differences between the plots is not intended to imply that the differences are significant. They are simply provided to advise the reader of our observations.

The 850 mb morning wind distributions for Dulles Airport for all periods and high mercury deposition periods for Culpeper are presented in Figure 3-2. Winds at this level are most frequently from the west to northwest. A comparison of the wind diagrams for the morning sounding time for all days and days within the high deposition periods reveals that the distributions are similar but that there are some differences. For example, there is a slightly greater tendency for easterly winds and a slightly lesser tendency for northerly winds during the high deposition periods.

The 850 mb evening wind distributions for Dulles Airport for all periods and high mercury deposition periods for Culpeper are presented in Figure 3-3. The wind diagrams for the evening period show a greater tendency for both southwesterly and northerly winds during the high deposition periods.

The surface wind distributions for Charlottesville for all periods and high mercury deposition periods for Culpeper are presented in Figure 3-4. Winds at the surface are most frequently from the south to southwest. The wind diagrams for both sets of days are similar, but there are some differences.

The 850 mb morning wind distributions for Dulles Airport for all periods and high mercury deposition periods for Shenandoah are presented in Figure 3-5. Winds at this level are most frequently from the west to northwest. A comparison of the wind diagrams for the morning sounding time for all days and days within the high deposition periods reveals that the distributions are similar but that there are some differences. For example, the wind diagrams show a slightly greater tendency for northeasterly winds and a slightly lesser tendency for northwesterly to northerly winds during the high deposition periods. Winds from the southwest are also slightly less frequent.

The 850 mb evening wind distributions for Dulles Airport for all periods and high mercury deposition periods for Shenandoah are presented in Figure 3-6. As for the morning period, the wind diagrams for the evening period show a slightly greater tendency for northeasterly winds and a slightly lesser tendency for northwesterly to northerly winds during the high deposition periods.

The surface wind distributions for all periods and high mercury deposition periods for Shenandoah are presented in Figure 3-7. Winds at the surface are most frequently from the west to northwest at this high elevation site. The wind diagrams show a greater tendency for westerly winds during the high deposition periods.

The 850 mb morning wind distributions for Wallops Island for all periods and high mercury deposition periods for Harcum are presented in Figure 3-8. Winds at this level and time are most frequently from the southwest to northwest. Comparison of the wind diagrams reveals a different distribution during the high deposition periods that includes a greater predominance of winds from the northwest.

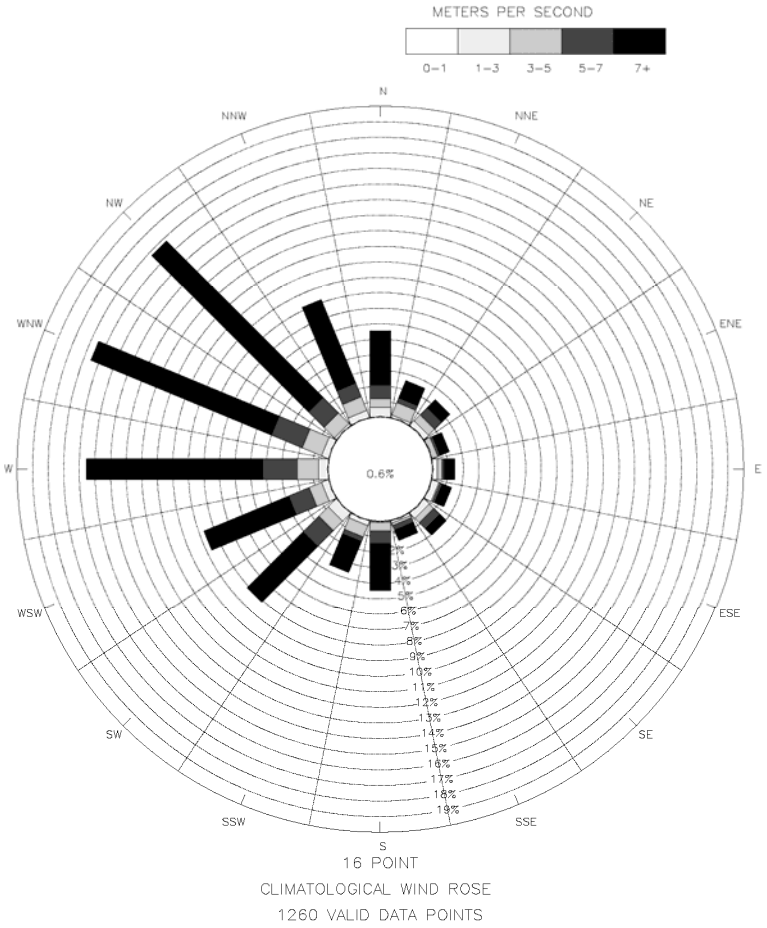
The 850 mb evening wind distributions for Wallops Island for all periods and high mercury deposition periods for Harcum are presented in Figure 3-9. Winds are predominantly from the west to northwest, with some periods of southerly to southwesterly winds. The wind diagrams for the evening period show a slightly greater tendency for southerly winds during the high deposition periods.

The surface wind distributions for Norfolk for all periods and high mercury deposition periods for Harcum are presented in Figure 3-10. The wind rose for the surface indicates a broad range of wind directions, with a greater frequency of winds from the northeast and south-southwest, compared to other directions. For the higher deposition periods, the predominance of these directions is less pronounced and there is an increase in the frequency of winds from the south-southeast.

For all three sites, the wind rose diagrams show that wind directions are slightly different during high deposition periods compared to all periods. This could be an indication of regional or local transport of mercury emissions from the indicated directions (very generally from the east or northeast for Culpeper and Shenandoah, and from the south or southwest for Harcum).

Figure 3-2. Distribution of Wind Speed and Direction at the 850 mb Level for the Sterling, VA (Dulles Airport) Sounding for 0700 EST.

(a) All Periods (November 2002 to June 2006)



(b) High Mercury Deposition Periods for Culpeper (VA08)

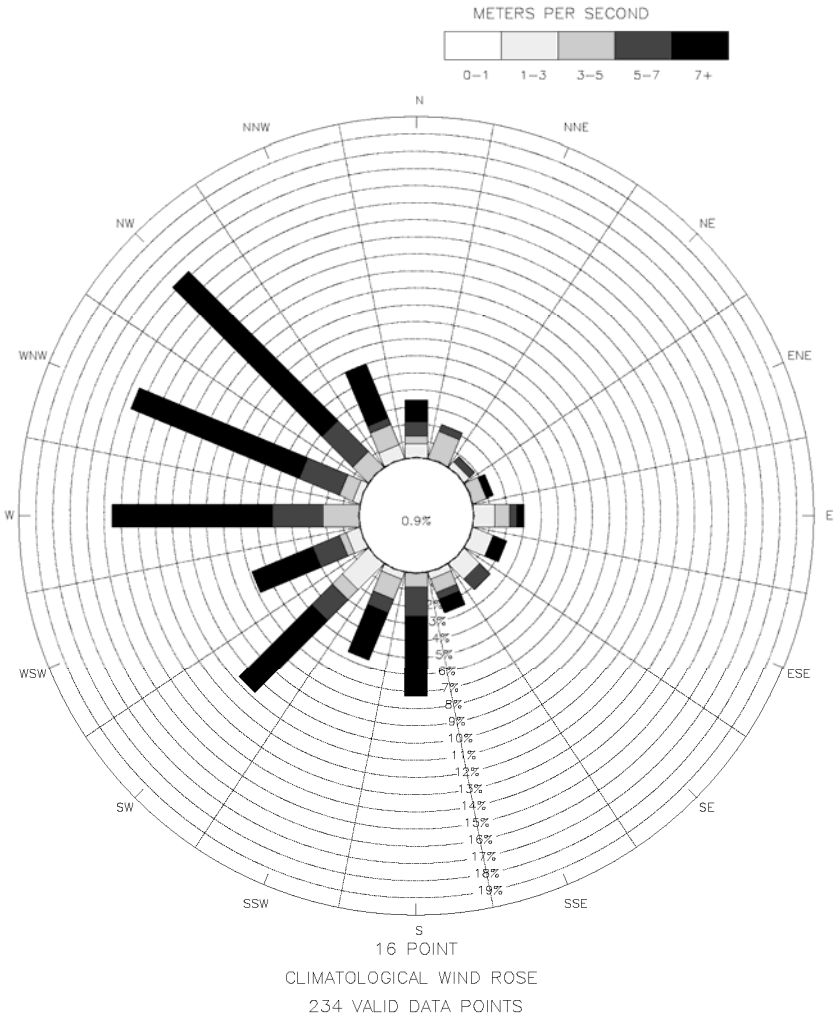
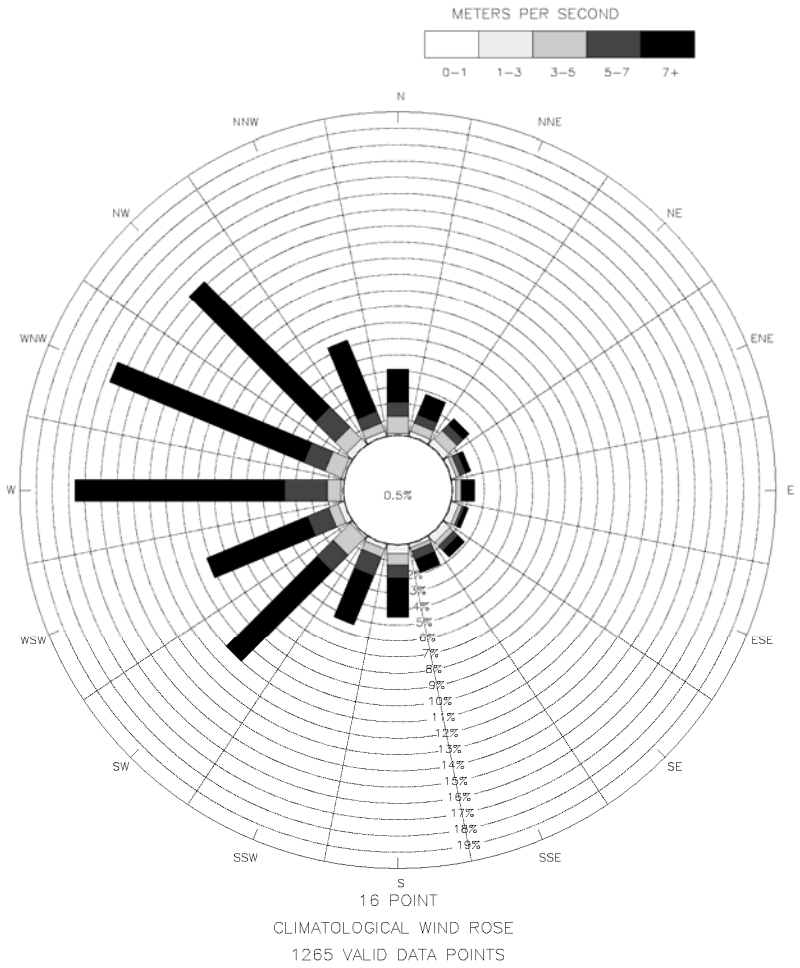


Figure 3-3. Distribution of Wind Speed and Direction at the 850 mb Level for the Sterling, VA (Dulles Airport) Sounding for 1900 EST.

(a) All Periods (November 2002 to June 2006)



(b) High Mercury Deposition Periods for Culpeper (VA08)

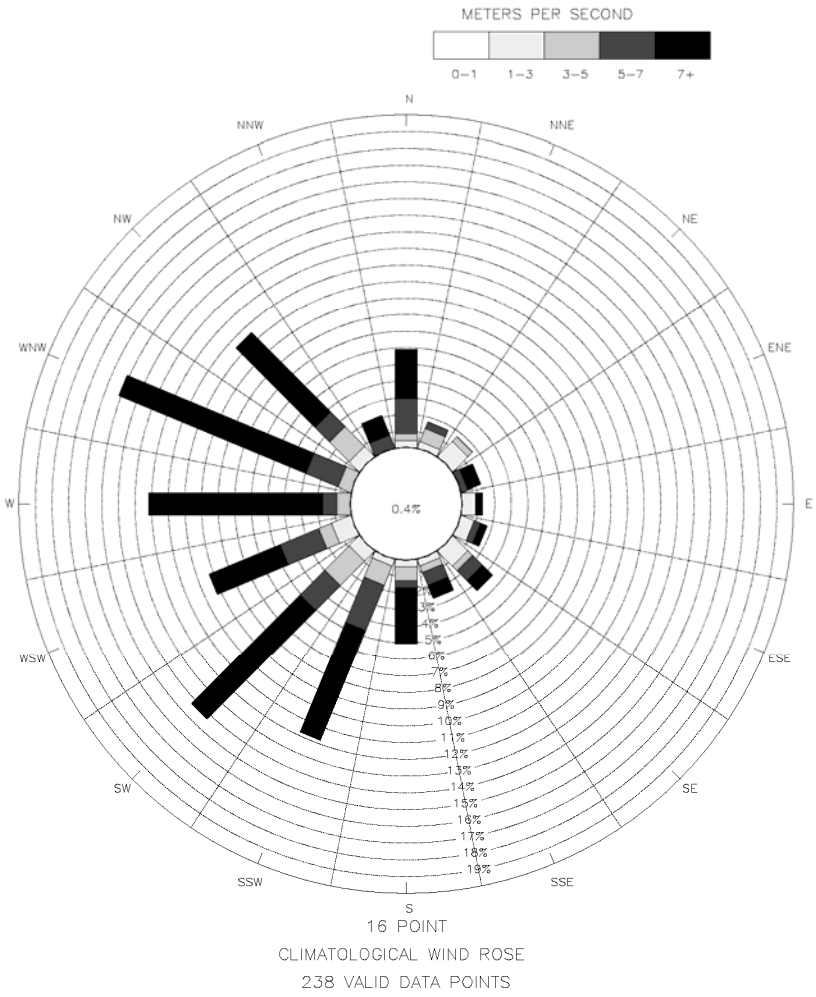
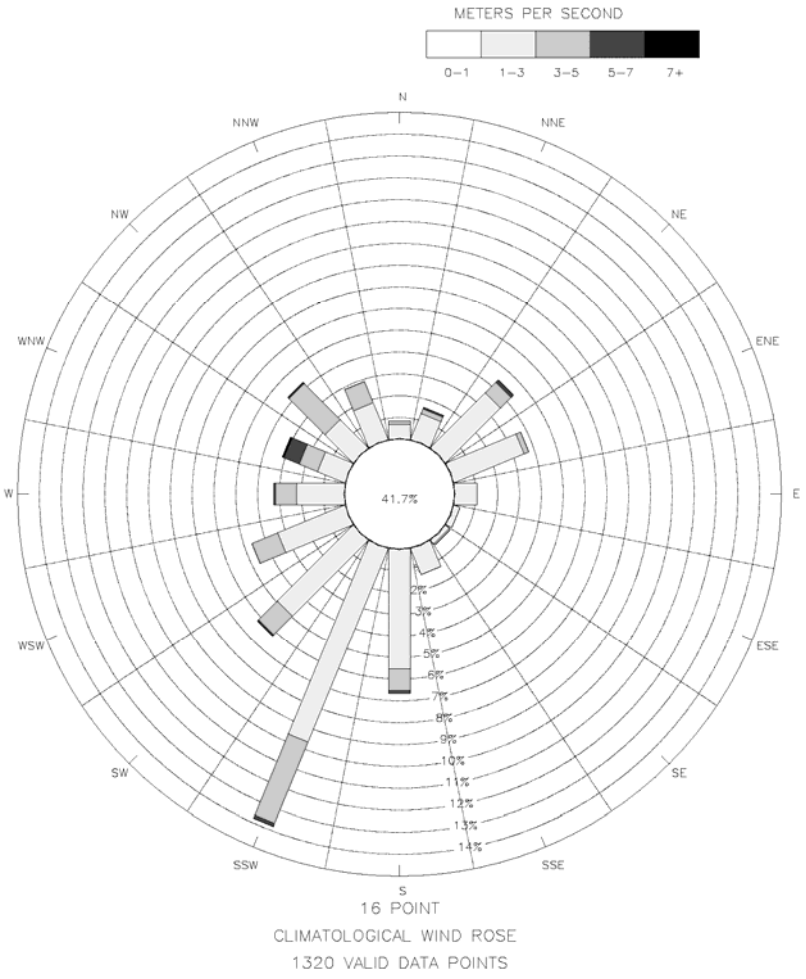


Figure 3-4. Distribution of Surface Wind Speed and Direction for Charlottesville, VA.

(a) All Periods (November 2002 to June 2006)



(b) High Mercury Deposition Periods for Culpeper (VA08)

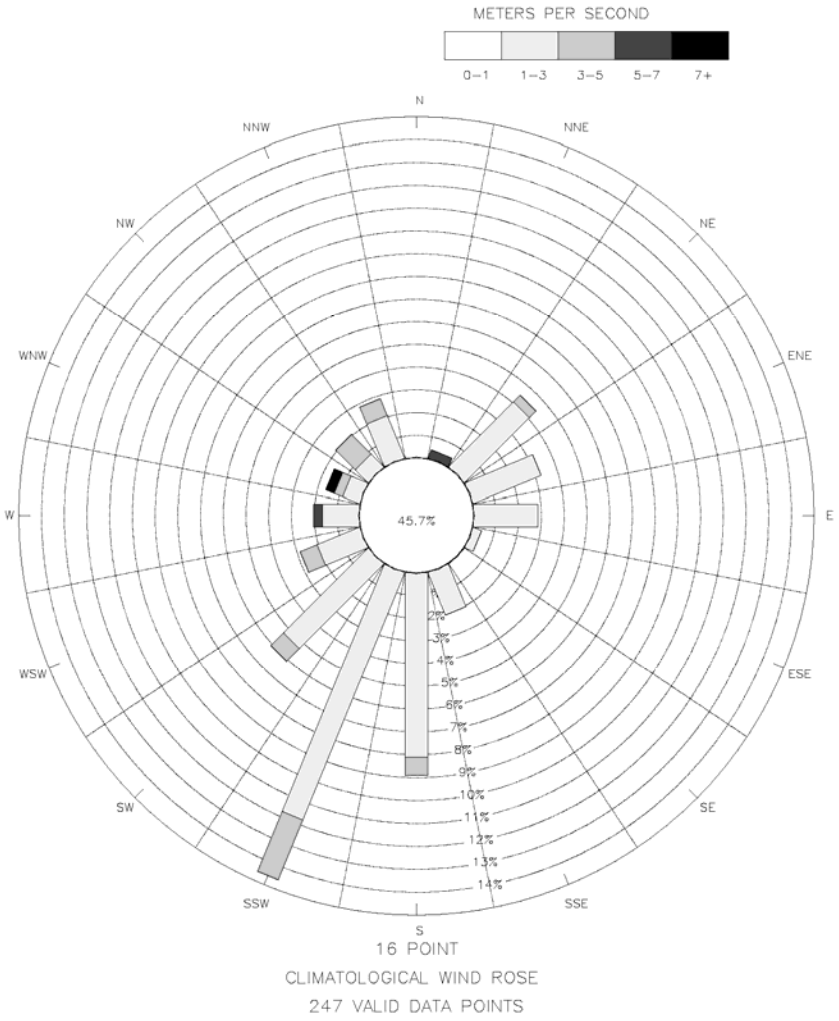
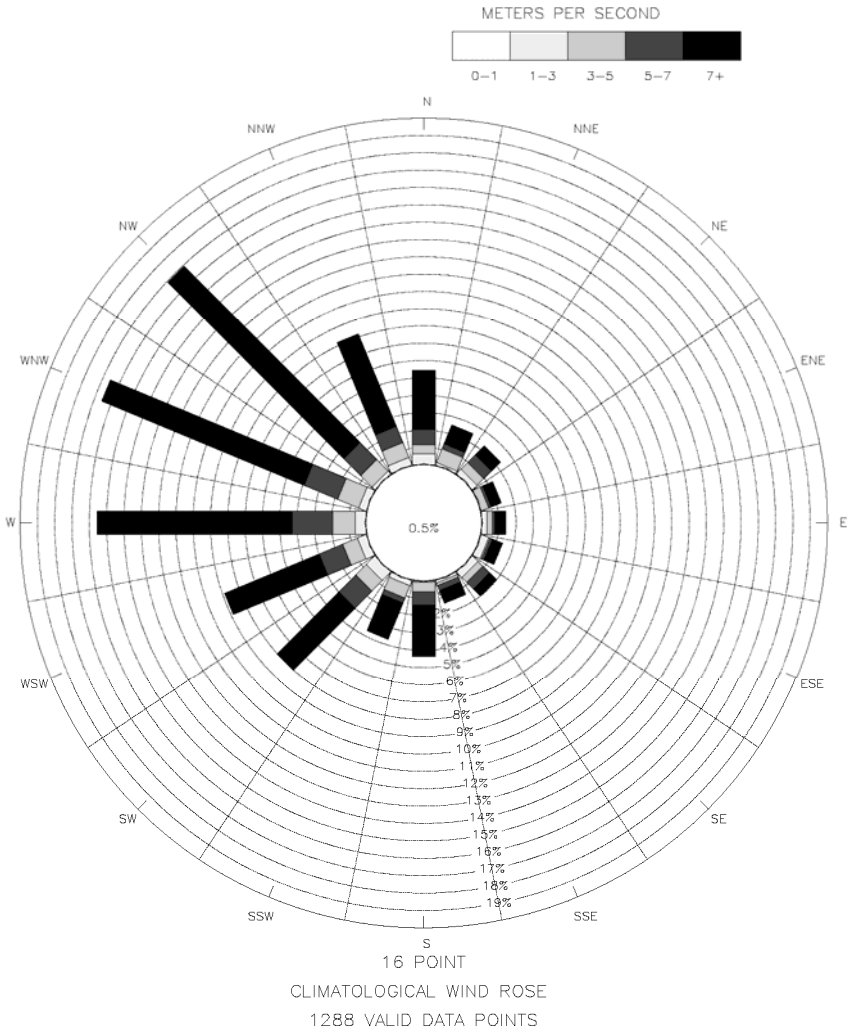


Figure 3-5. Distribution of Wind Speed and Direction at the 850 mb Level for the Sterling, VA (Dulles Airport) Sounding for 0700 EST.

(a) All Periods (November 2002 to June 2006)



(b) High Mercury Deposition Periods for Shenandoah National Park (VA28)

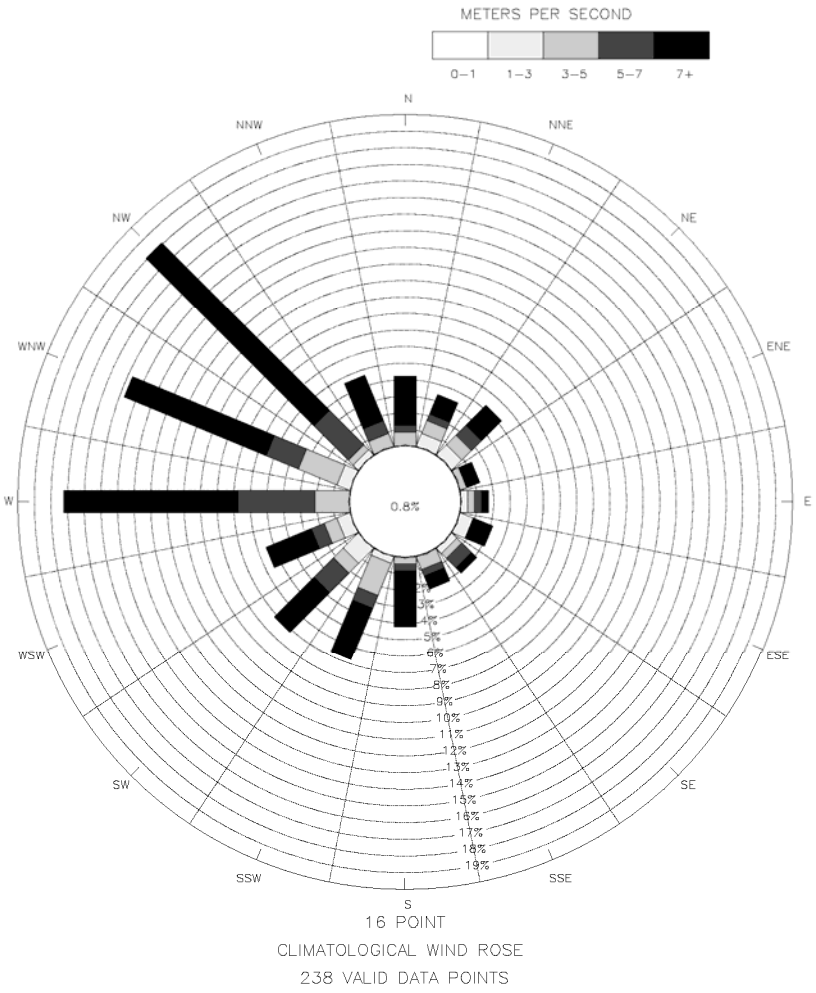
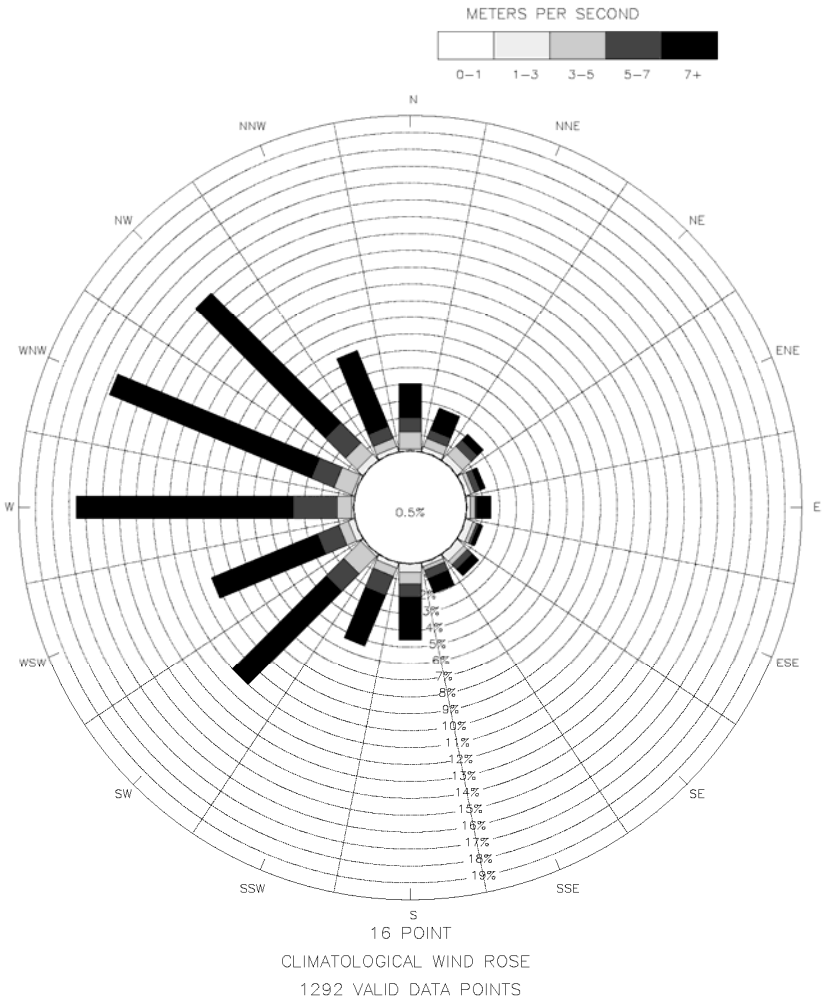


Figure 3-6. Distribution of Wind Speed and Direction at the 850 mb Level for the Sterling, VA (Dulles Airport) Sounding for 1900 EST.

(a) All Periods (November 2002 to June 2006)



(b) High Mercury Deposition Periods for Shenandoah National Park (VA28)

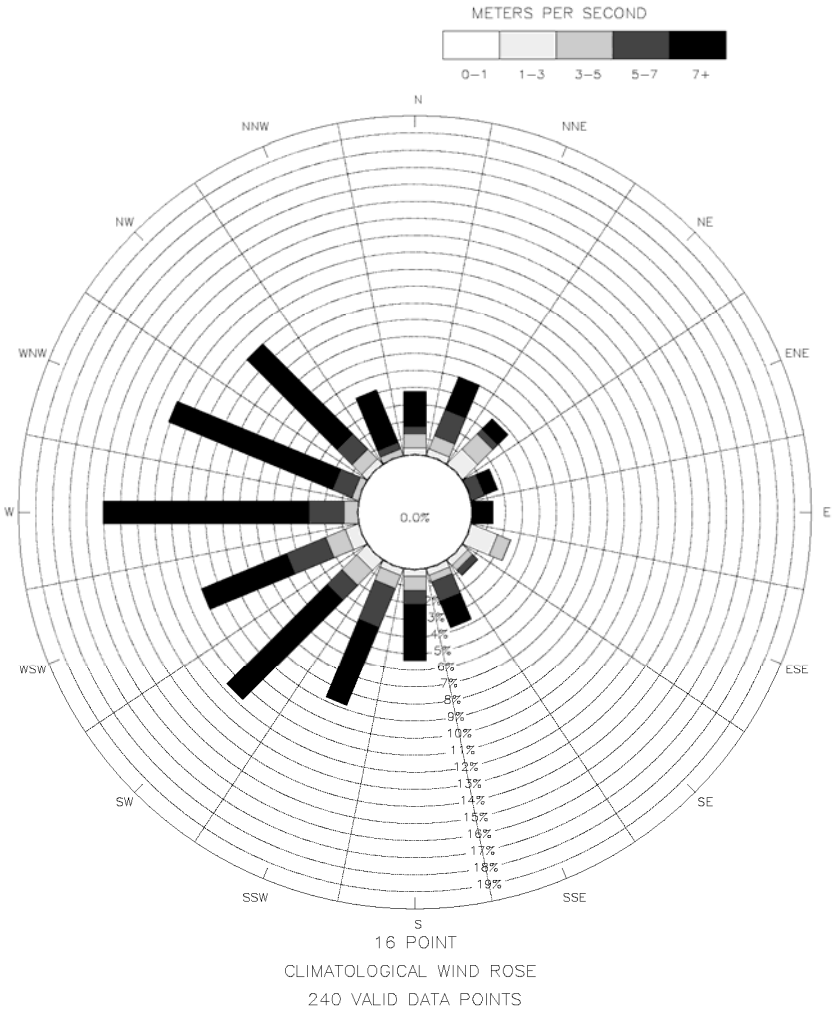
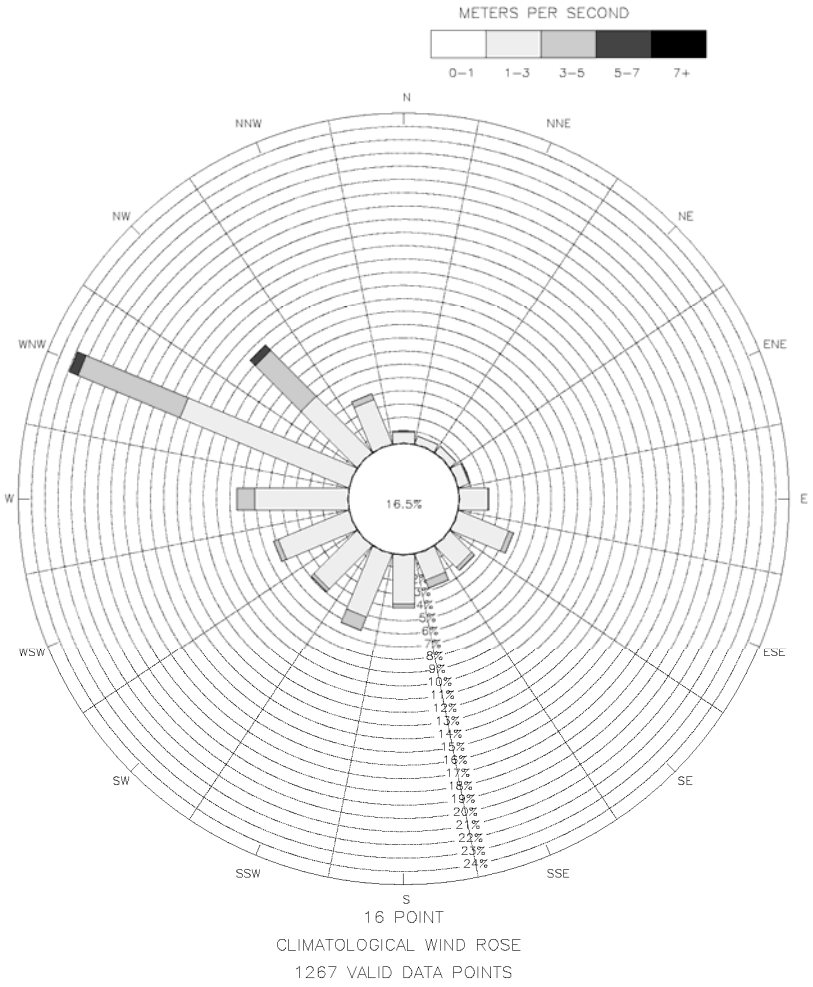


Figure 3-7. Distribution of Surface Wind Speed and Direction for Shenandoah National Park (Big Meadows).

(a) All Periods (November 2002 to June 2006)



(b) High Mercury Deposition Periods for Shenandoah National Park (VA28)

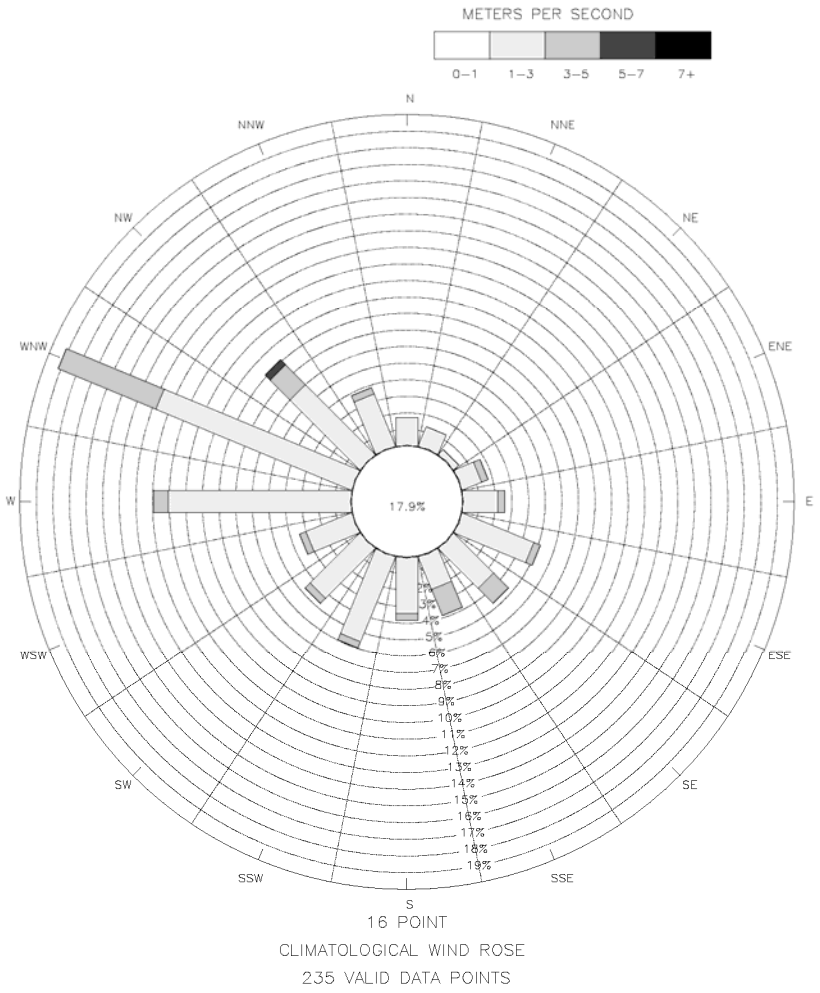
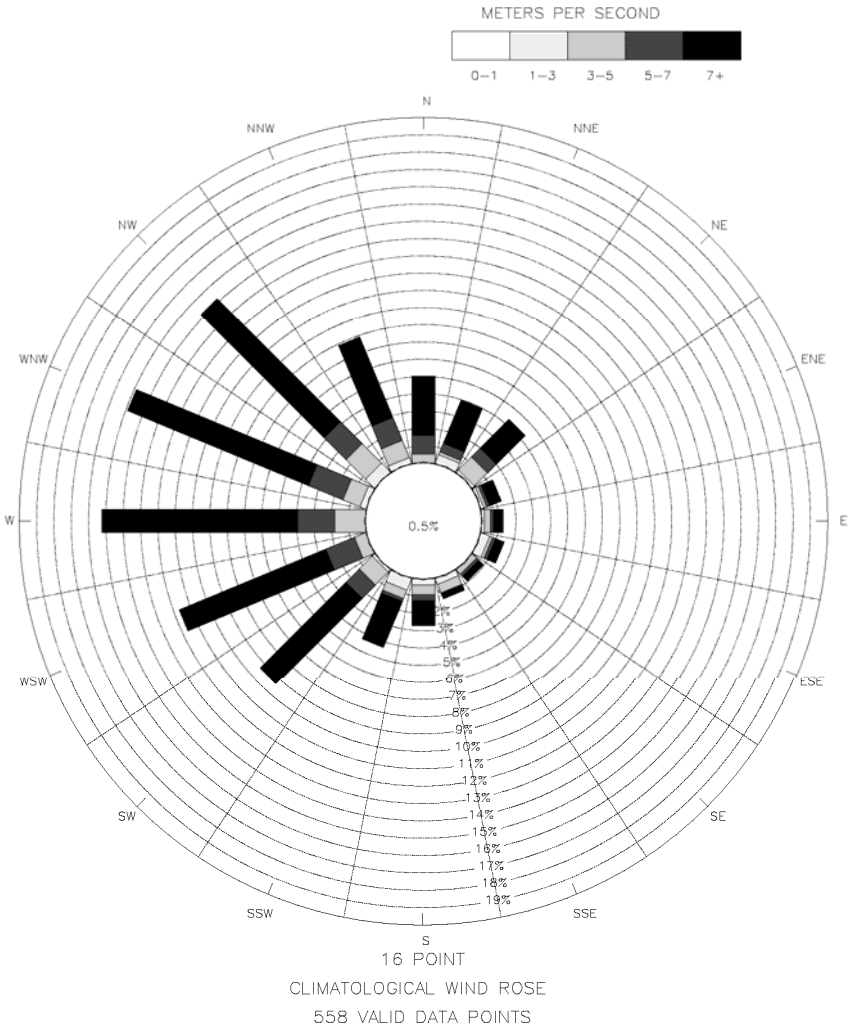


Figure 3-8. Distribution of Wind Speed and Direction at the 850 mb Level for the Wallops Island, VA Sounding for 0700 EST.

(a) All Periods (December 2004 to June 2006)



(b) High Mercury Deposition Periods for Harcum (VA98)

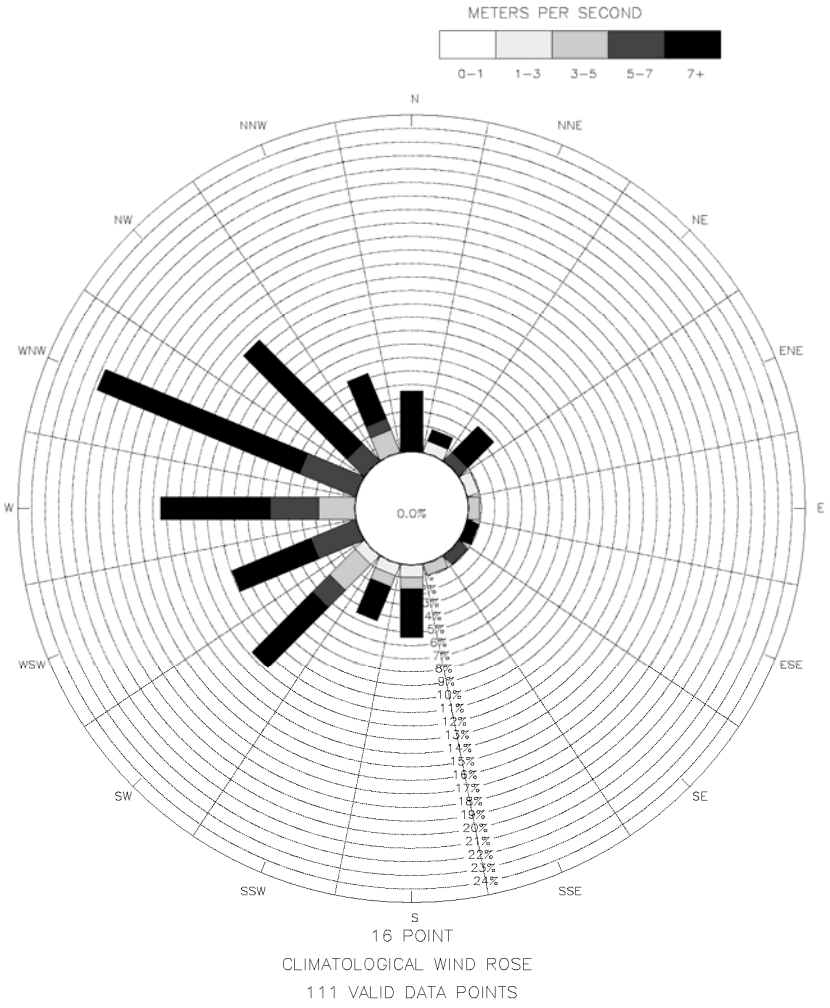
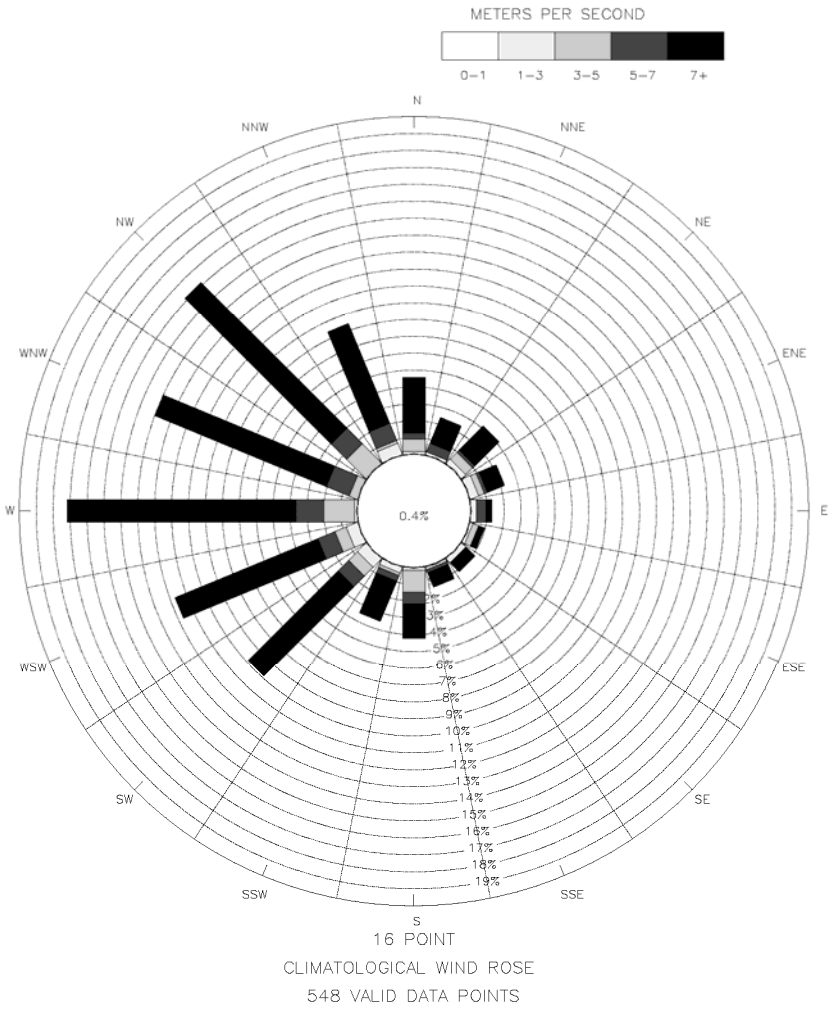


Figure 3-9. Distribution of Wind Speed and Direction at the 850 mb Level for the Wallops Island, VA Sounding for 1900 EST.

(a) All Periods (December 2004 to June 2006)



(b) High Mercury Deposition Periods for Harcum (VA98)

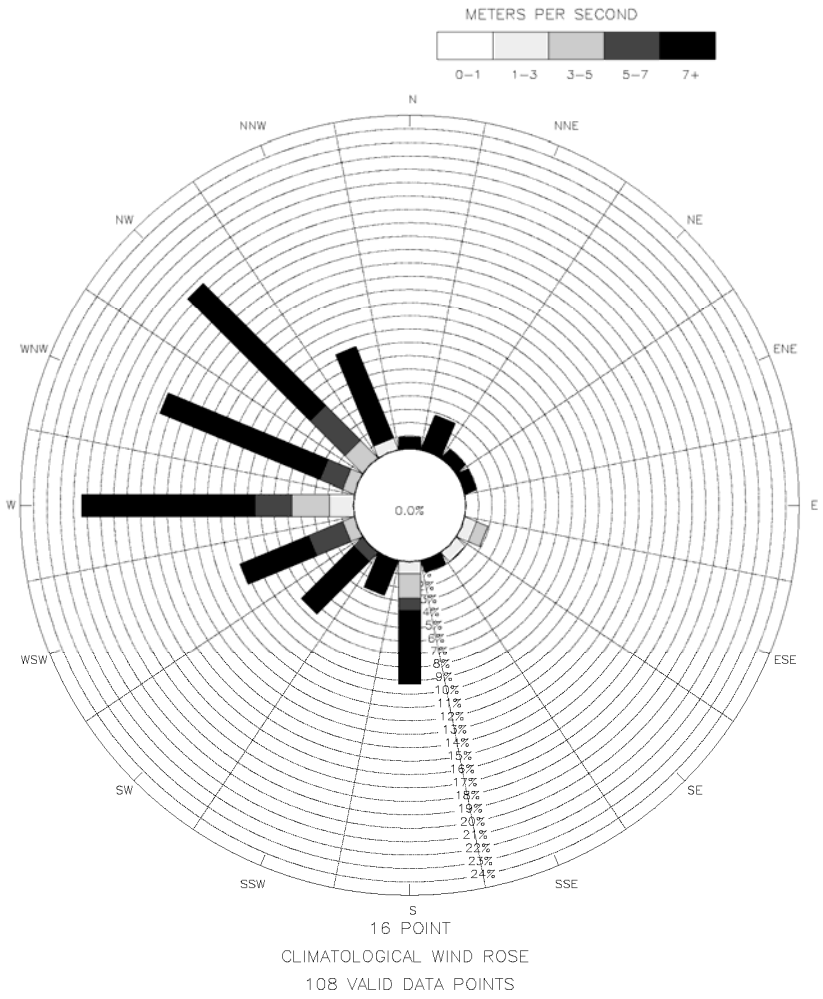
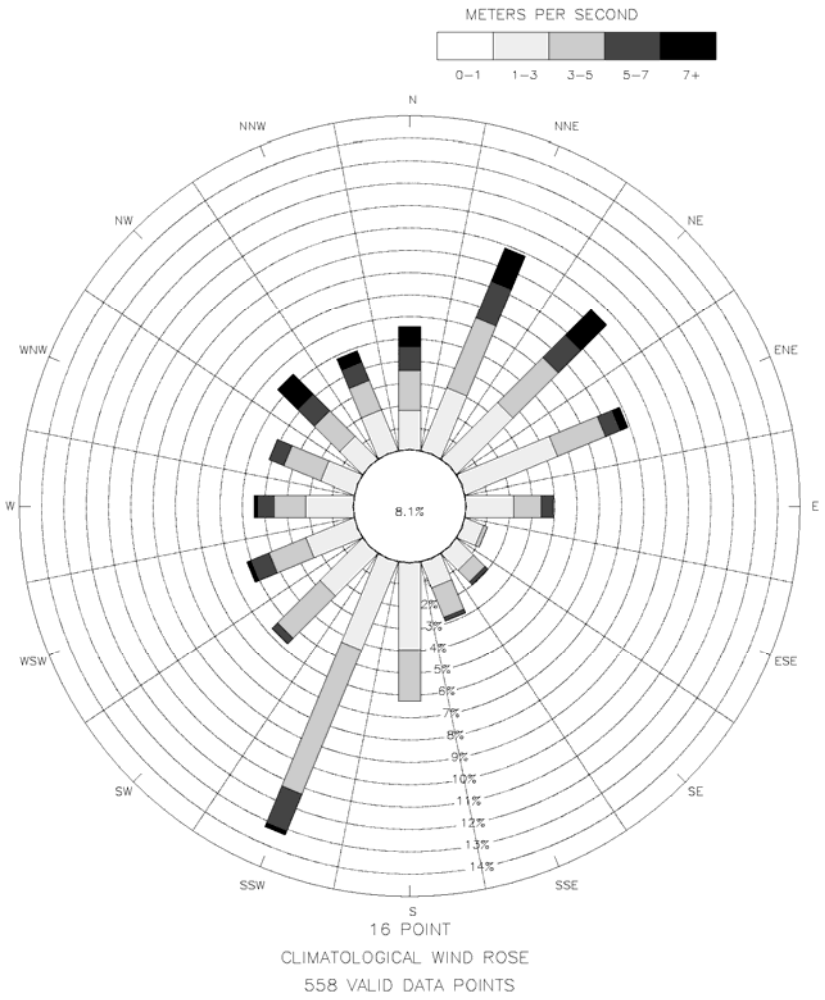
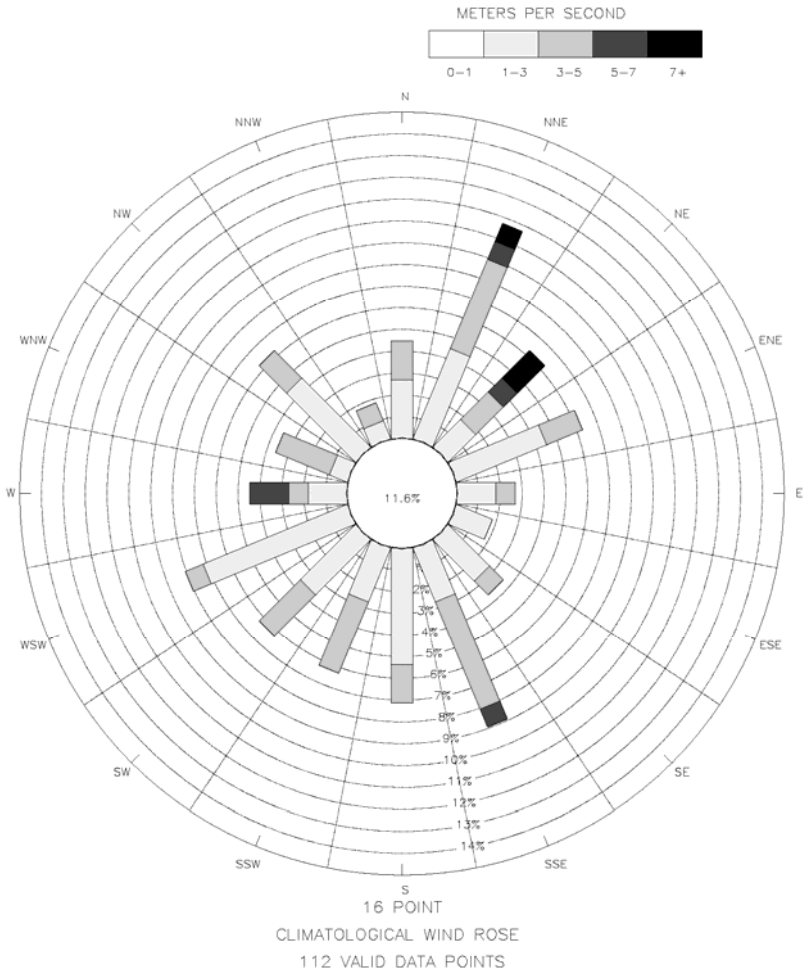


Figure 3-10. Distribution of Surface Wind Speed and Direction for Norfolk, VA.

(a) All Periods (December 2004 to June 2006)



(b) High Mercury Deposition Periods for Harcum (VA98)



3.4. Other Meteorological Factors

The factors that influence mercury wet deposition at the Virginia sites were further examined using correlation analysis and Classification and Regression Tree (CART) analysis.

3.4.1. Correlation Analysis

To further examine possible relationships between observed mercury wet deposition and meteorology, we calculated the correlation between deposition amount and various parameters. For this analysis, the correlation (R) is defined as the sample covariance between the two datasets divided by the product of the standard deviations for each dataset, which is equivalent to:

$$R = \left(n\left(\sum XY\right) - \left(\sum X\right)\left(\sum Y\right)\right) \Big/ \sqrt{\left(n\sum X^2 - \left(\sum X\right)^2\right)\left(n\sum Y^2 - \left(\sum Y\right)^2\right)},$$

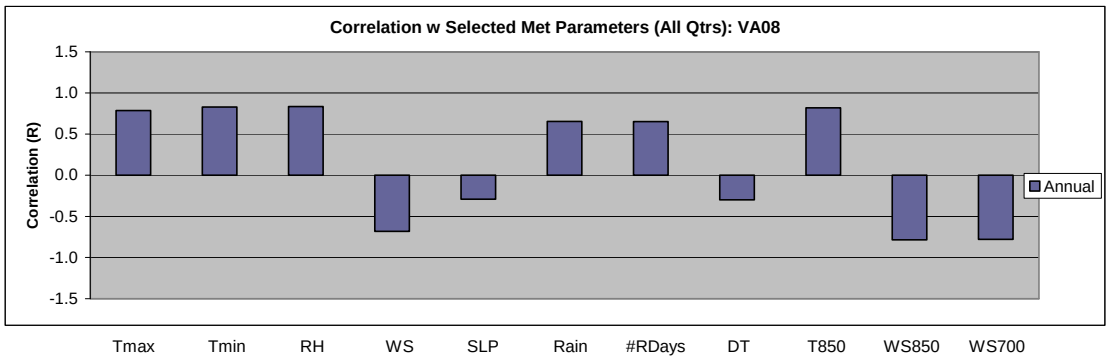
where the two datasets *X* and *Y* each have *n* data points.

The same pairings of MDN and meteorological monitoring sites as discussed above were used for the correlation analysis.

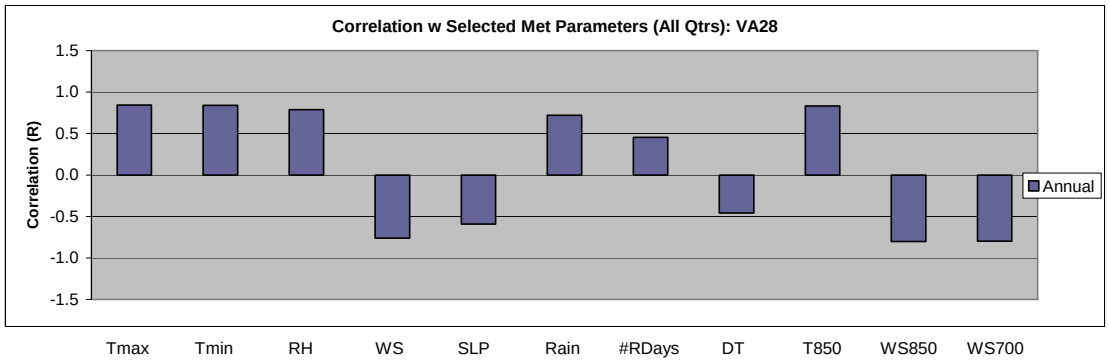
Figure 3-11 shows the R values for mercury wet deposition and the following parameters: maximum temperature (Tmax), minimum temperature (Tmin), relative humidity (RH), surface wind speed (WS), sea level pressure (SLP), rainfall total (Rain), number of days with measurable rainfall (#RDays), temperature gradient between the 900 mb level and the surface (DT), temperature at the 850 mb level (T850), wind speed at 850 mb level (WS850), and wind speed at the 700 mb level (WS700).

Figure 3-11. Correlation Between Annual Mercury Wet Deposition and Selected Meteorological Parameters.

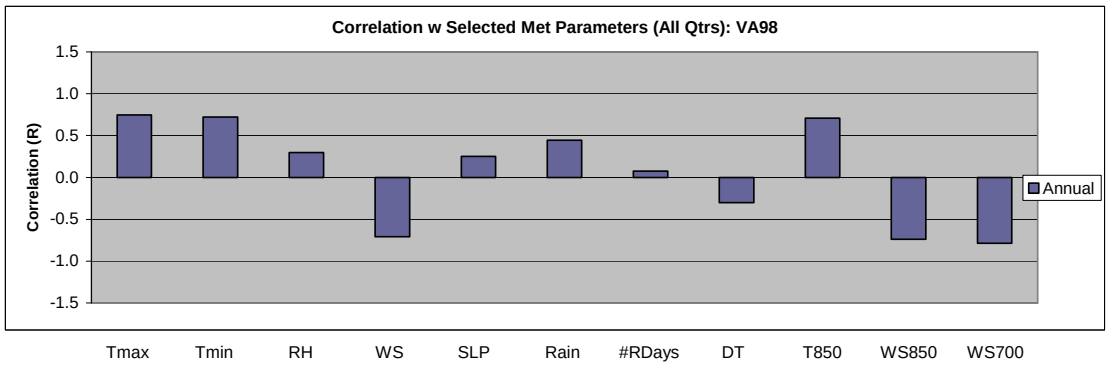
(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



(c) Harcum (VA98)



The direction and approximate magnitude of the correlations is very similar among the three sites. For all three sites, there is a positive correlation between rainfall, temperature, and relative humidity such that the greater the values of these parameters, the greater the deposition. High temperatures, high relative humidity, and rainfall are all greatest during the summer months so these correlations are consistent with the quarterly distributions of deposition shown in Section 1 of the report. There is a negative correlation between wind speed and stability which indicates that higher deposition is associated with lower wind speeds and unstable conditions. Again these are representative of summertime conditions (and in the case of stability, rainfall events) and consistent with the timing of the higher observed deposition amounts.

Interestingly, no single parameter (such as rainfall) stands out as being very highly correlated with mercury wet deposition. This indicates that while rainfall is important, other meteorological factors may influence deposition amounts. This is explored further in the next section.

3.4.2. CART Analysis

CART analysis was used to obtain information on the key meteorological factors that influence mercury wet deposition at each of the three MDN monitoring sites.

Overview of CART

The Classification and Regression Tree (CART) analysis technique (Breiman et al., 1984; Steinberg and Colla, 1997) is a statistical analysis technique and was used in this study to classify the mercury deposition periods based on deposition amount and meteorological conditions. The CART analysis software was used to separate the periods into different groups (classification "bins"), such that periods placed within the same bin exhibit similar meteorological features and are characterized by similar average daily mercury wet deposition amounts. For example, one bin may include high deposition periods associated with significant rainfall, instability, and low wind speeds; while another may include high deposition periods with moderate rainfall, northeasterly winds, and higher wind speeds, with transport indicated. Each bin is assigned to a pre-defined classification category. The classification parameter (which is used to define the classification categories) is average daily deposition amount. Since the length of the mercury deposition periods varies, average daily deposition, rather than total deposition for the period, was used as the classification parameter. The remaining parameters (for separating the periods into bins) include a variety of meteorological parameters. CART assumes a causal relationship between the meteorological input parameters and mercury wet deposition (the classification parameter).

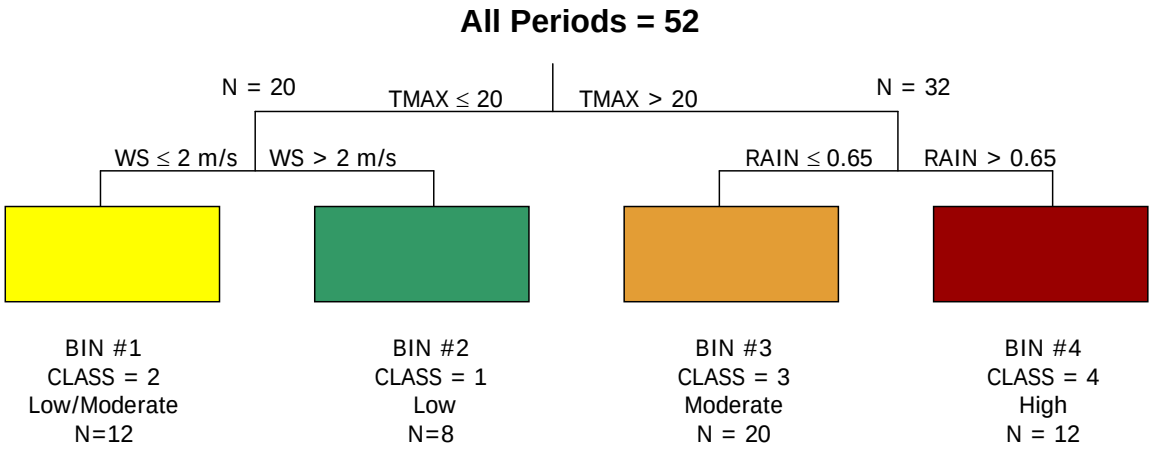
The results of the CART analysis take the form of an upside-down "tree," with branches representing different values of the input parameters leading to bins representing different values of the classification parameter (in this case, mercury wet deposition). Each bin corresponds to a particular range of mercury deposition and a particular set of meteorological conditions. By examining the parameters associated with each classification category, and specifically the parameters and parameter values used to segregate the periods into the various classification bins, the analyst can gain insight into the key differences between high and low deposition periods as well as the mechanisms contributing to high-deposition events.

CART keeps track of the frequency with which each parameter is used in constructing the classification tree and uses this information to rank the various input parameters in terms of relative importance. This information can then be used to infer the relative importance of each parameter to mercury wet deposition.

Each value of the classification parameter may be represented by more than one bin, allowing for the possibility that different combinations of the independent input parameters can be associated with a single value of the classification parameter. By segregating the data values into the classification bins, CART also provides information regarding the frequency of occurrence of the conditions associated with each classification bin (or group of periods). In this manner, the likely recurrence rate for a particular type of period and the associated prevailing conditions are obtained.

A simple example of a CART classification tree diagram is provided in Figure 3-12. In this example, 52 periods are grouped into four classification bins that correspond to different levels of mercury deposition. The bins are distinguished by three independent input parameters: maximum temperature, wind speed, and rainfall amount. In this example, Bin #4 includes 12 periods that are classified as belonging to the highest deposition category (Class 4). Periods with average daily maximum temperatures greater than 20°C and average daily rainfall amounts greater than 0.65 inches are placed in this bin. Bins 1, 2, and 3 are comprised of periods with different deposition and meteorological characteristics.

Figure 3-12. Simple CART Classification Tree Diagram, with Splits on Maximum Temperature (TMAX), Wind Speed (WS), and Precipitation Amount (RAIN).



Note that this is a very simple example of a CART tree. For the VDEQ CART analyses, the CART trees have approximately 15 to 35 bins and include multiple bins for each classification category.

CART Application Procedures

CART was applied separately for each of the three MDN monitoring sites in Virginia as well as five monitoring sites in the surrounding states. The classification parameter is average daily wet mercury deposition. Five deposition ranges, corresponding to Categories 1 to 5, were used for classification. The first category was defined by zero deposition and the remaining four categories were defined by the 20, 50, 80 percentile values of the average daily deposition amount for each site. The categories are therefore defined by the following mercury wet deposition amounts and ranges:

Category 1: No deposition

Category 2: Greater than 0 but less than or equal to the 20 percentile value of deposition

Category 3: Greater than the 20 percentile value but less than or equal to the 50 percentile value

Category 4: Greater than the 50 percentile value but less than or equal to the 80 percentile value

Category 5: Greater than the 80 percentile value

Surface meteorological parameters are used to characterize the local meteorological conditions for the days corresponding to the MDN observation period. Note that most periods include seven days, but this did vary from site to site and throughout the year. The surface meteorological inputs for CART are listed below.

- Average of the daily maximum temperatures (ºC)
- Average of the daily minimum temperatures (ºC)
- Average of the daily (24-hr) average relative humidity values (%)
- Average of the daily (24-hr) average surface wind speed (ms^{-1})
- Average of the daily (24-hr) average surface pressure (mb)
- Predominant surface wind direction (northeast, southeast, southwest, or northwest quadrant), if applicable. Otherwise, calm or variable winds.
- Percent of days with a potential for recirculation[1] (%)
- Average daily rainfall (in)
- Percent of days with measurable rainfall (%)
- Maximum 24-hr rainfall (in).

Upper-air meteorological parameters are used to characterize the regional-scale meteorological conditions. The upper-air parameters are as follows:

- Average of the daily 900 mb to surface am temperature difference (°C)
- Average of the daily 850 mb am temperatures (°C)
- Average of all 850 mb wind speeds for the periods (morning and evening) (ms^{-1})
- Predominant 850 mb wind direction (considering both morning and evening) (northeast, southeast, southwest, or northwest quadrant), if applicable. Otherwise, calm or variable winds.
- Average of all 700 mb wind speeds for the periods (morning and evening) (ms^{-1})
- Predominant 700 mb wind direction (considering both morning and evening) from the (northeast, southeast, southwest, or northwest quadrant), if applicable. Otherwise, calm or variable winds.

[1] Recirculation potential index is defined as: 24-hour average vector wind speed/24-hour average scalar wind speed. This is an indicator of wind persistence. If the value is 1, this indicates that the wind was blowing from the same direction during the entire period. A value of 0 indicates that the wind direction was from one direction for half the time and from the opposite direction the other half of the time. Thus a low value indicates the potential for recirculation.

- Percent of pairs of consecutive days with potential for recirculation aloft (calculated using the daily average wind speed and wind direction (average of morning and evening) and consecutive pairs of days e.g., day1/day2, day2/day3, day3/day4).

The MDN and meteorological site groupings are as follows:

MDN Site = Culpeper (VA08), Surface meteorology = Charlottesville, Upper-air meteorology = Dulles Airport

MDN Site = Shenandoah National Park (VA28), Surface meteorology = Shenandoah, Upper-air meteorology = Dulles Airport

MDN Site = Harcum (VA98), Surface meteorology = Norfolk, Upper-air meteorology = Wallops Island and Dulles Airport

MDN Site = Pettigrew State Park (NC42), Surface meteorology = Elizabeth City, NC, Upper-air meteorology = Morehead City/Newport

MDN Site = Waccamaw (NC08), Surface meteorology = Wilmington, NC, Upper-air meteorology = Morehead City/Newport

MDN Site = Arendtsville (PA00), Surface meteorology = Arendtsville, Upper-air meteorology = Dulles Airport

MDN Site = Allegheny Railroad NHS (PA13), Surface meteorology = Altoona, PA, Upper-air meteorology = Dulles Airport

MDN Site = Great Smoky Mountains National Park (TN11), Surface meteorology = Great Smoky Mountains NP, Upper-air meteorology = Roanoke/Blacksburg

CART Analysis Results

CART was applied separately for each site. In presenting the results, we focus on the Virginia MDN sites and examine classification accuracy, average values of the input parameters by category and by bin, and parameter importance.

CLASSIFICATION ACCURACY

As a first step in reviewing and using the CART results we examined classification accuracy – or the ability of CART to assign each period to the correct deposition category using only the meteorological information. Overall classification accuracy is approximately 80 percent for all three sites, with 80 to 93 percent of the high deposition periods correctly classified. The classification results are presented in Table 3-1. The numbers in the table are the number of cases included in the CART analysis.

Table 3-1. Summary of CART classification accuracy. Units are number of classification periods.

(a) Culpeper (VA08)

CART Category (Right)	1	2	3	4	5
Actual Category (Below)					
1	26	0	1	1	0
2	3	25	1	2	0
3	1	5	37	3	1
4	2	1	6	35	4
5	0	0	2	1	27

(b) Shenandoah National Park (VA28)

CART Category (Right)	1	2	3	4	5
Actual Category (Below)					
1	20	0	0	0	0
2	2	24	4	1	0
3	2	3	29	13	2
4	0	0	2	43	3
5	0	0	0	6	26

(c) Harcum (VA98)

CART Category (Right)	1	2	3	4	5
Actual Category (Below)					
1	9	0	1	0	0
2	0	7	2	4	0
3	0	0	18	1	0
4	0	1	4	14	0
5	0	0	0	1	13

Misclassification can occur due to a number of reasons including: monitoring network limitations (the deposition and meteorological monitoring sites are typically not collocated), use of discrete classification categories (periods with deposition values near the category boundaries may be misplaced into a lower or higher category, but in this case the deposition difference is only

slight), the complexity of the inter-variable relationships, the completeness of the dataset with respect to defining these relationships, and data errors or missing data.

For Culpeper and Shenandoah, CART trees with approximately 25-35 bins were selected to optimize classification accuracy and physical reasonableness. Fewer bins (approximately 15) were selected for Harcum due to the smaller dataset. The majority of the high deposition periods were grouped into one to four key bins.

Comparisons of average values of the CART input parameters by classification category and bin provide the basis for identifying those factors that potentially contribute to the differences in mercury deposition and distinguish each category and bin. The relative importance of each parameter in constructing the CART classification trees (information that is provided by CART) allows us to assess the importance of the meteorological factors in determining deposition amount.

SUMMARY OF RESULTS FOR CULPEPER

Mean values for wet deposition and each meteorological parameter are summarized in Table 3-2 for the five categories of mercury wet deposition (defined by no deposition (Category 1) and the 0 to 20, 20 to 50, 50 to 80, and greater than 80 percentile values of average daily wet deposition (Categories 2 through 5)).

Table 3-2. Summary of Average Input Parameters for Each CART Classification Category: Culpeper, VA (VA08)

(All Parameters with the Exception of the Daily Maximum Rainfall Amount and the Wind Direction Parameters Are First Averaged Over Each Day within Each Mercury Deposition Sampling Period)

	Category 1	Category 2	Category 3	Category 4	Category 5
Hg wet deposition (ng/m2)	0.0	3.8	13.7	32.3	79.7
Surface Meteorological Parameters					
Maximum surface temperature (°C)	18.4	13.4	15.2	20.7	23.5
Minimum surface temperature (°C)	6.5	2.3	5.2	10.0	13.8
Relative humidity (%)	58.2	59.4	66.5	69.1	75.3
Surface wind speed (ms^{-1})	1.9	2.2	1.9	1.8	1.6
Surface wind direction (deg)	217	180	211	180	180
% of days with recirculation likely	9.3	10.5	11.0	12.0	9.4
Sea level pressure (mb)	1018	1018	1017	1016	1015
Rainfall amount (in)	0.0	0.1	0.1	0.2	0.3
% of days with measurable rain	32.9	43.7	46.1	60.6	65.0
Daily maximum rainfall amount (in)	0.1	0.3	0.6	0.9	1.2
Upper-Air Meteorological Parameters					
850 mb temperature (AM) (°C)	4.2	1.0	3.7	8.2	11.3
900 mb to sfc temp gradient (AM) (°C)	0.1	0.5	0.2	0.2	-0.6
850 mb wind speed (ms^{-1})	10.3	11.5	11.6	9.4	9.1
700 mb wind speed (ms^{-1})	14.2	15.8	15.8	12.8	12.1
850 mb wind direction (deg)	279	279	277	275	265
700 mb wind direction (deg)	283	276	271	274	270
% of days with recirculation likely	3.4	1.2	2.4	3.2	6.1

A column-by-column comparison of the values in Table 3-2 reveals some clear tendencies in several of the meteorological parameters.

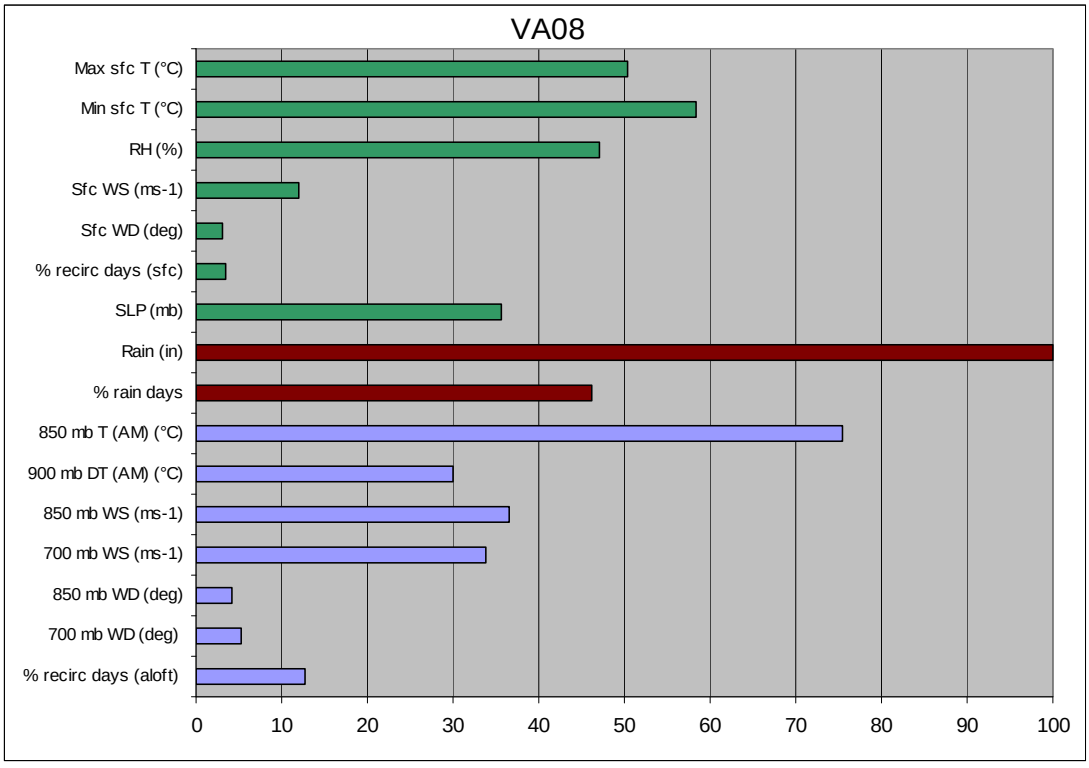
Mercury wet deposition at the Culpeper site is associated with high temperatures, high relative humidity, and rainfall. All three of the rainfall parameters increase steadily with increasing wet deposition. Surface wind speeds decrease with increasing deposition, but for all categories the surface wind directions are southerly to southwesterly.

The upper-air meteorological parameters (based here on Dulles Airport) indicate that higher mercury wet deposition occurs with higher 850 mb temperatures. Conditions within the atmospheric boundary layer are less stable, compared to the other categories.

As for the surface, lower wind speeds aloft are aligned with higher deposition amounts. Average wind directions aloft shift slightly from northwesterly to westerly for the higher deposition periods. Recirculation aloft is more likely during high deposition periods, compared to the other periods.

Key classification parameters for CART include the precipitation parameters, 850 mb temperature, surface temperature parameters, and relative humidity. The relative importance of each parameter, on a scale of 0 to 100, is displayed in Figure 3-13.

Figure 3-13. Relative Importance of the Meteorological Parameters from the Culpeper CART Analysis.



The information in Table 3-2 provides a general overview of how average conditions vary across (and potentially lead to) different mercury deposition amounts for the Culpeper site. Within the high deposition categories, there are other key differences among the parameters that result in different types of high deposition events. We have used the CART results to examine these differences.

Only certain of the CART bins are assigned to Category 5, and contain the majority of the 20 percent highest deposition periods. Of these, we identified those bins with the most number of correctly classified high deposition periods as key bins. Table 3-3 considers the input parameter values for the key high-deposition bins for Culpeper.

Table 3-3. Summary of Average Input Parameters for CART High Deposition Bins: Culpeper, VA (VA08)

(All Parameters with the Exception of the Daily Maximum Rainfall Amount and the Wind Direction Parameters Are First Averaged Over Each Day within Each Mercury Deposition Sampling Period)

	Bin 20	Bin 26	Bin 29	Bin 32
No. of observation periods	9	4	8	10
Hg wet deposition (ng/m2)	45.1	48.1	77.1	103.6
Surface Meteorological Parameters				
Maximum surface temperature (°C)	16.8	8.7	26.2	30.2
Minimum surface temperature (°C)	6.3	0.0	17.0	20.5
Relative humidity (%)	71.2	62.3	83.3	77.9
Surface wind speed (ms^{-1})	2.0	2.5	1.2	1.2
Surface wind direction (deg)	236	180	180	180
% of days with recirculation likely	11.1	11.3	12.5	7.9
Sea level pressure (mb)	1013	1017	1015	1016
Rainfall amount (in)	0.3	0.3	0.3	0.3
% of days with measurable rain	63.9	66.9	72.8	63.1
Daily maximum rainfall amount (in)	1.4	1.3	1.4	1.3
Upper-Air Meteorological Parameters				
850 mb temperature (AM) (°C)	5.1	1.3	13.3	16.7
900 mb to sfc temp gradient (AM) (°C)	0.8	2.2	-1.9	-1.4
850 mb wind speed (ms^{-1})	10.6	16.1	7.2	6.7
700 mb wind speed (ms^{-1})	14.3	22.1	9.8	8.7
850 mb wind direction (deg)	275	288	297	270
700 mb wind direction (deg)	275	270	297	279
% of days with recirculation likely	2.8	0.0	8.8	8.7

Bins 20, 26, 29 and 32 are all Category 5 bins. While many of the characteristics are similar, there are some differences. These provide possible insight into the factors influencing the deposition periods within each bin.

Bins 20 and 26 are distinguished from the other high deposition bins by lower deposition amounts, lower temperatures, and higher wind speeds. Rainfall amounts are similar to those for the other high deposition periods. Thus these high deposition periods correspond to cooler season events. Differences in temperature, wind speed, surface wind direction, and stability

also distinguish periods in Bin 20 from those in Bin 26. Periods in Bin 26 have lower temperatures, higher wind speeds, and greater stability. Average surface winds are from the southwest for Bin 20 and from the south for Bin 26.

For Bin 29, higher deposition amounts are coupled with high relative humidity and the greatest percentage of days with measurable rainfall among the key Category 5 bins. Periods within this bin are also the least stable. The humidity and instability suggest that the rainfall is associated with local thunderstorm activity.

On average, the periods in Bin 32 have the highest wet deposition amounts, as well as the highest temperatures and lowest wind speeds among the key high-deposition bins.

SUMMARY OF RESULTS FOR SHENANDOAH

Mean values for wet deposition and each meteorological parameter are summarized in Table 3-4 for the five categories of mercury wet deposition (defined by no deposition (Category 1) and the 0 to 20, 20 to 50, 50 to 80, and greater than 80 percentile values of average daily wet deposition (Categories 2 through 5)).

Table 3-4. Summary of Average Input Parameters for Each CART Classification Category: Shenandoah National Park (VA28)

(All Parameters with the Exception of the Daily Maximum Rainfall Amount and the Wind Direction Parameters Are First Averaged Over Each Day within Each Mercury Deposition Sampling Period)

	Category 1	Category 2	Category 3	Category 4	Category 5
Hg wet deposition (ng/m2)	0.0	4.0	14.9	32.5	85.4
Surface Meteorological Parameters					
Maximum surface temperature (°C)	9.8	4.9	10.7	13.0	16.3
Minimum surface temperature (°C)	2.5	-2.1	4.2	6.3	9.9
Relative humidity (%)	68.3	68.5	76.4	77.4	81.8
Surface wind speed (ms^{-1})	2.2	2.7	2.4	2.3	2.2
Surface wind direction (deg)	277	270	268	254	258
% of days with recirculation likely	10.4	6.9	10.5	10.8	9.5
Sea level pressure (mb)	1019	1018	1016	1016	1015
Rainfall amount (in)	0.0	0.0	0.1	0.2	0.4
% of days with measurable rain	13.8	31.0	39.5	45.2	53.0
Daily maximum rainfall amount (in)	0.1	0.3	0.6	1.1	1.5
Upper-Air Meteorological Parameters					
850 mb temperature (AM) (°C)	3.6	-0.1	5.7	7.8	10.6
900 mb to sfc temp gradient (AM) (°C)	0.9	0.5	0.0	0.2	-0.6
850 mb wind speed (ms^{-1})	10.0	12.1	10.5	9.9	9.4
700 mb wind speed (ms^{-1})	14.2	16.9	14.4	13.3	12.1
850 mb wind direction (deg)	277	270	268	254	258
700 mb wind direction (deg)	280	276	275	270	272
% of days with recirculation likely	3.3	1.2	4.1	2.6	3.5

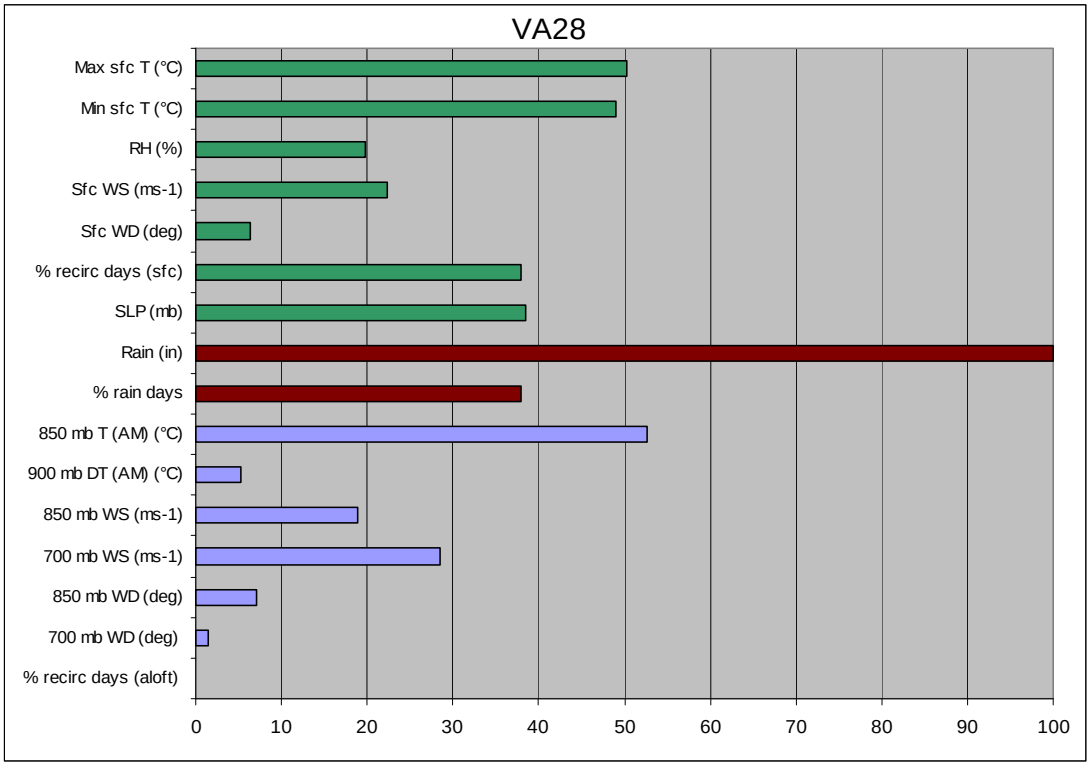
Mercury wet deposition at the Shenandoah site is associated with higher temperatures, high relative humidity, and rainfall. All three of the rainfall parameters increase steadily with increasing wet deposition. Surface wind speeds decrease with increasing deposition, and surface wind directions back slightly from west-northwesterly to west-southwesterly.

The upper-air meteorological parameters (based here on Dulles Airport) indicate that higher mercury wet deposition occurs with higher 850 mb temperatures. Conditions within the atmospheric boundary layer are less stable, compared to the other categories.

Lower wind speeds aloft are also associated with higher deposition amounts. Average wind directions at 850 mb also shift slightly from west-northwesterly to west-southwesterly for the higher deposition periods.

Key classification parameters for CART include the precipitation and temperature parameters; pressure, recirculation (near the surface), and wind speed (near the surface and aloft) are also relatively important. The relative importance of each parameter, on a scale of 0 to 100, is displayed in Figure 3-14.

Figure 3-14. Relative Importance of the Meteorological Parameters from the Shenandoah National Park CART Analysis.



Within the high deposition categories, there are other key differences among the parameters that result in different types of high deposition events. We have used the CART results to examine these differences.

Of the CART bins assigned to Category 5, two contain the majority of the 20 percent highest deposition periods. Table 3-5 considers the input parameter values for the key high-deposition bins.

Table 3-5. Summary of Average Input Parameters for CART High Deposition Bins: Shenandoah National Park, VA (VA28)

(All Parameters with the Exception of the Daily Maximum Rainfall Amount and the Wind Direction Parameters Are First Averaged Over Each Day within Each Mercury Deposition Sampling Period)

	Bin 23	Bin 27
No. of observation periods	7	23
Hg wet deposition (ng/m2)	41.2	95.0
Surface Meteorological Parameters		
Maximum surface temperature (°C)	8.4	19.5
Minimum surface temperature (°C)	0.5	13.8
Relative humidity (%)	72.9	85.4
Surface wind speed (ms^{-1})	3.0	1.9
Surface wind direction (deg)	90	270
% of days with recirculation likely	7.1	9.8
Sea level pressure (mb)	1016	1015
Rainfall amount (in)	0.3	0.4
% of days with measurable rain	43.6	57.7
Daily maximum rainfall amount (in)	1.6	1.5
Upper-Air Meteorological Parameters		
850 mb temperature (AM) (°C)	3.9	13.6
900 mb to sfc temp gradient (AM) (°C)	1.8	-1.0
850 mb wind speed (ms^{-1})	12.9	8.2
700 mb wind speed (ms^{-1})	16.4	10.3
850 mb wind direction (deg)	90	270
700 mb wind direction (deg)	0	270
% of days with recirculation likely	0.0	5.0

Bins 23 and 27 appear to contain cooler and warmer season deposition events, respectively. A key difference is that the periods in Bin 27 have higher average deposition amounts. The bins are further distinguished from one another by differences in temperature, relative humidity, wind speed, wind direction, and stability. Rainfall amounts are similar, but the Bin 27 periods have a greater percentage of days with measurable precipitation. For Bin 23, average winds (for both the surface and aloft) are from the north or east, compared to the west for Bin 27.

SUMMARY OF RESULTS FOR HARCUM

Mean values for wet deposition and each meteorological parameter are summarized in Table 3-6 for the five categories of mercury wet deposition (defined by no deposition (Category 1) and the 0 to 20, 20 to 50, 50 to 80, and greater than 80 percentile values of average daily wet deposition (Categories 2 through 5)).

Table 3-6. Summary of Average Input Parameters for Each CART Classification Category: Harcum, VA (VA98)

(All Parameters with the Exception of the Daily Maximum Rainfall Amount and the Wind Direction Parameters Are First Averaged Over Each Day within Each Mercury Deposition Sampling Period)

	Category 1	Category 2	Category 3	Category 4	Category 5
Hg wet deposition (ng/m2)	0.0	2.3	11.4	27.1	69.0
Surface Meteorological Parameters					
Maximum surface temperature (°C)	20.2	16.1	17.2	18.6	22.8
Minimum surface temperature (°C)	12.0	8.1	9.1	11.2	14.4
Relative humidity (%)	61.7	67.6	64.2	69.2	67.9
Surface wind speed (ms^{-1})	4.5	4.3	4.8	4.3	3.8
Surface wind direction (deg)	207	63	0	45	180
% of days with recirculation likely	7.7	21.8	17.3	13.1	21.4
Sea level pressure (mb)	1015	1014	1014	1010	1013
Rainfall amount (in)	0.0	0.1	0.1	0.1	0.1
% of days with measurable rain	18.8	33.8	30.2	44.4	58.0
Daily maximum rainfall amount (in)	0.1	0.4	0.4	0.9	0.6
Upper-Air Meteorological Parameters					
850 mb temperature (AM) (°C)	7.3	4.2	4.4	5.8	8.4
900 mb to sfc temp gradient (AM) (°C)	-0.7	-1.3	0.7	-0.9	-1.4
850 mb wind speed (ms^{-1})	10.3	11.7	11.6	10.2	10.2
700 mb wind speed (ms^{-1})	13.1	16.3	15.9	13.7	13.4
850 mb wind direction (deg)	307	283	281	283	266
700 mb wind direction (deg)	284	270	284	270	270
% of days with recirculation likely	2.5	1.0	0.6	4.6	2.7

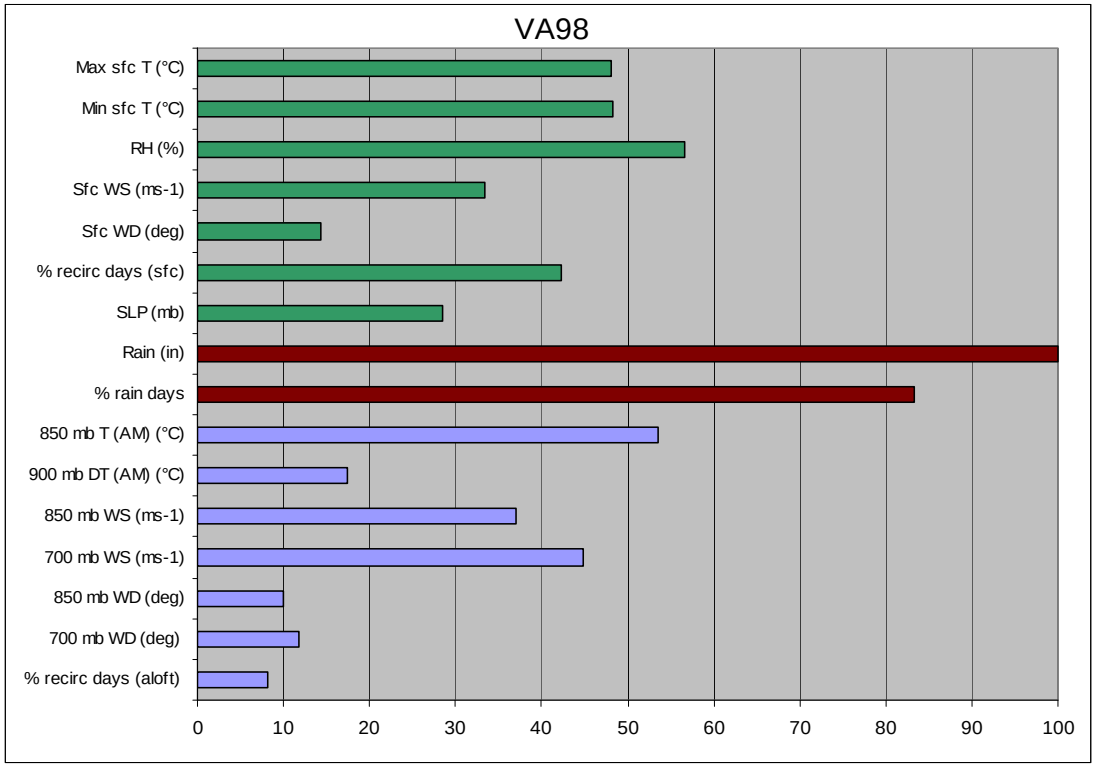
Mercury wet deposition at the Harcum site is generally associated with higher temperatures and lower wind speeds. The number of rain days increases with increasing wet deposition, but the other two rainfall parameters do not follow the pattern of deposition as clearly. Considering the non-zero deposition periods, surface wind directions veer from northerly/northeasterly to southerly with increasing deposition.

The upper-air meteorological parameters (based here on Wallops Island) indicate that higher mercury wet deposition occurs with slightly higher 850 mb temperatures and slightly lower wind speeds. Average wind directions at 850 mb also shift slightly from west-northwesterly to westerly for the higher deposition periods.

It is also interesting to note the differences in average wind direction between the surface and the 850 mb level. This could be due to the influence of the Chesapeake Bay on surface wind directions.

Key classification parameters for CART include the precipitation parameters, relative humidity and temperature parameters. Recirculation (near the surface) is indicated to be relatively important and suggests some influence from the sea- or bay breeze. Wind speed aloft is also relatively important for the Harcum CART analysis. The relative importance of each parameter, on a scale of 0 to 100, is displayed in Figure 3-15.

Figure 3-15. Relative Importance of the Meteorological Parameters from the Harcum CART Analysis.



All but two of the 14 highest deposition periods are assigned to Bin 13 and the average values closely match those for all Category 5 periods, as presented in Table 3-6. Due to the limited period of record for the Harcum site, CART was not able to identify multiple high-deposition regimes.

3.5. Effects of Meteorology on Mercury Trends

Variations in meteorology contribute to the observed variations in quarterly and annual mercury wet deposition. These variations in meteorology may make if difficult to identify trends in the data that are due to changes in emissions. In this section, we examine "meteorologically adjusted" annual mercury deposition values for the two MDN sites in Virginia with multiple complete years of data (Culpeper and Shenandoah) as well as several sites in neighboring states. The meteorologically adjusted deposition values are then compared with emissions estimates for an analysis of recent trends.

In developing the "meteorologically adjusted" deposition values, our objective was to create a deposition metric that is not sensitive to yearly meteorological variation. This exercise relies on results of the Classification and Regression Tree (CART) analysis, as discussed earlier in this section.

CART was used to classify the mercury deposition periods according to deposition amount and meteorological conditions. While the category of a bin reflects the amount of mercury wet deposition associated with the bin's meteorological conditions, the number of periods and days in a bin represents the frequency with which those conditions occur. Since the bins are determined

using a multi-year period, individual years may be normalized such that the different sets of meteorological conditions are represented no more or less than they are on average over all years in the period. This is the basis for our creation of meteorologically adjusted design values.

The specific steps include:

Step 1: Determine the average number of days per bin and per year to include in the normalized year (accounting for differences in the number of days per deposition measurement period).

Step 2. For each bin, calculate the daily average deposition amount represented by each bin, for each year included in the analysis and for all years. Use only days from correctly classified deposition periods in the calculation.

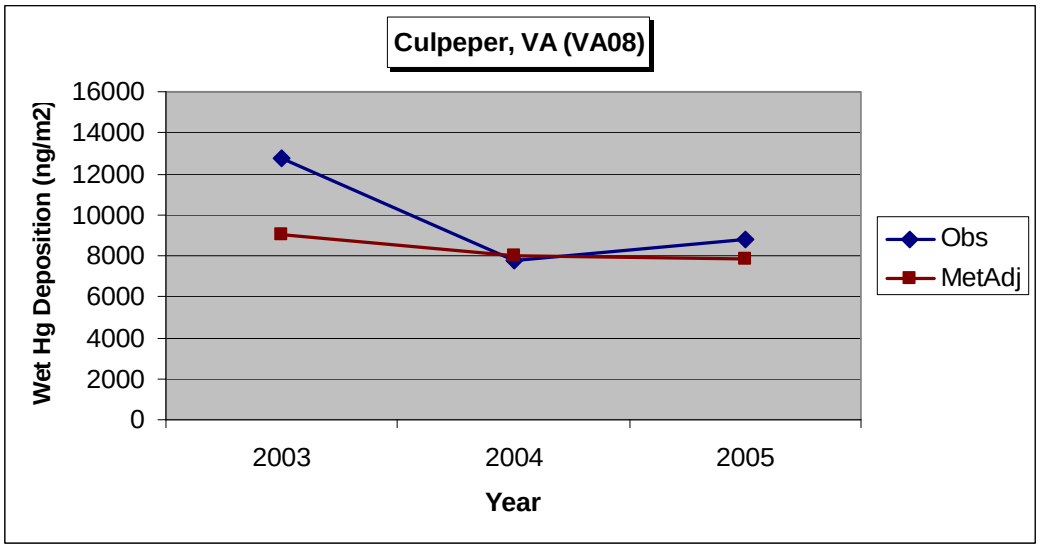
Step 3: If a bin is not represented in a given year, assign the overall average value to that bin.

Step 4: For each bin and each year, calculate the adjusted deposition amount. This is equal to the average number of days per bin per year (from Step 1) multiplied by the average deposition amount for each bin (from Steps 2 and 3).

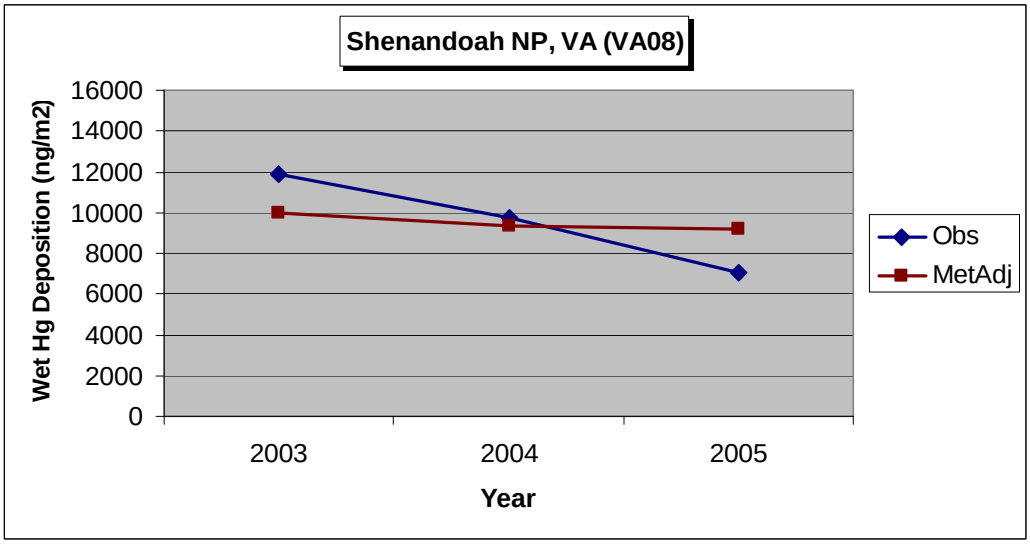
The resulting meteorologically adjusted deposition values for the Culpeper (VA08) and Shenandoah National Park (VA28) sites are illustrated in Figure 3-16.

Figure 3-16. Actual & Meteorologically-Adjusted Annual Mercury Wet Deposition (ng m^{-2}) for MDN Monitoring Sites in Virginia.

(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)

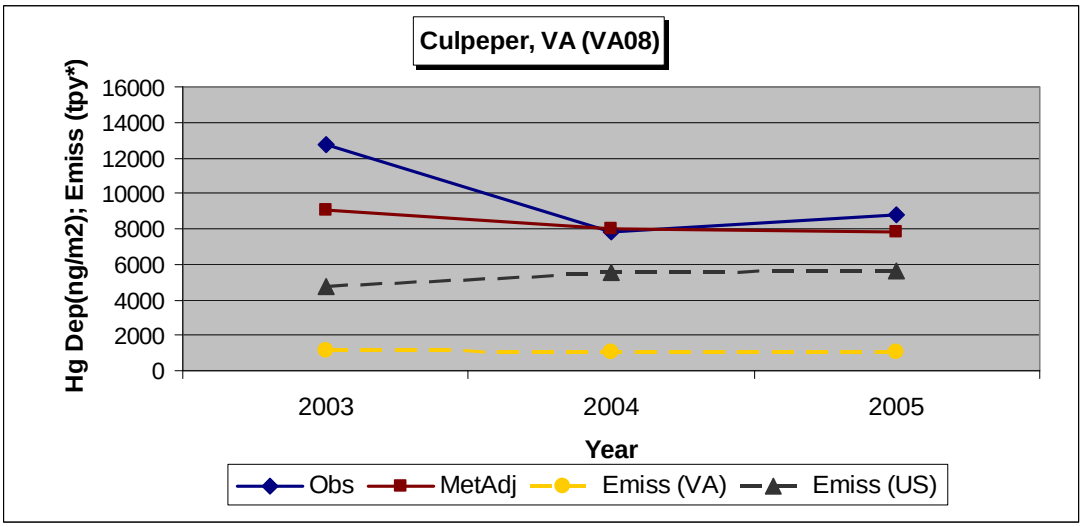


The meteorologically adjusted deposition amounts exhibit less variation among the years and indicate a slight downward trend in mercury deposition during this three-year period.

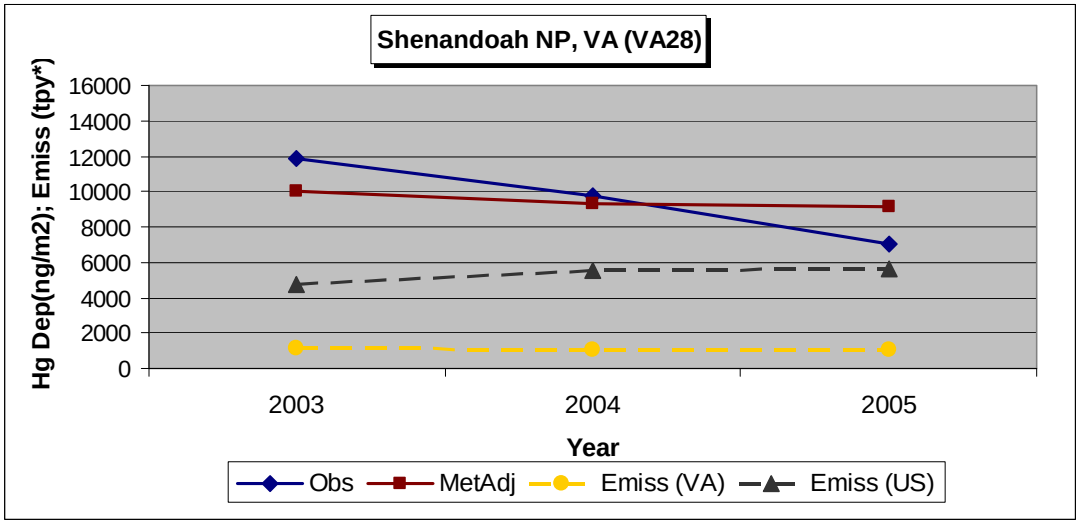
The meteorologically adjusted values are consistent with mercury emissions data from the EPA Toxics Release Inventory (TRI) (EPA, 2007). Figure 3-17 show the observed and meteorologically adjusted deposition values along with the TRI emissions for Virginia and the entire U.S. Note that for plotting purposes, the emissions totals for Virginia (tons per year (tpy)) have been multiplied by 1000 and the emissions totals (tpy) for the U.S. have been multiplied by 50.

Figure 3-17. Actual & Meteorologically-Adjusted Annual Mercury Wet Deposition (ng m-2) for MDN Monitoring Sites in Virginia Plotted Together with TRI Annual Mercury Emissions Totals (scaled tpy) for Virginia and the Entire U.S.

(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



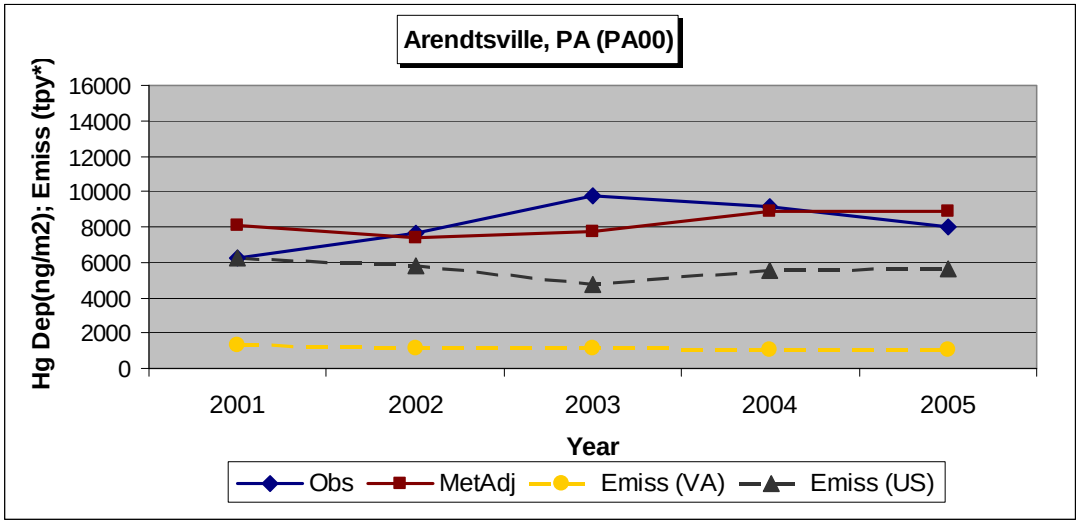
The meteorologically adjusted deposition values (for both sites) and the emissions for Virginia decrease slightly during the three-year period. The tendencies exhibited by the meteorological adjusted values are consistent with the emissions (much more so than the observed tendencies).

Meteorologically adjusted deposition values for those sites with longer periods of record that provided the best match to the Virginia sites Arendtsville (PA00), Allegheny Railroad NHS (PA13), and Pettigrew State Park (NC42) are plotted in Figure 3-18. Note that for plotting purposes, the emissions total for Virginia (tpy) has been multiplied by 1000 and the emissions totals (tpy) for the

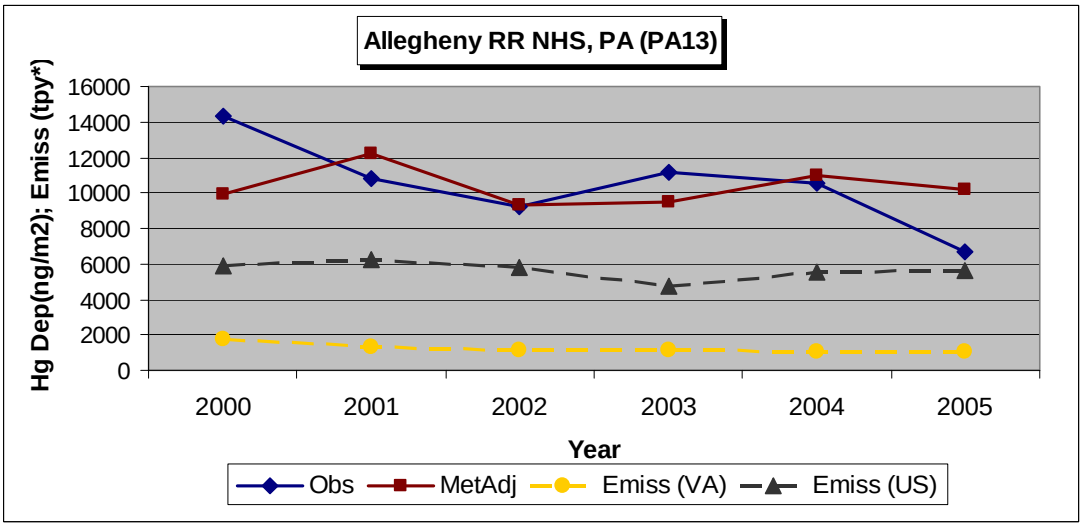
U.S. have been multiplied by 50. Also note that the emissions data are available beginning for 2000, so all plots begin in 2000 or later, based on MDN data availability.

Figure 3-18. Actual & Meteorologically-Adjusted Annual Mercury Wet Deposition (ng m-2) for Geographically Similar MDN Monitoring Sites in Surrounding States Plotted Together with TRI Annual Mercury Emissions Totals (tpy) for Virginia and the Entire U.S.

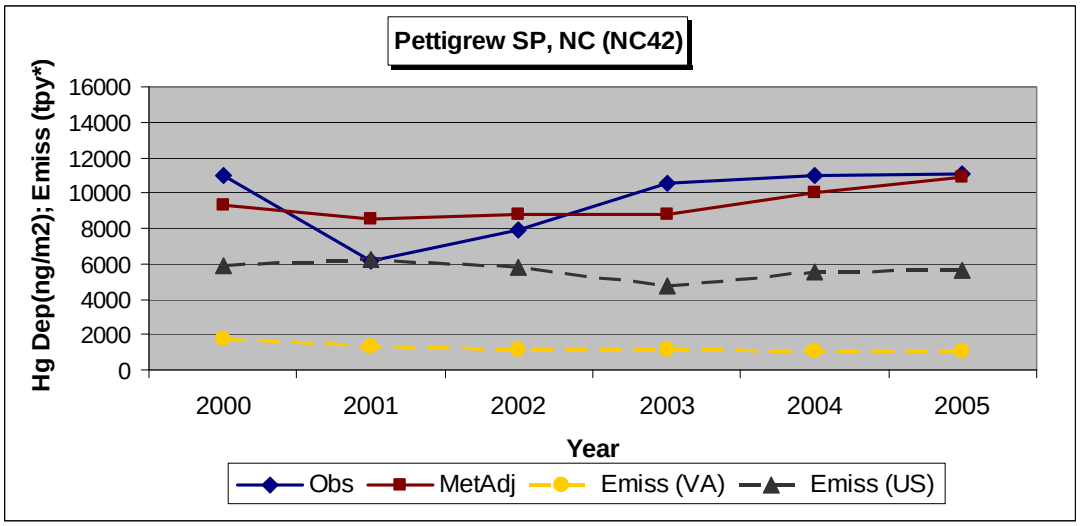
(a) Arendtsville (PA00)



(b) Allegheny Portage Railroad NHS (PA13)



(c) Pettigrew State Park (NC42)



The meteorologically adjusted deposition values for the three additional sites, also exhibit less variation among the years. For these sites, the trend for 2003 to 2005 is slightly upward, in contrast to that calculated for the Virginia sites. The meteorologically adjusted deposition values appear to track the U.S. emissions totals quite well.

4. Emissions Related Influences

Global, national, regional, and local sources of air mercury emissions contribute to mercury deposition. Understanding these contributions is an important step toward identifying measures that will effectively reduce mercury deposition and environmental mercury levels.

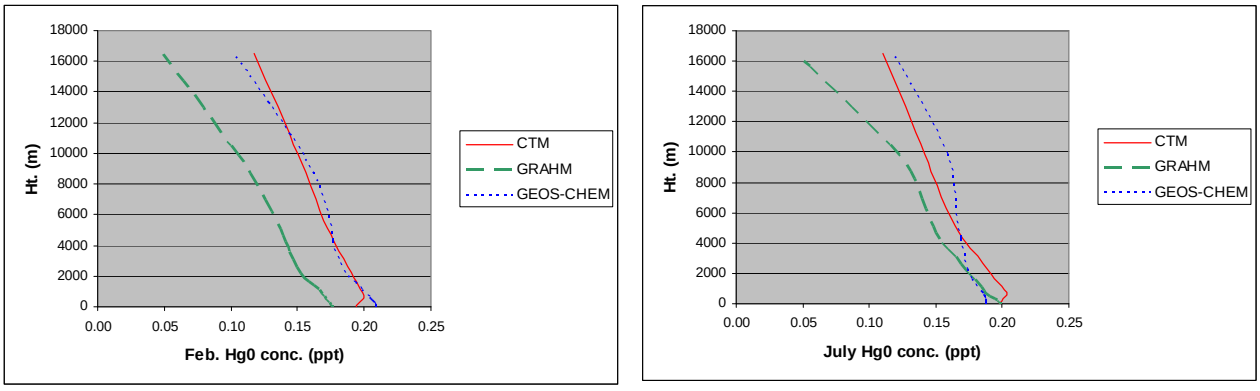
4.1. Global Background

It is expected that global background concentrations of mercury are high enough to influence the magnitude of mercury deposition within the U.S. The magnitude of global background concentrations is not, however, well known. In particular, the concentrations of the oxidized forms of mercury are very uncertain. Recent modeling studies have estimated that background concentrations of elemental mercury are about 1.6 nanograms per cubic meter (ng m^{-3}) (Pai et al., 1999; Myers et al., 2003). Support for this estimate can be found in experimental studies (e.g., Blanchard et al., 2002).

As part of the North American Mercury Model Inter-comparison Study (NAMMIS), several global simulation models were used to estimate global background concentrations of elemental, divalent gaseous, and particulate mercury to be used as boundary conditions for modeling of the continental U.S. (Bullock et al., 2006). These included the Chemical Transport Model (CTM), the Global/Regional Atmospheric Heavy Metals model (GRAHM), and the GEOS-Chem model.

A summary and comparison of the boundary concentrations of Hg(0) derived from the three global models is presented in Figure 4-1 (from Myers et al., 2006). The concentrations depicted in the plots represent the average concentration around the perimeter of the U.S. Each data point represents the average for one layer of a regional model, averaged over all grid cells that comprise the perimeter of a modeling domain that encompasses the continental U.S. and portions of Canada and Mexico. The boundary conditions are compared for February and July in order to examine the temporal variation of concentrations. The units are parts per trillion (ppt). At standard temperature and pressure conditions (STP), 0.2 ppt is approximately 1.8 ng m^{-3} of mercury. Differences among the global models reflect the uncertainty in global background estimates. The plots also show that the concentrations vary in the vertical and with time of year.

Figure 4-1. Comparison of CTM, GRAHM, and GEOS-CHEM Derived Boundary Concentrations (ppt) for a Modeling Domain Encompassing the U.S. for HG(0): February and July 2001.



4.2. National, Regional, and Local Emissions

Mercury in the atmosphere can be attributed to both natural and anthropogenic sources. Natural sources of mercury include soils, rocks, volcanoes, and the oceans. Within the U.S., most natural mercury emissions are associated with land types found in the western part of the continent. Prescribed burning and wild fires, which occur in many different areas throughout the U.S., can cause re-emission of natural and previously deposited emissions into the atmosphere.

Anthropogenic sources of mercury include coal-fired power plants and other industrial coal-burning facilities, municipal, medical, industrial and hazardous waste incinerators, chlor-alkali and other chemical manufacturing plants, taconite and other metallurgical processing facilities, pulp and paper manufacturing facilities, mining operations, cement plants, mobile sources, and a wide variety of other industrial and residential sources (EPA, 2005a).

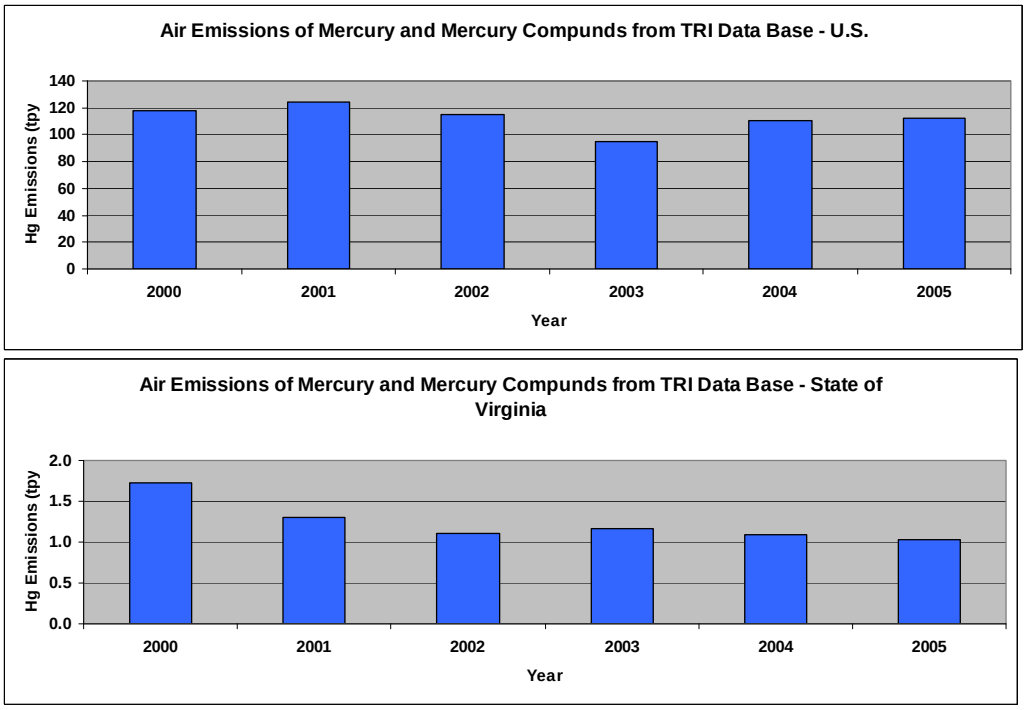
Table 4-1 summarizes total U.S. anthropogenic mercury emissions for a variety of point and non-point source categories, as contained in Version 3 of EPA's 2002 National Emissions Inventory (NEI). The table presents a breakdown by emitted species, including elemental mercury, divalent mercury, and particulate mercury. Over 60 percent of the emitted mercury is in the form of elemental mercury, 30 percent is divalent mercury, and about 10 percent is particulate mercury. The largest anthropogenic contributors to mercury emissions in the U.S. are coal-burning electric generation units (EGU's). Other large point source mercury emitters include metals processing sources and waste disposal/recycling sources.

Table 4-1. The 2002 U.S. Mercury Point and Non-Point Source Emission Inventory from Version 3 of the NEI.

	Point Source				Non-Point Source				Point and Non-Point Source			
	HG0	HG2	HGP	Total	HG0	HG2	HGP	Total	HG0	HG2	HGP	Total
TIER 2 CODES	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)	(lb/year)
FUEL COMB. ELEC. UTIL.	61539	42851	4446	108836	8	5	3	16	61547	42856	4449	108852
Coal	59787	41975	3818	105580	2	1	1	5	59789	41976	3819	105584
Oil	1007	510	350	1867	6	3	2	11	1013	513	352	1878
Gas	0	0	0	1				0	0	0	0	1
Other	274	164	110	548				0	274	164	110	548
Internal Combustion	431	259	172	863				0	431	259	172	863
FUEL COMB. INDUSTRIAL	4008	2365	1577	7950	1723	1037	690	3449	5731	3402	2267	11399
Coal	2051	1226	818	4095	91	55	37	183	2143	1281	854	4278
Oil	1168	690	461	2319	1504	905	601	3010	2672	1595	1062	5329
Gas	59	27	19	105				0	59	27	19	105
Other	699	404	271	1373	131	79	52	263	830	483	323	1636
Internal Combustion	32	19	13	64				0	32	19	13	64
FUEL COMB. OTHER	256	154	103	513	4314	2584	1723	8621	4571	2738	1826	9134
Commercial/Institutional Coal	223	134	89	447	24	15	10	49	248	149	99	496
Commercial/Institutional Oil	25	15	10	49	2716	1628	1088	5431	2740	1643	1097	5480
Commercial/Institutional Gas	0	0	0	0				0	0	0	0	0
Misc. Fuel Comb. (Except Residential)	8	5	3	17	55	33	22	111	64	39	26	128
Residential Wood					4	3	2	9	4	3	2	9
Residential Other					1511	905	604	3021	1511	905	604	3021
CHEMICAL & ALLIED PRODUCT MFG	10804	688	114	11606				0	10804	688	114	11606
Organic Chemical Mfg	3	0	0	4				0	3	0	0	4
Inorganic Chemical Mfg	10439	568	28	11035				0	10439	568	28	11035
Polymer & Resin Mfg	1	0	0	1				0	1	0	0	1
Agricultural Chemical Mfg	165	97	65	327				0	165	97	65	327
Paint, Varnish, Lacquer, Enamel Mfg	9	1	1	11				0	9	1	1	11
Other Chemical Mfg	139	21	19	180				0	139	21	19	180
METALS PROCESSING	21973	2862	2811	27645				0	21973	2862	2811	27645
Non-Ferrous Metals Process	1781	239	232	2253				0	1781	239	232	2253
Ferrous Metals Processing	19929	2555	2526	25010				0	19929	2555	2526	25010
Metals Processing NEC	269	70	48	388				0	269	70	48	388
PETROLEUM & RELATED INDUSTRIES	180	27	25	232				0	180	27	25	232
Oil & Gas Production	0	0	0	0				0	0	0	0	0
Petroleum Refineries & Related Industries	26	7	5	38				0	26	7	5	38
Asphalt Manufacturing	153	20	20	193				0	153	20	20	193
OTHER INDUSTRIAL PROCESSES	10877	2270	1927	15075				0	10877	2270	1927	15075
Agriculture, Food, & Kindred Products	41	19	13	74				0	41	19	13	74
Textiles, Leather, & Apparel Products	0	0	0	0				0	0	0	0	0
Wood, Pulp & Paper, & Publishing Products	709	426	284	1418				0	709	426	284	1418
Rubber & Miscellaneous Plastic Products	15	9	6	30				0	15	9	6	30
Mineral Products	8541	1453	1343	11337				0	8541	1453	1343	11337
Machinery Products	58	41	7	107				0	58	41	7	107
Transportation Equipment	1	0	0	1				0	1	0	0	1
Miscellaneous Industrial Processes	1504	327	275	2106				0	1504	327	275	2106
SOLVENT UTILIZATION	107	30	23	159				0	107	30	23	159
Degreasing	0	0	0	0				0	0	0	0	0
Graphic Arts	4	2	1	7				0	4	2	1	7
Surface Coating	29	17	11	57				0	29	17	11	57
Other Industrial	74	11	10	94				0	74	11	10	94
STORAGE & TRANSPORT	562	92	85	739				0	562	92	85	739
Bulk Terminals & Plants	11	7	4	22				0	11	7	4	22
Petroleum & Petroleum Product Storage	0	0	0	0				0	0	0	0	0
Organic Chemical Storage	0	0	0	0				0	0	0	0	0
Inorganic Chemical Storage	1	0	0	1				0	1	0	0	1
Bulk Materials Storage	550	85	80	715				0	550	85	80	715
WASTE DISPOSAL & RECYCLING	24747	13578	8030	46355	23	14	9	46	24770	13592	8039	46401
Incineration	12921	11972	6468	31361	13	8	5	26	12934	11980	6473	31387
Open Burning	0	0	0	0				0	0	0	0	0
POTW	2	0	0	2				0	2	0	0	2
TSDF	1	0	0	1				0	1	0	0	1
Landfills	21	3	3	27	10	6	4	20	31	9	7	47
Other	11826	1606	1555	14987	0	0	0	0	11826	1606	1555	14987
MISCELLANEOUS	30	16	9	55	1840	1102	737	3679	1870	1118	746	3734
Agriculture & Forestry					69	41	28	138	69	41	28	138
Other Combustion					224	134	90	448	224	134	90	448
Health Services	30	16	9	55	854	513	342	1710	884	529	351	1764
Fluorescent Lamp Breakage					692	415	277	1384	692	415	277	1384
Total	135049	65017	19160	219227	7908	4742	3162	15812	142957	69759	22322	235038

Figure 4-2 presents mercury emission totals for the U.S. and the Commonwealth of Virginia derived from the national Toxics Release Inventory (TRI) for the period 2000 to 2005. This inventory provides an alternative but consistent estimate of the year-to-year variation of anthropogenic mercury emissions and can be used to discern any significant trends during this period. The data indicate no clear trends in total U.S. mercury emissions with a slight decrease in mercury emissions since 2000 for the Commonwealth of Virginia.

Figure 4-2. Mercury Emissions for the U.S. and the Commonwealth of Virginia from the TRI Data Base.



The Commonwealth of Virginia recently updated the mercury point source emission estimates for 2002 and 2005. Figure 4-3 presents a comparison of the speciated mercury emission totals for the updated 2002 inventory with those contained in EPA's NEI Version 3 inventory for Virginia. The figure provides a comparison of emissions for the top 20 mercury emitters and for all point source emitters in the state. Nearly 95 percent of mercury emissions for point and non-point sources are from the top 20 sources. The data indicate that the NEI 2002 emissions for these same 20 sources are comparable, but the NEI has higher estimates of emissions when all point sources are considered.

Figure 4-3. Mercury Emissions for the Commonwealth of Virginia: VDEQ 2002 vs. NEI.

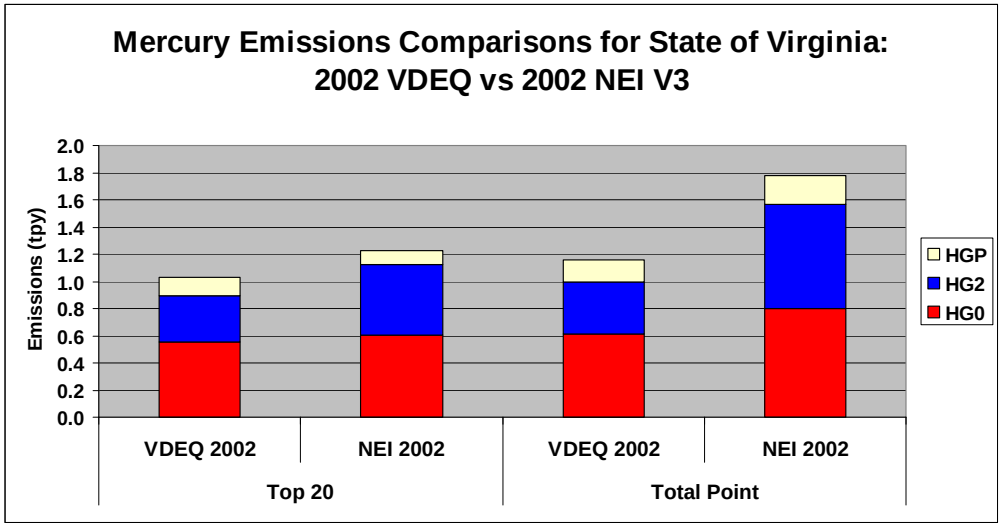
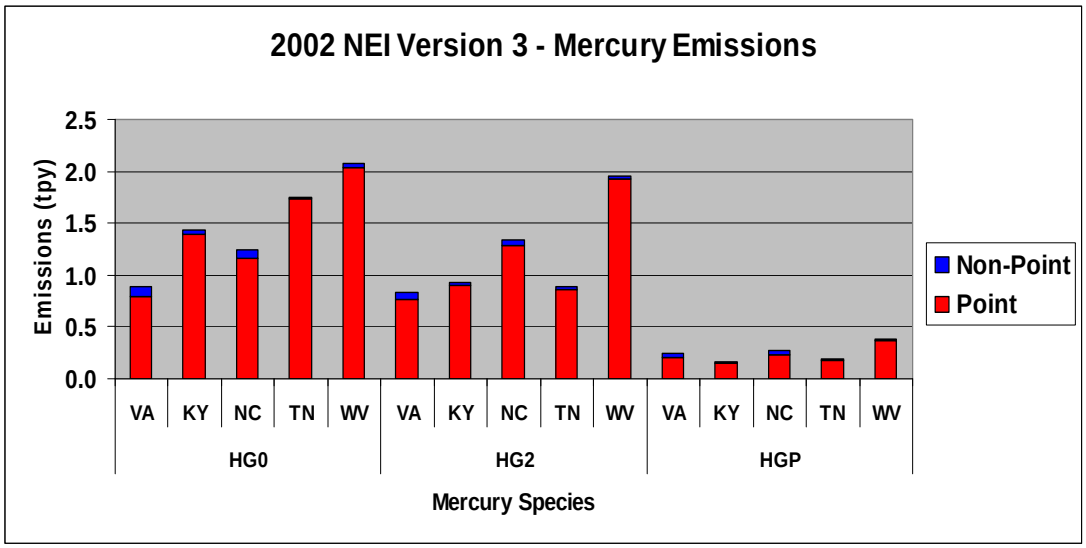


Table 4-2 presents emission totals for the top 20 Virginia mercury point sources. As noted for the national inventory, the top emitters for Virginia are the EGU's. Figure 4-4 presents speciated mercury emission totals for point and non-point sources in Virginia and the neighboring states of Kentucky, West Virginia, North Carolina, and Tennessee as contained in the 2002 NEI inventory. The higher mercury emissions in these predominantly upwind neighboring states likely influence and impact areas within Virginia.

Table 4-2. Top 20 Virginia Mercury Point Source Emitters for 2002.

		VDEQ Data						
		2002 Emissions				Speciation		
		HG0	HG2	HGP	Total	HG0	HG2	HGP
Facility Name	EGU?	(lb/yr)	(lb/yr)	(lb/yr)	(lb/yr)			
Dominion - Chesterfield Power Station	EGU	179.42	107.65	71.77	358.83	50%	30%	20%
Chaparral Steel	non-EGU	233.75	29.29	29.26	292.30	80%	10%	10%
Dominion - Bremo	EGU	83.86	50.32	33.55	167.73	50%	30%	20%
American Electric Power- Clinch River	EGU	38.21	121.00	0.00	159.21	24%	76%	0%
Dominion - Chesapeake Energy Center	EGU	78.69	47.22	31.48	157.38	50%	30%	20%
Potomac River Generating Station	EGU	11.83	106.43	0.00	118.26	10%	90%	0%
Dominion - Yorktown Power Station	EGU	53.82	32.29	21.53	107.64	50%	30%	20%
Jewel Coke Company LLP	non-EGU	84.50	10.56	10.56	105.63	80%	10%	10%
Dominion - Possum Point Power Station	EGU	50.09	30.06	20.04	100.19	50%	30%	20%
Stone Container Enterprises (Smurfit)	non-EGU	46.81	27.22	3.73	77.76	60%	35%	5%
Stone Container Corporation - Hopewell	non-EGU	34.84	20.91	13.94	69.69	50%	30%	20%
American Electric Power (Glen Lyn)	EGU	26.06	39.08	0.00	65.14	40%	60%	0%
Intermet Foundry Archer Creek	non-EGU	51.97	6.53	6.51	65.01	80%	10%	10%
RES dba Steel Dynamics	non-EGU	48.64	6.08	6.08	60.80	80%	10%	10%
Spruance Genco LLC	EGU	27.75	16.65	11.10	55.50	50%	30%	20%
Mead Westvaco Packaging Resources	non-EGU	12.96	4.88	9.07	26.91	48%	18%	34%
Covanta Fairfax, Inc.	EGU	12.87	7.72	5.15	25.73	50%	30%	20%
James River Cogeneration Company	EGU	12.65	7.59	5.06	25.30	50%	30%	20%
Celanese/Cinergy Solutions (21418)	non-EGU	9.20	5.52	3.68	18.40	50%	30%	20%
Dominion - Clover Power Station	EGU	8.34	5.00	3.34	16.68	50%	30%	20%

Figure 4-4. Comparison of Mercury Emissions for Virginia and Several Surrounding States.



5. Indications from Prior Modeling Studies

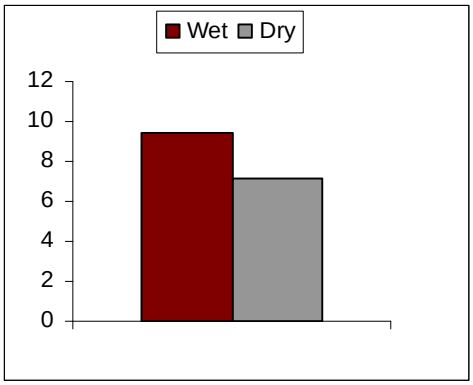
Analysis of the available MDN mercury deposition data for Virginia and the surrounding states has allowed us to examine the role of meteorology in mercury wet deposition, as well as the spatial and temporal characteristics of wet deposition throughout the region. In this section, we use existing mercury deposition modeling results to estimate the relative importance of wet versus dry deposition, examine the modeled species distributions, and quantify the potential contributions from global background as well as national, regional, and local emissions sources.

In a recent study for the EPA Office of Water (OW), Myers et al. (2006) used the REgional Modeling System for Aerosols and Deposition (REMSAD) to simulate mercury deposition for the entire U.S. for an annual simulation period of 2001. This study focused on tracking airborne mercury emissions and quantifying the contribution of various sources and source categories to mercury deposition in each of the contiguous 48 states.

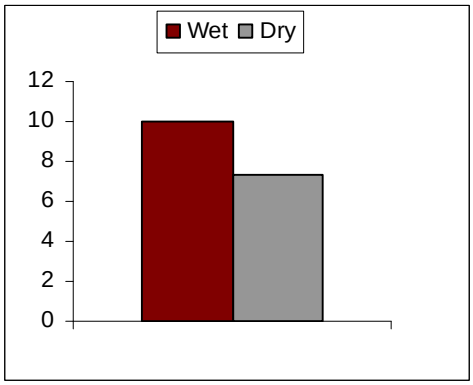
The REMSAD model simulates both wet and dry deposition. Figure 5-1 illustrates the REMSAD-derived estimates of wet and dry deposition for the Culpeper, Shenandoah, and Harcum monitoring sites. These results suggest that for all three sites, dry deposition is a significant contributing factor to total deposition. The simulated dry deposition amount is about 60 to 75 percent as large as the wet deposition amount. Overall, the simulated dry deposition represents about 40 percent or more of the total deposition.

Figure 5-1. REMSAD-Simulated Annual Wet and Dry Mercury Deposition (kg ha^{-1}) for MDN Monitoring Sites in Virginia.

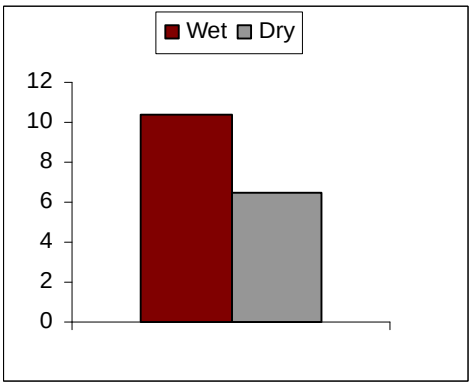
(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



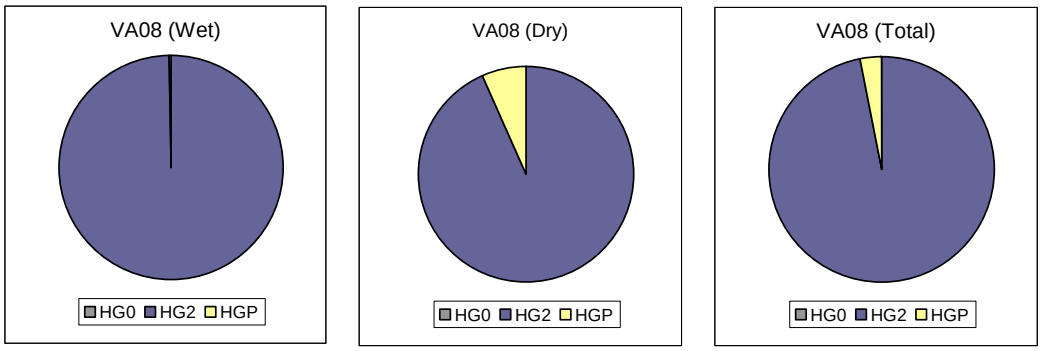
(c) Harcum (VA98)



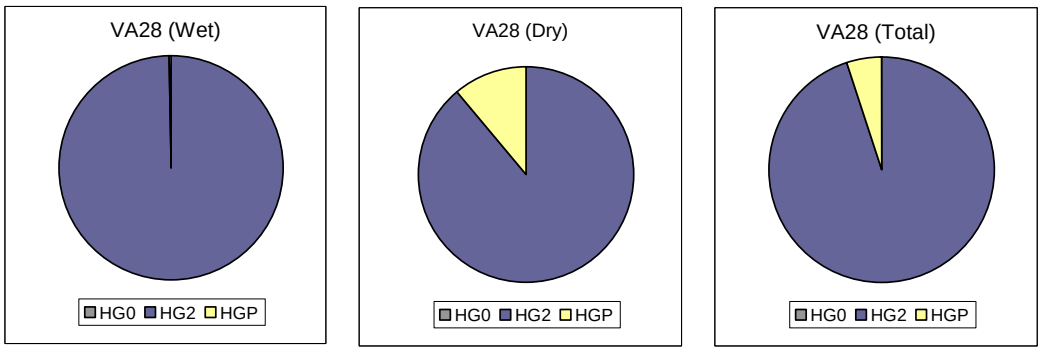
The mercury species simulated by the REMSAD model include Hg(0), Hg(2) (reactive gaseous mercury), and Hg(p). Figure 5-2 illustrates the REMSAD-derived estimates of deposition by species for the Culpeper, Shenandoah, and Harcum monitoring sites. For all three sites, wet deposition is predominantly Hg(2), where as dry deposition includes on the order of about 10 percent Hg(p). Note that in the simulations for the OW project, dry deposition of Hg(0) was assumed to be zero since deposited elemental mercury may be rapidly re-emitted back to the atmosphere.

Figure 5-2. REMSAD-Simulated Species Distribution for Wet, Dry and Total Mercury Deposition for MDN Monitoring Sites in Virginia.

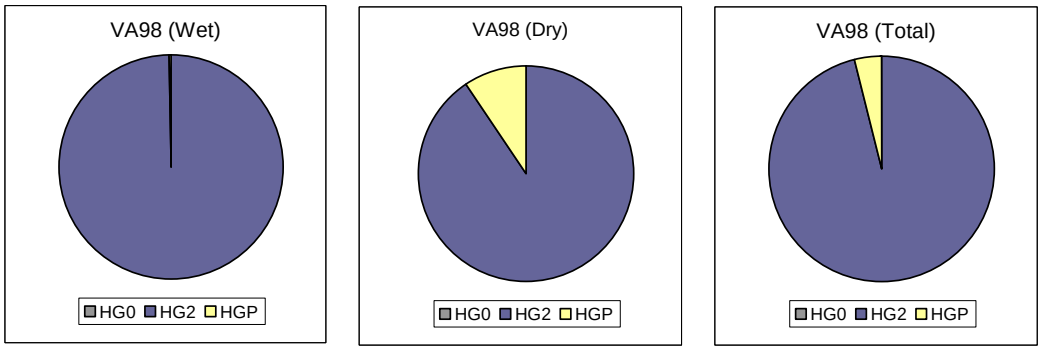
(a) Culpeper (VA08)



(b) Shenandoah National Park (VA28)



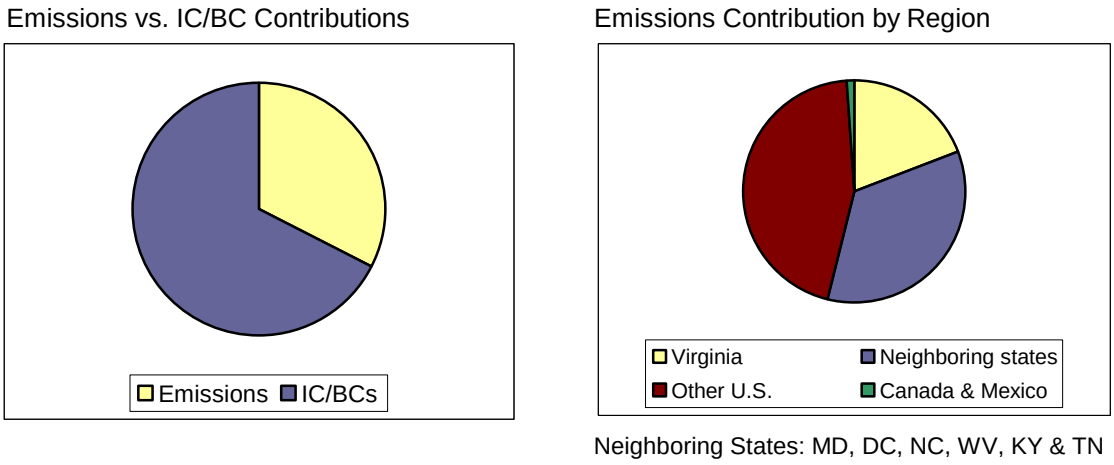
(c) Harcum (VA98)



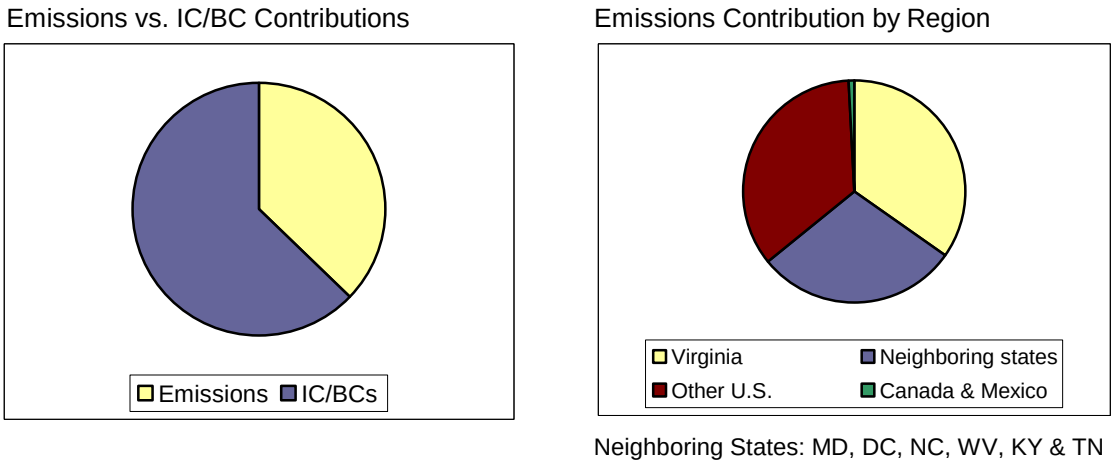
The REMSAD Particle and Precursor Tagging Methodology (PPTM) was used in the OW study to quantify the contribution of emissions from various sources and source regions to mercury deposition throughout the modeling domain. These contributions are illustrated in Figure 5-3 for the Culpeper, Shenandoah, and Harcum monitoring sites. The first pie chart presents the contribution to total deposition from all emissions sources and the model initial/boundary conditions, which we use here to represent background. Note that in the context of this display, "emissions" refers to emissions from sources in the U.S., Canada, and Mexico. The second pie further attributes the emissions contributions to 1) sources within the Commonwealth of Virginia, 2) sources in neighboring states, 3) sources in all other U.S. states, and 4) sources in Canada and Mexico. The neighboring states include Maryland, the District of Columbia, North Carolina, West Virginia, Kentucky, and Tennessee.

Figure 5-3. Contributions to REMSAD-Simulated Annual Mercury Deposition (kg ha^{-1}) for MDN Monitoring Sites in Virginia.

(a) Culpeper (VA08)

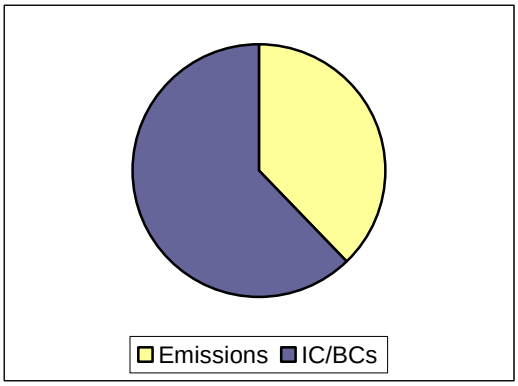


(b) Shenandoah National Park (VA28)

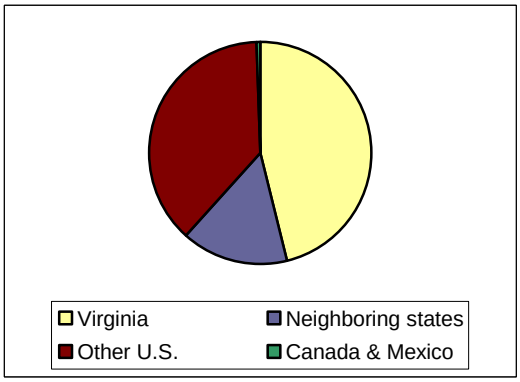


(c) Harcum (VA98)

Emissions vs. IC/BC Contributions



Emissions Contribution by Region

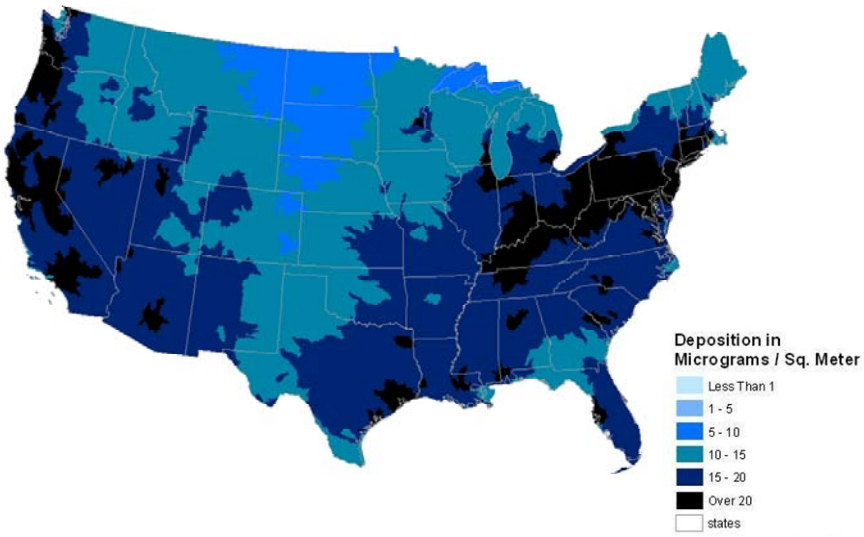


Neighboring States: MD, DC, NC, WV, KY & TN

These results indicate that global background (as characterized by the REMSAD initial and boundary conditions) may comprise 60 to 70 percent of the contribution to mercury deposition at the Virginia MDN sites. The emissions contributing to the simulated deposition are from Virginia, the neighboring states, and other states within the U.S.

EPA applied the Community Multi-scale Air Quality (CMAQ) model for the same 2001 simulation period to support the development of the Clean Air Mercury Rule (CAMR). The modeling results (EPA, 2005b) support the conclusion that mercury deposition is a regional-scale issue (see Figure 5-4).

Figure 5-4. CMAQ-Simulated Annual Mercury Deposition (μg m^{-2}) from the CAMR Modeling.



Source: EPA

In addition to the breakdown by state and region, PPTM was also used in the OW study to quantify the contribution of emissions from specific sources. These results (not shown) reveal local source-specific contributions to mercury deposition at the three monitoring sites.

6. Summary Conceptual Description

This report provides a conceptual description of mercury deposition for several locations in Virginia and the surrounding states. This description is based on observed mercury deposition data, meteorological data, emissions inventory information, and some recent existing mercury deposition modeling results.

A key focus of this discussion is mercury wet deposition for three Mercury Deposition Network (MDN) sites in Virginia: Culpeper, Shenandoah National Park, and Harcum. The period of record for the MDN data is late 2002 through 2006 for Culpeper, late 2002 to the present for Shenandoah, and approximately 2005 to the present for the Harcum site. The Culpeper site is located in north central Virginia. The Shenandoah site is a high elevation monitoring site located within the national park (in northwestern Virginia), while the Harcum site is located along the southern portion of the inner coast of the Chesapeake Bay.

Analysis of the data and recent modeling results has provided insight into some key questions regarding the nature of mercury deposition.

- **Is mercury deposition primarily a local issue, or are regional, national, and global factors important?**

  Based on a review of the available data and prior modeling results, it is expected that global, national, regional, and local factors contribute to mercury deposition in Virginia. The primary source of mercury to impaired water bodies is believed to be atmospheric deposition, which is comprised of both natural and anthropogenic emissions. These emissions can be directly emitted or re-emitted to the atmosphere after being deposited at another location.

  Various atmospheric processes influence the transport and deposition of mercury and these involve a variety of scales ranging from global to local. Specifically:

  - Mercury may be transported globally by atmospheric circulation systems and prior mercury deposition modeling results indicate that global background may comprise 60 to 70 percent of the contribution to mercury deposition at the Virginia MDN sites.
  - Mercury may also be subject to regional-scale transport. Prior modeling also indicates that emissions contributing to the simulated deposition are from Virginia, the neighboring states, and other states within the U.S. Similarities in observed mercury wet deposition among monitoring sites in Virginia and several neighboring states also support the conclusion that mercury deposition is a regional-scale issue.
  - Finally, prior modeling also reveals local source-specific contributions to mercury deposition at the three monitoring sites.

- **Does mercury deposition vary with time?**

  Annual mercury wet deposition amounts vary by year for monitoring sites in Virginia and the surrounding states.

  In addition, within each calendar year, there are variations in deposition by week, month, and quarter, primarily in accordance with variations in rainfall amount.

  Mercury deposition (and rainfall amount) appears to have an annual cycle, with higher deposition amounts during the second and third quarters (April through June and July through September, respectively).

- **Does mercury deposition vary from location to location?**

  Measurements of wet mercury deposition data indicate that deposition varies from location to location. For the period 2003-2005, annual mercury deposition for the Virginia MDN sites is about the same as that for nearby sites in southern Pennsylvania, and lower than that for nearby sites in North Carolina and Tennessee. In some cases, deposition characteristics are similar for geographically similar sites within the mid-Atlantic region. For each of the Virginia MDN sites, it is possible to identify a longer term monitoring site (from a neighboring state) that has similar deposition characteristics.

  Prior modeling performed by EPA also indicates that mercury deposition varies from location to location and more specifically that annual mercury deposition is related to the distribution of emission sources, especially within the eastern U.S.

- **How does meteorology influence mercury deposition in Virginia?**

  A number of different meteorological factors influence mercury deposition in Virginia. Key factors include precipitation, temperature, wind speed, and the potential for recirculation. The relative importance of each of these factors varies among the three monitoring sites. In addition, there are different types of meteorological conditions and combinations of parameters that lead to high deposition.

  Precipitation is an important mechanism for wet mercury deposition. Mercury wet deposition is correlated with rainfall, but rainfall amount does not fully explain the observed variations in deposition.

  For all three MDN sites, there is a positive correlation between rainfall, temperature, and relative humidity such that the greater the values of these parameters, the greater the deposition. Higher deposition is associated with lower wind speeds and a well mixed atmosphere. The conditions are representative of summertime conditions and consistent with the timing of the higher observed deposition amounts.

  Wind directions, both near the surface and at upper levels, may influence the regional and local transport of mercury emissions from source regions or individual sources for subsequent deposition at the monitoring sites (and to bodies of water) in Virginia. For all three MDN sites, wind directions are slightly different during high deposition periods compared to all periods and indicate possible regional or local transport of mercury emissions from the east or northeast for Culpeper and Shenandoah, and from the south or southwest for Harcum.

  Finally, dry deposition of mercury is influenced by several meteorological factors including the temperature characteristics of the atmosphere and the wind speed.

- **Are there discernable trends in mercury deposition and have recent changes in deposition been accompanied by changes in emissions or primarily driven by meteorological variability?**

  Variations in meteorology contribute to observed variations in quarterly and annual mercury wet deposition.

  Annual deposition amounts that have been adjusted to account for these variations in meteorology exhibit much less variation among the years. For the Virginia sites, the meteorologically adjusted deposition values for 2003-2005 are consistent with changes in the emissions for Virginia. For the Culpeper and Shenandoah sites, the adjusted deposition values indicate a slight downward trend.

For sites in Pennsylvania and North Carolina, the meteorologically adjusted deposition trends for 2000-2005 are consistent with changes in the U.S. emissions. For 2003 to 2005 the trend is slightly upward, in contrast to that for the Virginia sites.

- **What is the relative importance of wet versus dry deposition, and the various mercury species?**

  Prior modeling results suggest that for all three Virginia sites, dry deposition is a significant contributing factor to total mercury deposition. Overall, the simulated dry deposition represents about 40 percent or more of the total deposition. Prior modeling also indicates that both wet and dry deposition are predominantly reactive gaseous mercury, and that dry deposition includes about 10 percent particulate mercury.

  These results are consistent with monitoring data. The National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory conducted a monitoring study during the summer of 2005 at the Harcum site and found that dry deposition was significant and was dominated by reactive gaseous mercury.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Appendix C: Emissions Data Analysis Report

Virginia Department of Environmental Quality (VDEQ)

The Virginia Mercury Study: Review and Assessment of Virginia Mercury Emissions Data and Recent Mercury Studies

Mercury Modeling Study Contract № 13360
Report

February 13, 2008

07-045

ICF INTERNATIONAL

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Virginia Department of Environmental Quality (VDEQ)

The Virginia Mercury Study: Review and Assessment of Virginia Mercury Emissions Data and Recent Mercury Studies

Mercury Modeling Study Contract № 13360 Report

February 13, 2008

Prepared for
Michael Kiss
Virginia Department of Environmental Quality
629 East Main Street
Richmond, VA 23219
(804) 698-4061

Prepared by:
Jay Haney, YiHua Wei, Sharon Douglas, Tom Myers
ICF International
101 Lucas Valley Road, Suite 260
San Rafael, CA 94903
(415) 507-7164

Tim Lavallee
LPES, Inc.
14053 Lawns Creek Road
Smithfield, VA 23430

Diane Shotynski
Thruput LLC
7261 Sleigh Hill Drive
Saltville, VA 24370

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1. Introduction

This report summarizes a review and analysis of the sources of atmospheric mercury emissions located within the Commonwealth of Virginia and surrounding areas. This review was conducted as part of the Virginia Mercury Study, which includes an air quality modeling analysis focusing on mercury air deposition to waterways.

1.1. Background

Mercury in the atmosphere can be attributed to both natural and anthropogenic sources. Natural sources of mercury include soils, rocks, volcanoes, and the oceans. Within the U.S., most natural mercury emissions are associated with land types found in the western part of the continent. Prescribed burning and wild fires, which occur in many different areas throughout the U.S., can cause re-emission of natural and previously deposited emissions into the atmosphere.

Anthropogenic sources of mercury include coal-fired power plants and other industrial coal-burning facilities, municipal, medical, industrial and hazardous waste incinerators, chlor-alkali and other chemical manufacturing plants, taconite and other metallurgical processing facilities, pulp and paper manufacturing facilities, mining operations, cement plants, mobile sources, and a wide variety of other industrial and residential sources (EPA, 2005a).

Recent national control legislation promulgated by EPA in the Clean Air Interstate Rule (CAIR) will serve to reduce emissions of NO_x, SO_2, and mercury from coal-fired power plants. The Clean Air Mercury Rule (CAMR) will build on CAIR and provide for additional future mercury emission reductions from these sources. Although controls have been mandated for a number of Virginia coal-fired power plant sources, an air quality modeling analysis will be conducted to quantify the effects of these controls on future-year mercury concentrations and deposition to waterways in the Commonwealth and to determine if more controls are needed.

Recently, the Virginia Department of Environmental Quality (VDEQ) updated the statewide mercury point source emission inventory and developed inventories for 2002 and 2005. These inventories were updated using information received from 75 facilities based on a survey. The information received from each of the facilities was reviewed in this analysis and will be used to estimate future-year emissions. The future-year estimates will be used in the air quality modeling and deposition analysis.

1.2. Objectives

The objectives of this portion of the Virginia Mercury Study are to: 1) conduct a review and analysis of recently updated mercury point source information for sources located in Virginia that will subsequently be used in the air deposition analysis, 2) estimate future-year emissions for 2010, 2015, and 2018 for these sources, and 3) conduct a literature search of recently completed mercury studies related to air deposition, emissions/controls, and air quality modeling and modify the planned approach to the modeling analysis, if warranted, to take advantage of the latest science related to mercury deposition modeling. The first two objectives ensure that the best available mercury emissions inventory is used for the base and future-year modeling analyses, while the third objective ensures that the air deposition modeling analysis will be conducted using the latest available modeling tools and approaches.

1.3. Atmospheric Mercury

Airborne mercury (Hg), emitted from various manmade and natural sources, is comprised of three forms: elemental mercury (Hg(0)), reactive gaseous mercury (RGM), and particulate mercury (Hg(p)). RGM is known to be comprised almost entirely of divalent mercury (Hg^{2+} or Hg(II)), since mercury compounds at other valence states tend to be chemically unstable in the atmosphere (Bullock et al., 2007). Hg(p) is also primarily comprised of divalent mercury, but may also include elemental mercury.

Elemental mercury is the dominant atmospheric species and comprises about 99 percent of the total mercury in the atmosphere. Hg(0) is characterized by low reactivity and low solubility in water. The dry deposition velocity is believed to be relatively low. Hg(0) has a long atmospheric lifetime (perhaps on the order of months to years) and is therefore dispersed and transported/circulated globally.

RGM represents less than one percent of atmospheric mercury. It is highly reactive and highly soluble. It can be actively removed from the atmosphere through both wet and dry deposition processes. As a result, the atmospheric lifetime of RGM is expected to be on the order of one day to one week. Based on these properties, RGM likely contributes to mercury deposition near the source location (locally or regionally).

Hg(p) also represents less than one percent of atmospheric mercury. It is moderately reactive and highly soluble in water. It is likely removed from the atmosphere primarily through wet deposition, since the dry deposition velocity of Hg(p) is expected to be low (based on that for similar fine particles). The atmospheric lifetime of Hg(p) is estimated to be on the order of one day to one week, or longer in the absence of precipitation. Based on these properties, Hg(p) also likely contributes to mercury deposition near the source location (locally or regionally).

1.4. Report Outline

Section 2 of this report summarizes the review of the Virginia point source inventory and Section 3 summarizes the base- and future-year estimates that will be used for the modeling analysis. Section 4 presents a summary of recent mercury studies that were reviewed as part of the literature search task. Finally, a comprehensive bibliography of recently completed reports and presentations is provided in the Appendix.

2. Overview of the Virginia Point Source Inventory

2.1. Review of 2002 Point Source Inventory

This section provides an overview of the process followed in reviewing and updating the mercury point source emissions inventory. As part of this study, point source inventories for 2002 and 2005 were obtained from VDEQ. These inventories were recently compiled based on responses to an information survey conducted by VDEQ to obtain the latest available emission inventory data for mercury point sources located in Virginia. Information regarding process type, emission totals, and mercury speciation was solicited and obtained. For those sources that did not have any speciation information based on recent stack testing, VDEQ instructed them to specify the default speciation profiles that were used in EPA's CAMR modeling analysis.

The intent of this review was to evaluate the information and identify missing data that, if updated, would improve the overall quality of the emission inventory. As noted, the 2002 emission inventory will be used in the base-year air quality modeling analysis and will be the basis for development of the future-year mercury emission inventories, so it is important to review the information and make any changes necessary to ensure that the latest and best information be made available for the modeling analysis.

In February 2007, a CD was received from VDEQ containing emission inventory files for seventy-five Virginia point sources. Of the facilities included, thirty-four supplied complete information and forty-one facilities had some missing or questionable information. Below, we summarize the findings of the initial review of the inventory.

The following table outlines the completeness of the initial responses to the DEQ data request.

	Number of Facilities
VDEQ potential source list	75
Supplied complete information	34
No information was supplied	5
Emissions rates incomplete	6
Speciation data incomplete	15
Stack parameter information incomplete	15
General source information incomplete	10

Detailed information for each category of missing data/information is provided below. Updates received from VDEQ for each of these categories are italicized in each of the sections.

No Information Provided

Information for five facilities on VDEQ's original list of potential mercury facilities was not included in the emission inventory. The facilities, along with the Virginia registration number, include:

1.	UVA Medical Center	40359
2.	Tangier Town	40714
3.	Perdue Farms–Soybean Oil Processing	60277
4.	Norman M Cole Jr Pollution Control Plant	70714
5.	Merck & Co	80524

Upon review by VDEQ, the UVA Medical Center and the Merck & Co. sources were removed from the list of potential mercury emitters. The Tangier Town and Norman M Cole Jr Pollution Control Plant sources were deemed insignificant sources of mercury. New emissions for the Perdue Farms source were provided by VDEQ.

Incomplete Emissions Information

Mercury emission rates were missing or questionable for six of the facilities. The equations and approach to determining the emission rates varied appreciably – approaches included AP-42, mass balance, stack test data, SW-486 and NCASI. In many cases, no supporting calculations are provided. Facilities with missing mercury emission rate information include:

1.	RES dba Steel Dynamics	20131	*Provided total Hg emissions for plant*
2.	Rock Tenn Co Mill	30188	*No updates provided*
3.	Dominion–Mecklenburg Power Station	30861	*Added new Hg emissions*
4.	Philip Morris USA Inc–Park 500	50722	*No updates provided*
5.	Burlington Industries LLC Hurt Fin	30379	*Added new Hg emissions*
6.	Stone Container Enterprises (Smurfit)	40126	*Confirmed that three stacks in facility have no Hg emissions*

Specific updates, as noted in the list above, were provided by VDEQ for these sources.

Speciation Information

Speciation information was missing for fifteen of the facilities. Facilities with speciation information missing included:

1.	MeadWestvaco Packaging Resources	20328
2.	RES dba Steel Dynamics	20131
3.	Philip Morris USA Mfg Center	50076
4.	Hopewell WWTP	50735
5.	James River Cogeneration Company	50950

6.	Spruance Genco LLC	51033
7.	Cogentrix Virginia Leasing Corp	61049
8.	H L Mooney Water Reclamation Facility	71751
9.	Georgia Pacific Corp Big Island Plt	30389
10.	Honeywell Nylon LLC–Hopewell	50232
11.	Philip Morris USA Inc.–Blended Leaf	50080
12.	Philip Morris USA Inc.–Leaf Processing	50082
13.	Burlington Industries LLC Hurt Fin	30379
14.	Griffin Pipe Products Company	30397
15.	Stone Container Enterprises (Smurfit)	40126

New information on mercury speciation profiles was obtained from VDEQ for all of these sources.

Incomplete Stack Parameter Information

Stack parameter information for fifteen facilities was initially incomplete or questionable. The deficient information ranged from missing geographic location, questionable entries, and missing physical stack parameters. Facilities with stack parameter information missing include:

1.	MeadWestvaco Packaging Resources	20328
2.	Dominion–Mecklenburg Power Station	30861
3.	Dominion–Clover Power Station	30867
4.	Birchwood Power Partners, L.P.	40809
5.	Honeywell Nylon LLC–Hopewell	50232
6.	Stone Container Corporation–Hopewell	50370
7.	Philip Morris USA Inc–Park 500	50722
8.	City of Harrisonburg– Resource Recovery	81016
9.	Dan River Incorporated Schoolfield	30240
10.	University of Virginia	40200
11.	US Navy Little Creek Amphibious Base	60033
12.	Burlington Industries LLC Hurt Fin	30379
13.	Griffin Pipe Products Company	30397
14.	Stone Container Enterprises (Smurfit)	40126
15.	Hopewell Cogeneration Ltd Partnership	50967

New stack information was obtained from VDEQ for all of these sources.

Incomplete General Information

General emission unit information for ten facilities was incomplete or questionable. Primarily this included SCC and MACT codes. In many cases, it was not clear whether the sources met the requirements for MACT. It was not possible to tell if all emission sources for the individual facilities were included in the preliminary inventory. Facilities with incomplete general emission unit information included:

1. Virginia Tech 20124
2. MeadWestvaco Virginia Specialty 20329
3. Internet Foundry Archer Creek 30121
4. Solite LLC/Giant Resource Recovery 30200
5. Burlington Industries LLC Hurt Fin 30379
6. Georgia Pacific Corp Big Island Plt 30389
7. Griffin Pipe Products Company 30397
8. Stone Container Enterprises (Smurfit) 40126
9. Hopewell Cogeneration Ltd Partnership 50967
10. Mohawk Industries Inc-Lees Carpet 80269

New information was obtained from VDEQ for all of these sources.

Specific Information Requested for Updating the Virginia Point Source Inventory

In addition to the general missing information related to emissions and stack parameters identified above, efforts were made to obtain the following information:

1. SCC codes for the following facilities.
    a. Chemical Lime Company 20225
    b. Celanese/Cinergy Solutions (21418) 20304
    c. Commonwealth Chesapeake Power 40898
    d. James River Cogeneration Company 50950
    e. Spruance Genco LLC 51033
    f. Cogentrix Virginia Leasing Corp 61049

New SCC code information was obtained from VDEQ for all of these sources.

2. Verify that the mercury speciation profiles for the following electric generating units (EGUs), which were specified as default 20/30/50 (hgp/hg2/hg0), are the latest available (or obtain updated profiles, if available).
    a. Dominion–Altavista Power Station 30859
    b. Dominion–Clover Power Station 30867
    c. Dominion–Bremo 40199

d. Dominion–Gordonsville Power Station 40808
e. Dominion–Chesterfield Power Station 50396
f. Dominion–Yorktown Power Station 60137
g. Dominion–Chesapeake Energy Center 60163
h. Dominion–Southampton Power Station 61093
i. Dominion–Elizabeth River CT Station 61108
j. Dominion–Possum Point Power Station 70225
k. Covanta Alexandria/Arlington, Inc. 71895
l. Covanta Fairfax, Inc. 71920

No new facility-specific speciation profile information was available for any of these sources.

2.2. Updated 2002 Point Source Inventory

Based on the initial review of the inventory as summarized in the previous section, updated information was received from VDEQ. Table 2-1 presents the final 2002 Virginia mercury point source inventory, summarized by facility. The table includes speciated emissions for EGU's and non-EGU's (other industrial sources) and the sources are listed in descending order by total facility mercury emissions. As noted above, for those sources that did not obtain any speciation information based on recent stack testing, they were instructed by VDEQ to specify the default speciation profiles that were used in EPA's CAMR modeling analysis (EPA, 2005a).

Table 2-1 VDEQ 2002 Point Source Mercury Emissions Inventory—Ranked by Facility Total Emissions

	Facility Name	County	Source Type	HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	*Total (lb/yr)*
1	Dominion–Chesterfield Power Station	Chesterfield	EGU	179.42	107.65	71.77	*358.83*
2	Chaparral Steel	Dinwiddie	non-EGU	233.75	29.29	29.26	*292.30*
3	Dominion–Bremo	Fluvanna	EGU	83.86	50.32	33.55	*167.73*
4	American Electric Power- Clinch River	Russell	EGU	38.21	121.00	0.00	*159.21*
5	Dominion–Chesapeake Energy Center	Chesapeake	EGU	78.69	47.22	31.48	*157.38*
6	Potomac River Generating Station	Alexandria	EGU	11.83	106.43	0.00	*118.26*
7	Dominion–Yorktown Power Station	York	EGU	53.82	32.29	21.53	*107.64*
8	Jewel Coke Company LLP	Buchanan	non-EGU	84.50	10.56	10.56	*105.63*
9	Dominion-Possum Point Power Station	Prince William	EGU	50.09	30.06	20.04	*100.19*
10	Stone Container Enterprises (Smurfit)	King William	non-EGU	46.81	27.22	3.73	*77.76*
11	Stone Container Corporation -Hopewell	Hopewell	non-EGU	34.84	20.91	13.94	*69.69*
12	American Electric Power	Giles	EGU	26.06	39.08	0.00	*65.14*
13	Intermet Foundry Archer Creek	Campbell	non-EGU	51.97	6.53	6.51	*65.01*
14	RES dba Steel Dynamics	Roanoke	non-EGU	48.64	6.08	6.08	*60.80*
15	Spruance Genco LLC	Richmond	EGU	27.75	16.65	11.10	*55.50*
16	Mead Westvaco Packaging Resources	Covington	non-EGU	12.96	4.88	9.07	*26.91*
17	Covanta Fairfax, Inc.	Fairfax	EGU	12.87	7.72	5.15	*25.73*
18	James River Cogeneration Company	Hopewell	EGU	12.65	7.59	5.06	*25.30*
19	Celanese/Cinergy Solutions (21418)	Giles	non-EGU	9.20	5.52	3.68	*18.40*
20	Dominion–Clover Power Station	Halifax	EGU	8.34	5.00	3.34	*16.68*
21	Giant Yorktown Refinery	York	non-EGU	12.74	1.59	1.59	*15.93*
22	SPSA Refuse Derived Fuel Plant	Portsmouth	non-EGU	3.43	9.05	3.12	*15.61*
23	H L Mooney Water Reclamation Facility	Prince William	non-EGU	3.21	8.47	2.92	*14.61*
24	Hopewell WWTP	Hopewell	non-EGU	2.93	7.71	2.66	*13.30*
25	HRSD Chesapeake-Elizabeth Sewage	Virginia Beach	non-EGU	2.87	7.56	2.61	*13.04*
26	Cogentrix Virginia Leasing Corp	Portsmouth	EGU	5.85	3.51	2.34	*11.70*
27	Chemical Lime Company	Giles	non-EGU	9.20	1.15	1.15	*11.50*
28	Burlington Industries LLC Hurt Fin	Pittsylvania	non-EGU	5.53	3.32	2.21	*11.05*
29	HRSD Boat Harbor Sewage Treatment Plt	Newport News	non-EGU	2.11	5.56	1.92	*9.59*
30	Roanoke Cement Company	Botetourt	non-EGU	6.96	1.21	1.11	*9.28*
31	Alliant Ammunition & Powder Co.	Montgomery	non-EGU	4.57	2.74	1.83	*9.14*
32	Philip Morris USA Inc–Park 500	Chesterfield	non-EGU	4.35	2.61	1.74	*8.69*
33	Georgia Pacific Corp Big Island Plt	Bedford	non-EGU	3.84	2.30	1.53	*7.67*
34	Mohawk Industries Inc-Lees Carpet	Rockbridge	non-EGU	3.76	2.26	1.50	*7.52*
35	HRSD Virginia Initiative Plant	Norfolk	non-EGU	1.45	3.81	1.31	*6.57*
36	HRSD Army Base Sewage Treatment Plt	Norfolk	non-EGU	1.41	3.71	1.28	*6.40*
37	Intermet Corporation Radford	Radford	non-EGU	4.90	0.61	0.61	*6.12*
38	Bear Island Paper Company LLC	Hanover	non-EGU	2.96	1.77	1.18	*5.91*
39	US Navy Little Creek Amphibious Base	Virginia Beach	non-EGU	2.93	1.76	1.17	*5.87*
40	HRSD Williamsburg	James City	non-EGU	0.99	2.62	0.90	*4.51*
41	Georgia-Pacific/Emporia Plywood	Greensville	non-EGU	2.06	1.24	0.82	*4.12*

	Facility Name	County	Source Type	HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	*Total (lb/yr)*
42	Covanta Alexandria/Arlington, Inc.	Alexandria	EGU	1.96	1.17	0.78	*3.92*
43	Dan River Incorporated Schoolfield	Danville	non-EGU	1.86	1.11	0.74	*3.71*
44	International Paper Company	Isle Of Wight	non-EGU	1.82	1.09	0.73	*3.63*
45	Honeywell Nylon LLC–Hopewell	Hopewell	non-EGU	1.81	1.09	0.72	*3.62*
46	Birchwood Power Partners, L.P.	King George	EGU	1.41	2.05	0.13	*3.59*
47	Solite LLC/Giant Resource Recovery	Buckingham	non-EGU	1.45	0.50	0.55	*2.50*
48	University of Virginia	Charlottesville	non-EGU	1.25	0.75	0.50	*2.49*
49	Philip Morris USA Mfg Center	Richmond	non-EGU	1.24	0.74	0.50	*2.48*
50	Dominion-Southampton Power Station	Southampton	EGU	1.10	0.66	0.44	*2.19*
51	Dominion–Altavista Power Station	Campbell	EGU	1.09	0.65	0.44	*2.18*
52	O-N Minerals (Chemstone) Strasburg	Shenandoah	non-EGU	1.74	0.22	0.22	*2.17*
53	Rock Tenn Co Mill	Lynchburg	non-EGU	0.94	0.56	0.37	*1.87*
54	Virginia Tech	Montgomery	non-EGU	0.75	0.45	0.30	*1.49*
55	Martinsville Thermal, LLC	Henry	non-EGU	0.71	0.42	0.28	*1.41*
56	Commonwealth Chesapeake Power	Accomack	EGU	0.67	0.40	0.27	*1.34*
57	Dominion–Mecklenburg Power Station	Mecklenburg	EGU	0.84	0.25	0.03	*1.11*
58	Hopewell Cogeneration Ltd Partnership	Hopewell	non-EGU	0.53	0.32	0.21	*1.05*
59	INVISTA S.a.r.l. -Waynesboro	Waynesboro	non-EGU	0.52	0.31	0.21	*1.04*
60	Dominion–Gordonsville Power Station	Louisa	EGU	0.41	0.25	0.16	*0.82*
61	Griffin Pipe Products Company	Lynchburg	non-EGU	0.57	0.07	0.07	*0.71*
62	O-N Minerals (Chemstone) Clearbrook	Frederick	non-EGU	0.32	0.04	0.04	*0.40*
63	Hampton/NASA Steam Plant	Hampton	non-EGU	0.07	0.17	0.06	*0.30*
64	Perdue Farms–Soybean Oil Processing	Chesapeake	non-EGU	0.13	0.08	0.05	*0.26*
65	Philip Morris USA Inc.–Leaf Processing	Richmond	non-EGU	0.10	0.06	0.04	*0.20*
66	Mead Westvaco Virginia Specialty	Covington	non-EGU	0.07	0.01	0.01	*0.09*
67	Blacksburg Sanitation Authority	Montgomery	non-EGU	0.01	0.03	0.01	*0.06*
68	Philip Morris USA Inc.–Blended Leaf	Richmond	non-EGU	0.03	0.02	0.01	*0.05*
	Total			*1,217.64*	*770.03*	*329.22*	*2,316.89*

2.3. Comparison of 2002 Virginia Inventory with the NEI

The EPA compiles and maintains a national inventory of mercury emissions as contained in the National Emission Inventory (NEI). As part of this task, the latest version (Version 3) of the 2002 NEI mercury inventory was obtained from EPA. This inventory contains information for point sources and “non-point” sources, also referred to as area sources. These include various other types of fuel combustion sources that emit mercury. The NEI inventory obtained from EPA contains mercury emissions information for 379 distinct Virginia facilities. The top 25 of these sources represent 97 percent of total point source mercury emissions, so there are a number of facilities in this inventory with very small mercury emissions, the majority of which are landfills that emit less than 1 lb of mercury per year. The 2002 Virginia DEQ mercury point source inventory contains information for 68 facilities. The top 25 of these sources represent 92 percent of total point source mercury emissions. A number of the smaller facilities emit less than 5 lbs of mercury per year.

Table 2-2 presents a comparison of emissions for the 68 point sources contained in the updated Virginia inventory with those same sources contained in the NEI inventory. The table includes speciated emissions for elemental, divalent, and particulate mercury based on total mercury, and the assumed speciation profile for each source. The table shows some similarities in emissions totals but also major differences in emissions for a number of the top mercury point source emitters in Virginia. In addition, there are some differences in the assumed speciation profile for a number of sources. It is not evident why the emissions for some of the sources are different or why there are differences in assumed speciation profiles. It is assumed that the updated Virginia inventory includes the latest and most accurate information for these sources. The table also shows that some of the top mercury point sources in Virginia are not included in the current national inventory. Conversely, there are a number of moderate-sized sources listed in the NEI that are not included in the Virginia inventory and it was found that some of the sources in the NEI were closed prior to 2002. It is not clear why certain sources are missing from the NEI or why a few of the closed sources are still included, however, it is expected that emissions for Virginia's updated mercury point source inventory will be submitted to EPA, along with changes/corrections/shutdowns to any other Virginia source in the existing NEI, for inclusion in the next version of the NEI.

Table 2-2. Comparison of Mercury Emitters in the 2002 VDEQ Point Source Inventory with those same sources in the 2002 NEI Version 3 Inventory

	Facility Name	County	Source Type	Updated VDEQ Inventory							EPA 2002 NEI Version 3 Inventory						
				2002 Emissions				Speciation			2002 Emissions				Speciation		
				HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	Total (lb/yr)	HG0	HG2	HGP	HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	Total (lb/yr)	HG0	HG2	HGP
1	Dominion - Chesterfield Power Station	Chesterfield	EGU	179.42	107.65	71.77	358.83	50%	30%	20%	114.42	303.62	27.19	445.23	26%	68%	6%
2	Chaparral Steel	Dinwiddie	non-EGU	233.75	29.29	29.26	292.30	80%	10%	10%	312.79	39.10	39.10	390.98	80%	10%	10%
3	Dominion - Bremo Power Station	Fluvanna	EGU	83.86	50.32	33.55	167.73	50%	30%	20%	59.72	92.67	7.87	160.26	37%	58%	5%
4	American Electric Power- Clinch River	Russell	EGU	38.21	121.00	0.00	159.21	24%	76%	0%	41.74	110.76	9.92	162.42	26%	68%	6%
5	Dominion - Chesapeake Energy Center	Chesapeake	EGU	78.69	47.22	31.48	157.38	50%	30%	20%	46.98	124.65	11.16	182.79	26%	68%	6%
6	Potomac River Generating Station	Alexandria	EGU	11.83	106.43	0.00	118.26	10%	90%	0%	18.62	49.40	4.42	72.45	26%	68%	6%
7	Dominion - Yorktown Power Station	York	EGU	53.82	32.29	21.53	107.64	50%	30%	20%	40.07	87.88	10.98	138.93	29%	63%	8%
8	Jewel Coke Company LLP	Buchanan	non-EGU	84.50	10.56	10.56	105.63	80%	10%	10%	84.50	10.56	10.56	105.63	80%	10%	10%
9	Dominion-Possum Point Power Station	Prince William	EGU	50.09	30.06	20.04	100.19	50%	30%	20%	36.88	89.43	9.43	135.74	27%	66%	7%
10	Stone Container Enterprises (Smurfit)	King William	non-EGU	46.81	27.22	3.73	77.76	60%	35%	5%	0.03	0.02	0.01	0.06	50%	30%	20%
11	Stone Container Corporation - Hopewell	Hopewell	non-EGU	34.84	20.91	13.94	69.69	50%	30%	20%	33.70	20.22	13.48	67.39	50%	30%	20%
12	American Electric Power - Glen Lyn	Giles	EGU	26.06	39.08	0.00	65.14	40%	60%	0%	19.59	51.98	4.65	76.22	26%	68%	6%
13	Intermet Foundry Archer Creek	Campbell	non-EGU	51.97	6.53	6.51	65.01	80%	10%	10%	0.80	0.10	0.10	1.00	80%	10%	10%
14	RES dba Steel Dynamics	Roanoke	non-EGU	48.64	6.08	6.08	60.80	80%	10%	10%	185.07	23.13	23.13	231.33	80%	10%	10%
15	Spruance Genco LLC	Richmond	EGU	27.75	16.65	11.10	55.50	50%	30%	20%	3.77	1.09	1.21	6.08	62%	18%	20%
16	Mead Westvaco Packaging Resources	Covington	non-EGU	12.96	4.88	9.07	26.91	48%	18%	34%	0.45	0.27	0.18	0.89	50%	30%	20%
17	Covanta Fairfax, Inc.	Fairfax	EGU	12.87	7.72	5.15	25.73	50%	30%	20%	2.98	7.85	2.71	13.54	22%	58%	20%
18	James River Cogeneration Company	Hopewell	EGU	12.65	7.59	5.06	25.30	50%	30%	20%							
19	Celanese/Cinergy Solutions (21418)	Giles	non-EGU	9.20	5.52	3.68	18.40	50%	30%	20%	0.12	0.07	0.05	0.23	50%	30%	20%
20	Dominion - Clover Power Station	Halifax	EGU	8.34	5.00	3.34	16.68	50%	30%	20%	7.34	4.01	0.81	12.17	60%	33%	7%
21	Giant Yorktown Refinery	York	non-EGU	12.74	1.59	1.59	15.93	80%	10%	10%	10.56	1.32	1.32	13.20	50%	30%	20%
22	SPSA Refuse Derived Fuel Plant	Portsmouth	non-EGU	3.43	9.05	3.12	15.61	22%	58%	20%	3.35	8.83	3.04	15.22	22%	58%	20%
23	H L Mooney Water Reclamation Facility	Prince William	non-EGU	3.21	8.47	2.92	14.61	22%	58%	20%							
24	Hopewell WWTP	Hopewell	non-EGU	2.93	7.71	2.66	13.30	22%	58%	20%							
25	HRSD Chesapeake-Elizabeth Sewage	Virginia Beach	non-EGU	2.87	7.56	2.61	13.04	22%	58%	20%							
26	Cogentrix Virginia Leasing Corp	Portsmouth	EGU	5.85	3.51	2.34	11.70	50%	30%	20%							
27	Chemical Lime Company	Giles	non-EGU	9.20	1.15	1.15	11.50	80%	10%	10%	3.92	0.49	0.49	4.90	80%	10%	10%
28	Burlington Industries LLC Hurt Fin	Pittsylvania	non-EGU	5.53	3.32	2.21	11.05	50%	30%	20%							
29	HRSD Boat Harbor Sewage Treatment Plt	Newport News	non-EGU	2.11	5.56	1.92	9.59	22%	58%	20%							
30	Roanoke Cement Company	Botetourt	non-EGU	6.96	1.21	1.11	9.28	75%	13%	12%	4.73	0.82	0.76	6.30	75%	13%	12%
31	Alliant Ammunition & Powder Co.	Montgomery	non-EGU	4.57	2.74	1.83	9.14	50%	30%	20%	0.05	0.02	0.02	0.08	58%	20%	22%
32	Philip Morris USA Inc - Park 500	Chesterfield	non-EGU	4.35	2.61	1.74	8.69	50%	30%	20%							
33	Georgia Pacific Corp Big Island Plt	Bedford	non-EGU	3.84	2.30	1.53	7.67	50%	30%	20%							
34	Mohawk Industries Inc-Lees Carpet	Rockbridge	non-EGU	3.76	2.26	1.50	7.52	50%	30%	20%							

	Facility Name	County	Source Type	Updated VDEQ Inventory							EPA 2002 NEI Version 3 Inventory						
				2002 Emissions				Speciation			2002 Emissions				Speciation		
				HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	Total (lb/yr)	HG0	HG2	HGP	HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	Total (lb/yr)	HG0	HG2	HGP
35	HRSD Virginia Initiative Plant	Norfolk	non-EGU	1.45	3.81	1.31	6.57	22%	58%	20%							
36	HRSD Army Base Sewage Treatment Plt	Norfolk	non-EGU	1.41	3.71	1.28	6.40	22%	58%	20%							
37	Intermet Corporation Radford	Radford	non-EGU	4.90	0.61	0.61	6.12	80%	10%	10%	0.18	0.02	0.02	0.23	80%	10%	10%
38	Bear Island Paper Company LLC	Hanover	non-EGU	2.96	1.77	1.18	5.91	50%	30%	20%							
39	US Navy Little Creek Amphibious Base	Virginia Beach	non-EGU	2.93	1.76	1.17	5.87	50%	30%	20%							
40	HRSD Williamsburg	James City	non-EGU	0.99	2.62	0.90	4.51	22%	58%	20%							
41	Georgia-Pacific/Emporia Plywood	Greensville	non-EGU	2.06	1.24	0.82	4.12	50%	30%	20%	2.06	1.24	0.82	4.12	50%	30%	20%
42	Covanta Alexandria/Arlington, Inc.	Alexandria	EGU	1.96	1.17	0.78	3.92	50%	30%	20%	1.41	3.72	1.28	6.41	22%	58%	20%
43	Dan River Incorporated Schoolfield	Danville	non-EGU	1.86	1.11	0.74	3.71	50%	30%	20%	0.00	0.00	0.00	0.00	80%	10%	10%
44	International Paper Company	Isle Of Wight	non-EGU	1.82	1.09	0.73	3.63	50%	30%	20%							
45	Honeywell Nylon LLC - Hopewell	Hopewell	non-EGU	1.81	1.09	0.72	3.62	50%	30%	20%	0.53	0.32	0.21	1.06	50%	30%	20%
46	Birchwood Power Partners, L.P.	King George	EGU	1.41	2.05	0.13	3.59	39%	57%	4%	2.16	1.17	0.24	3.56	61%	33%	7%
47	Solite LLC/Giant Resource Recovery	Buckingham	non-EGU	1.45	0.50	0.55	2.50	58%	20%	22%	55.73	19.22	21.14	96.08	58%	20%	22%
48	University of Virginia	Charlottesville	non-EGU	1.25	0.75	0.50	2.49	50%	30%	20%							
49	Philip Morris USA Mfg Center	Richmond	non-EGU	1.24	0.74	0.50	2.48	50%	30%	20%	1.31	0.79	0.53	2.63	50%	30%	20%
50	Dominion-Southampton Power Station	Southampton	EGU	1.10	0.66	0.44	2.19	50%	30%	20%	0.94	0.29	0.31	1.54	61%	19%	20%
51	Dominion - Altavista Power Station	Campbell	EGU	1.09	0.65	0.44	2.18	50%	30%	20%	0.89	0.26	0.29	1.44	62%	18%	20%
52	O-N Minerals (Chemstone) Strasburg	Shenandoah	non-EGU	1.74	0.22	0.22	2.17	80%	10%	10%	1.76	0.22	0.22	2.20	80%	10%	10%
53	Rock Tenn Co Mill	Lynchburg	non-EGU	0.94	0.56	0.37	1.87	50%	30%	20%							
54	Virginia Tech	Montgomery	non-EGU	0.75	0.45	0.30	1.49	50%	30%	20%							
55	Martinsville Thermal, LLC	Henry	non-EGU	0.71	0.42	0.28	1.41	50%	30%	20%	0.13	0.08	0.05	0.25	50%	30%	20%
56	Commonwealth Chesapeake Power	Accomack	EGU	0.67	0.40	0.27	1.34	50%	30%	20%							
57	Dominion - Mecklenburg Power Station	Mecklenburg	EGU	0.84	0.25	0.03	1.11	75%	22%	2%	0.34	0.25	0.07	0.65	52%	38%	10%
58	Hopewell Cogenertion Ltd Partnership	Hopewell	non-EGU	0.53	0.32	0.21	1.05	50%	30%	20%	0.30	0.18	0.12	0.60	50%	30%	20%
59	INVISTA S.a.r.l. -Waynesboro	Waynesboro	non-EGU	0.52	0.31	0.21	1.04	50%	30%	20%							
60	Dominion - Gordonsville Power Station	Louisa	EGU	0.41	0.25	0.16	0.82	50%	30%	20%							
61	Griffin Pipe Products Company	Lynchburg	non-EGU	0.57	0.07	0.07	0.71	80%	10%	10%							
62	O-N Minerals (Chemstone) Clearbrook	Frederick	non-EGU	0.32	0.04	0.04	0.40	80%	10%	10%	0.32	0.04	0.04	0.40	80%	10%	10%
63	Hampton/NASA Steam Plant	Hampton	non-EGU	0.07	0.17	0.06	0.30	22%	58%	20%	64.92	171.16	59.02	295.11	22%	58%	20%
64	Perdue Farms - Soybean Oil Processing	Chesapeake	non-EGU	0.13	0.08	0.05	0.26	50%	30%	20%	0.98	0.59	0.39	1.95	50%	30%	20%
65	Philip Morris USA Inc. - Leaf Processing	Richmond	non-EGU	0.10	0.06	0.04	0.20	50%	30%	20%	0.03	0.02	0.01	0.07	50%	30%	20%
66	Mead Westvaco Virginia Specialty	Covington	non-EGU	0.07	0.01	0.01	0.09	80%	10%	10%							
67	Blacksburg Sanitation Authority	Montgomery	non-EGU	0.01	0.03	0.01	0.06	22%	58%	20%							
68	Philip Morris USA Inc. - Blended Leaf	Richmond	non-EGU	0.03	0.02	0.01	0.05	50%	30%	20%	2.25	1.35	0.90	4.51	50%	30%	20%

Figure 2-1 presents a comparison of total emissions for the 68 Virginia mercury point sources with emissions from those same sources contained in the NEI. A comparison of totals shows the NEI inventory with 25 percent higher emissions. As noted above, this is due to the fact that a few large emitters listed in the NEI have been closed in recent years or that this version of the NEI contains outdated and/or erroneous emission estimates for certain sources. For example, source #63 in Table 2-2 shows a total of 0.3 lbs/yr total mercury emissions in the updated Virginia inventory and 295 lbs/yr total mercury in the NEI inventory, which is obviously wrong based on the updated survey information.

For the mercury deposition modeling analysis, the updated Virginia point source inventory will be combined with emissions from point and non-point sources contained in the NEI. The emissions for the 68 facilities will be combined with emissions from other Virginia sources contained in the NEI inventory, but not included in the list of 68. The emissions for these other NEI sources were also reviewed by VDEQ as part of this work, and some of these sources were eliminated because they were either closed or were not regarded as "air" sources by VDEQ. Although the emissions from the remaining valid NEI sources are very small, they will be accounted for in the deposition modeling analysis. As noted above, it is expected that emissions for Virginia's updated mercury point source inventory will be submitted to EPA, along with changes/corrections/shutdowns to any other Virginia source in the existing NEI, for inclusion in the next version of the NEI.

Figure 2-1. Mercury Emissions for Virginia Point Sources: 2002 VDEQ vs. 2002 NEI V3

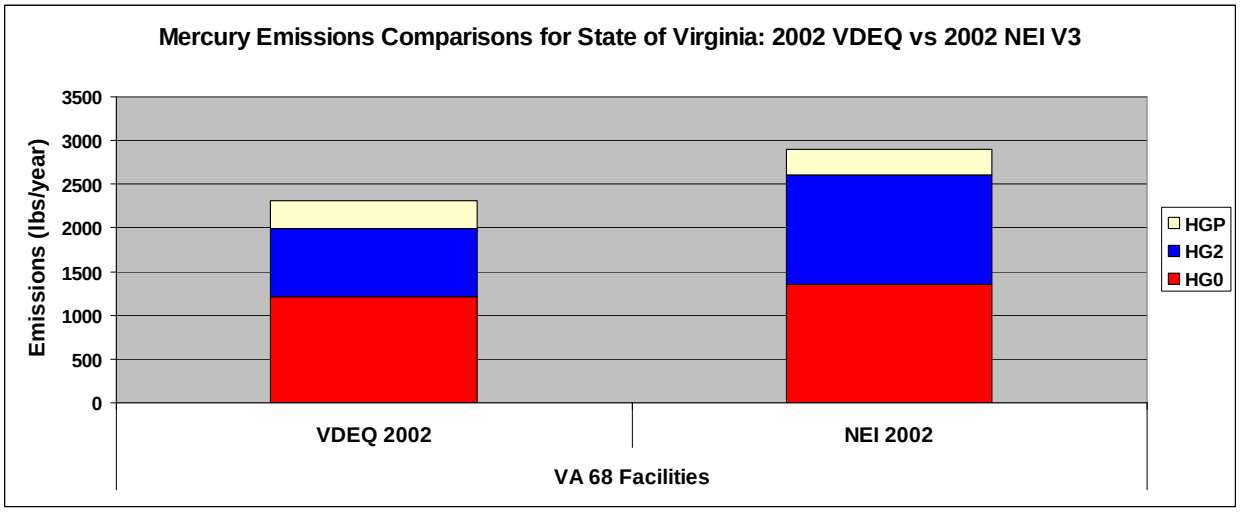
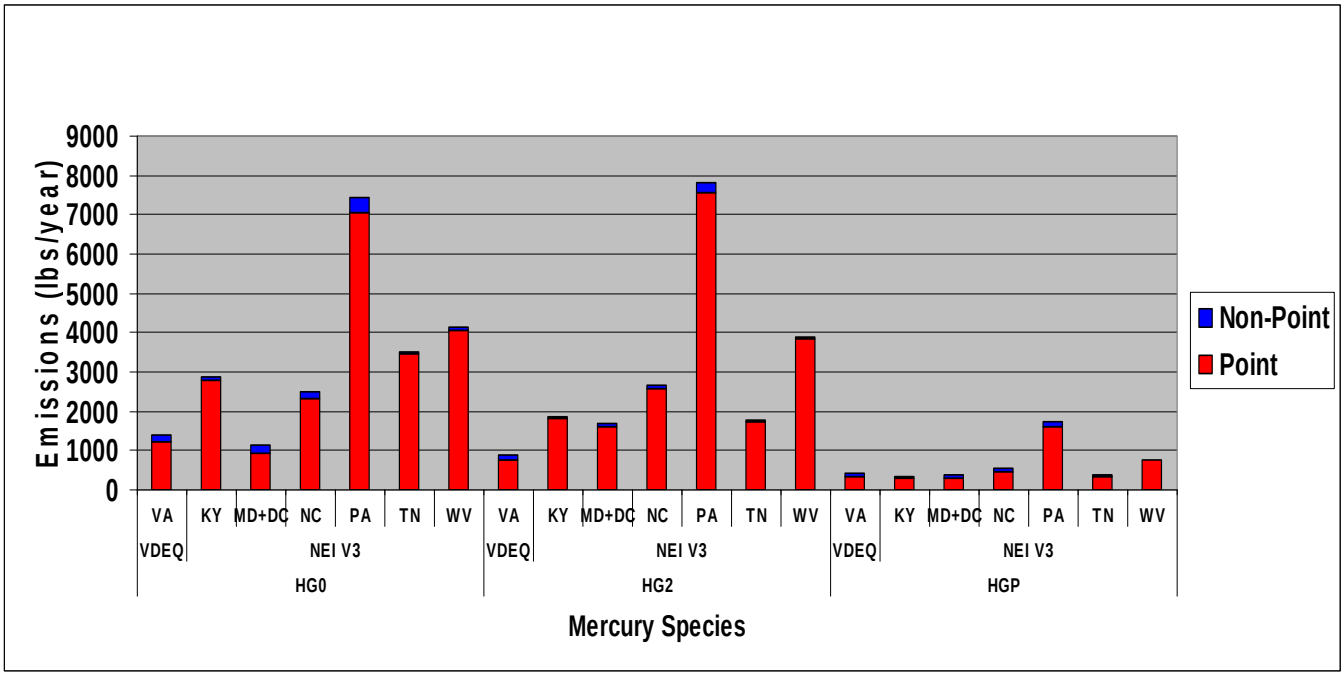


Figure 2-2 presents a comparison of the 2002 Virginia mercury emissions with those contained in the NEI for the neighboring states of Kentucky, Maryland/D.C., North Carolina, Pennsylvania, Tennessee, and West Virginia. These emissions and emissions from all other states in the modeling domain obtained from the NEI inventory will be used in the mercury air deposition modeling. Of the seven states, Virginia's emissions are comparable to the combined Maryland/D.C. emissions totals. The neighboring states have the potential to influence mercury deposition in Virginia watersheds and emissions from these states will be fully accounted for in the modeling analysis.

Figure 2-2. Comparison of the 2002 VDEQ Speciated Mercury Emissions Inventory with the 2002 NEI Version 3 Inventory for Selected Neighboring States

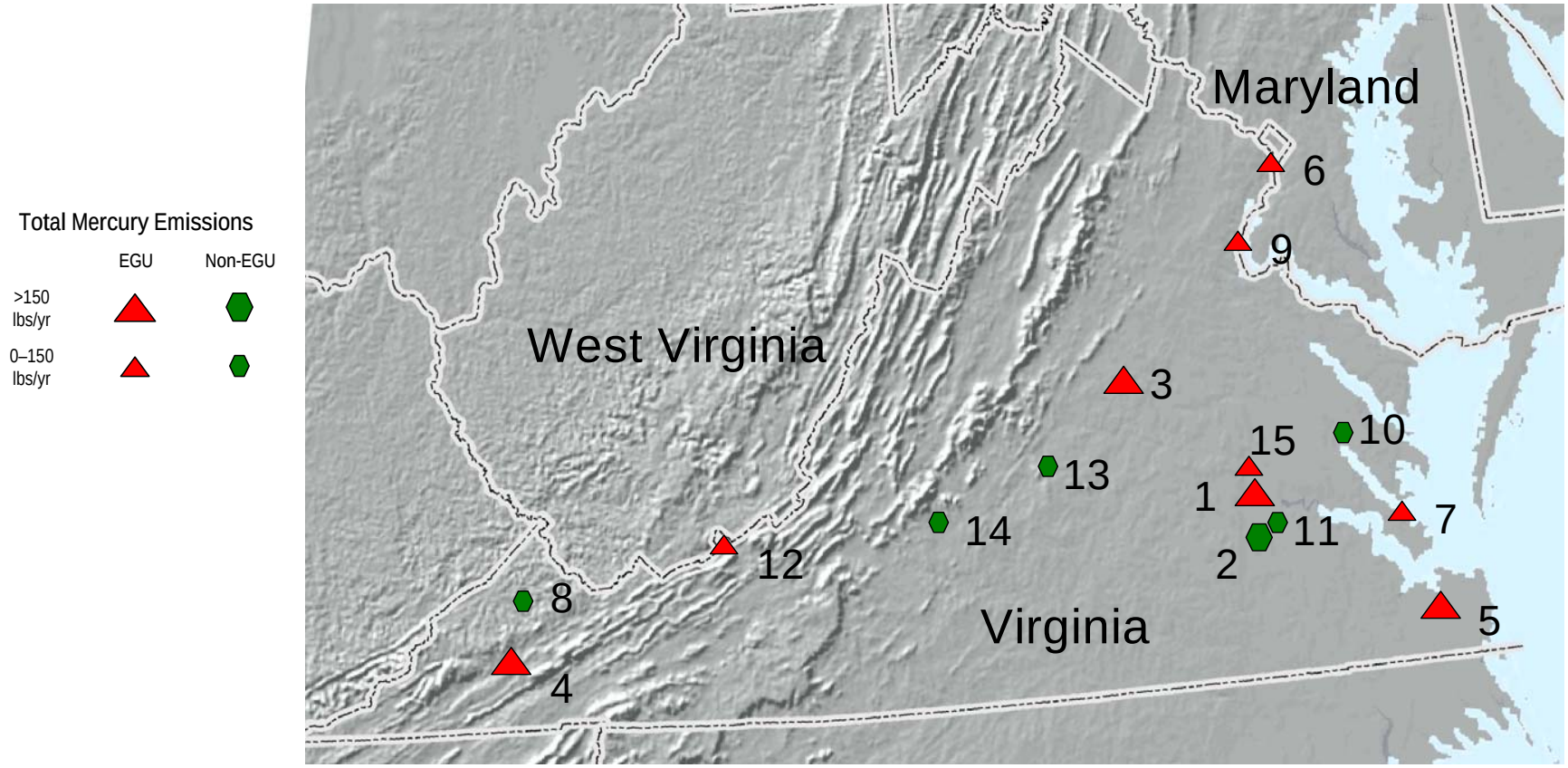


3. Summary of Virginia Mercury Inventory

3.1. Base-Year Emission Inventory for Modeling

The 2002 Virginia mercury point source inventory, as listed in Table 2-1, will be processed and used with the CMAQ air quality modeling system to estimate mercury deposition affecting Virginia waterways. To provide an example of the point-source emissions as they will be input to the model, Figure 3-1 presents the location and magnitude of the top 15 mercury point sources in Virginia for 2002 as contained in Table 2-1. These 15 EGU and non-EGU point sources represent 85 percent of total mercury point source emissions for Virginia in 2002. The figure presents information for total annual mercury emissions from these sources in two ranges: 0 – 150 lbs/yr and > 150 lbs/yr.

Figure 3-1. Location and Magnitude of the Top 15 Virginia Mercury EGU and Non-EGU Point Sources for 2002 (Hg-Total Mercury)



	Facility Name	County	Source Type		Facility Name	County	Source Type
1	Dominion–Chesterfield Power Station	Chesterfield	EGU	9	Dominion-Possum Point Power Station	Prince William	EGU
2	Chaparral Steel	Dinwiddie	non-EGU	10	Stone Container Enterprise (Smurfit)	King William	Non-EGU
3	Dominion–Bremo	Fluvanna	EGU	11	Stone Container Corporation -Hopewell	Hopewell	non-EGU
4	American Electric Power- Clinch River	Russell	EGU	12	American Electric Power	Giles	EGU
5	Dominion–Chesapeake Energy Center	Chesapeake	EGU	13	Intermet Foundry Archer Creek	Campbell	non-EGU
6	Potomac River Generating Station	Alexandria	EGU	14	RES dba Steel Dynamics	Roanoke	non-EGU
7	Dominion–Yorktown Power Station	York	EGU	15	Spruance Genco LLC	Richmond	EGU
8	Jewell Coke	Buchanan	Non-EGU				

3.2. Future-Year Emission Inventory Estimates for Virginia Sources

For this study, mercury air deposition will be assessed in the modeling analysis for 2002 and three future years: 2010, 2015, and 2018. As noted above, recent national control legislation promulgated by EPA in the Clean Air Interstate Rule (CAIR) will reduce emissions of NO_x, SO_2, and mercury from coal-fired power plants in the eastern US. Phase 1 controls for NOx are due in place by January 2009, while phase 1 controls for SO_2 are due by January 2010. Phase 2 controls for NO_x and SO_2 are both due by January 2015. Mercury emissions reduction benefits will be realized from the NO_x and SO_2 controls in place by January 2010. The Clean Air Mercury Rule (CAMR) will build on CAIR and provide for additional future mercury emission reductions from these sources. Mercury controls are mandated to be in place by January 2018 for those coal-fired power plants subject to the rule.

Presently, a number of Virginia sources have existing pollution control equipment installed and running, while others are planning on installing future controls. Table 3-1 presents a summary of control equipment currently being utilized or planned to be installed by Virginia coal-fired boilers. Most of the new control equipment is expected to be installed by 2010.

Table 3-1. Summary of Existing and Planned Emission Controls for Virginia Coal Fired Boilers

Facility Name	MW (NOx SIP Call)	MW Calculated	Control Equipment[1]	Projected Control Equipment	Projected Year To Install
Dominion - Chesterfield Power Station (1)					
3	113	110.0	OFA/LNB/ESP	FGD	2011
4	188	167.7	SCR/ESP/Staged combustion	FGD	2011
5	359	343.2	SCR/ESP/Staged combustion	FGD	2011
6	694	633.3	SCR/ESP/Staged combustion	FGD/FF	2008
Dominion - Bremo Power Station (4)					
3	69	86.9	ESP (hot sided)/BOOS		
4	185	161.8	ROFA/ESP (hot sided)		
American Electric Power - Clinch River (5)					
1	235	200.0	staged combustion/ESP		
2	235	200.0	staged combustion/ESP		
3	235	200.0	staged combustion/ESP		
Dominion - Chesapeake Energy Center[2] (6)					
1	113	123.8	OFA /ROFA/ESP	SA Coal 50% CE for Hg and 40% for S	2007
2	113	123.8	OFA/ROFA/ESP	SA Coal 50% CE for Hg and 40% for S	2007
3	185	158.4	LNB/SCR/ESP	SA Coal 50% CE for Hg and 40% for S	2007
4	239	223.4	LNB/SCR/ESP (all cold sided)	SA Coal 50% CE for Hg and 40% for S	2007
Potomac River Power Generating Station[3] (7)					
1	93	92.4	LNB/ESP		
2	93	92.4	LNB/ESP		
3	108	91.5	LNB/SOFA/ESP		
4	108	91.5	LNB/SOFA/ESP		
5	108	91.5	LNB/SOFA/ESP		
Dominion - Yorktown Power Station (8)					
1	188	161.6	LNB/OFA/SNCR/ESP	FGD	2015
2	188	166.2	LNB/OFA/SNCR/ESP	FGD	2015
Stone Container Corp., West Point Mill[4](10)					
2			Concentric firing/LNB/ESP	SO2 Scrubber	2008
Stone Container Corp., Hopewell (11)					
1		80.6	ESP		
American Electric Power - Glen Lyn (12)					
51	100	54.5	staged combustion/ESP		
52	100	54.5	staged combustion/ESP		
6	238	194.3	staged combustion/ESP		
Spruance Genco LLC (15)					
BLR01A		35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR01B	115	35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR02A		35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR02B	115	35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR03A		35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR03B	115	35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR04A		35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
BLR04B	115	35.7	SNCR/FGR/OFA/Meth/FF/D FGD		
James River Cogeneration (18)					
BLR01A		19.0	FGR/OFA/FF	SDA	2010
BLR01B		19.0	FGR/OFA/FF	SDA	2010
BLR01C	108.5	19.0	FGR/OFA/FF	SDA	2010
BLR02A		19.0	FGR/OFA/FF	SDA	2010
BLR02B		19.0	FGR/OFA/FF	SDA	2010
BLR02C	108.5	19.0	FGR/OFA/FF	SDA	2010
Dominion - Clover Power Station (20)					
1	424	389.0	LNB/SNCR/FF/Wet FGD		
2	424	389.0	LNB/SNCR/FF/Wet FGD		

Summary of Virginia Mercury Inventory

Facility Name		MW (NOx SIP Call)	MW Calculated	Control Equipment[1]	Projected Control Equipment	Projected Year To Install
Cogentrix Virginia Leasing-Portsmouth (26)						
	BLR01A		19.0	FGR/OFA/FF	SDA	2010
	BLR01B		19.0	FGR/OFA/FF	SDA	2010
	BLR01C	108.5	19.0	FGR/OFA/FF	SDA	2010
	BLR02A		19.0	FGR/OFA/FF	SDA	2010
	BLR02B		19.0	FGR/OFA/FF	SDA	2010
	BLR02C	108.5	19.0	FGR/OFA/FF	SDA	2010
Georgia-Pacific - Big Island Plant (33)						
	4		27.0	ESP		
	6		27.1	LNB/FGR (not coal fired)		
Dan River Inc—Schoolfield Complex (43)						
			24.0	ESP		
International Paper Co. - Franklin Mill (44)						
	3		47.2	ESP		
	17			shutdown		
	29			LNB/SCR		
Birchwood Power Partners Facility (46)						
	1	240	219.0	SCR/FF/DLS		
Dominion - Southampton Power Station (50)						
	1	71.1	38.1	OFA/DFGD/FF/Staged combustion		
62.7 MW total	2	71.1	38.1	OFA/DFGD/FF/Staged combustion		
Dominion - Altavista Power Station (51)						
	1	71.1	36.4	SNCR/LNB/DLS/FF		
	2	71.1	36.4	SNCR/LNB/DLS/FF		
Dominion - Mecklenburg Cogeneration Facility (57)						
	1		79.4	LNB/OFA/FF/FGD		
	2	139.9	79.4	LNB/OFA/FF/FGD		
Mead Westvaco Virginia Specialty, Covington (66)						
	1		52.4	LNB/ESP/FGD		
	2		41.9	FGR /ESP/FGD		
	3		55.2	FGR/ESP/FGD		
	4		76.9	LNB/ESP/FGD		
	5					
	11			LNB/FGR		

[1] Control equipment includes the following: selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), low-NOx burners (LNB), electrostatic precipitators (ESP), dry lime scrubbing (DLS), fabric filters (FF), over-fired air (OFA), flue-gas desulfurization (FGD), flue-gas recirculation (FGR), rotating opposed-fired air (ROFA), and burners out of service (BOOS).

[2] Chesapeake Energy Center was originally slated to be controlled by SDA. However, a Dominion update of the control plan notes these installations are indefinitely delayed, and South American coal with about half of the Hg content and about 40% lower sulfur content is currently being used at the facility.

[3] Potomac River is currently using Trona injection on 3, 4, and 5. They are also subject to the CAIR cap without trading provisions due to their location in a nonattainment area. They will be capped for both NOx and SO2.

[4] Installation of the SO2 scrubber by 2008 is the result of a federal consent decree and enforcement action.

For those EGU sources subject to EPA's CAMR reductions, future year emissions budgets have been established based on the CAMR provisions as well as Virginia-specific emissions rules. According to VDEQ, proposed mercury allowance allocations to coal fired electric steam generating units in Virginia, for the control period 2010 – 2017, were made according to State Air Pollution Control Board Regulation for Emission Trading Programs. A total of 95 percent of the allocated state budget of 1184 lbs (0.592 tons, excluding 4% set-aside for the new and 1%

for energy efficient units) are distributed to the existing units in proportion to their baseline heat input in million Btu. The baseline heat input for this purpose is the average of three highest amounts of the unit's control period heat input for the years 2000 through 2004.

Table 3-2 presents the estimated future-year budgets for those Virginia EGU's subject to CAMR for 2014, 2015-17, and 2018. The number in the table corresponds to the number in the 2002 inventory table (Table 2-2) above. Because many of the EGU sources listed have (or will have) controls in place to reduce mercury emissions below these budgets, the actual future year emissions to be used in the mercury deposition modeling analysis may be different than those listed in the table.

Table 3-2. Future Year Mercury Emissions Budgets for Virginia EGU's Subject to CAMR

#	Facility Name	County	Source Type	2002				2014	2015–2017	2018
				HG0 (lb/yr)	HG2 (lb/yr)	HGP (lb/yr)	Total (lb/yr)	Total (lb/yr)	Total (lb/yr)	Total (lb/yr)
1	Dominion - Chesterfield Power Station	Chesterfield	EGU	179.42	107.65	71.77	358.83	230.39	94.00	94.00
4	Dominion – Bremo Power Station	Fluvanna	EGU	83.86	50.32	33.55	167.73	44.45	18.14	18.14
5	American Electric Power- Clinch River	Russell	EGU	38.21	121.00	0.00	159.21	113.40	113.40	46.27
6	Dominion - Chesapeake Energy Center	Chesapeake	EGU	78.69	47.22	31.48	157.38	122.04	49.79	49.79
7	Potomac River Generating Station	Alexandria	EGU	11.83	106.43	0.00	118.26	72.96	72.96	29.77
8	Dominion - Yorktown Power Station	York	EGU	53.82	32.29	21.53	107.64	58.08	23.70	23.70
9	Dominion-Possum Point Power Station	Prince William	EGU	50.09	30.06	20.04	100.19	56.93	23.23	23.23
12	American Electric Power – Glen Lyn	Giles	EGU	26.06	39.08	0.00	65.14	47.69	47.69	19.46
15	Spruance Genco LLC	Richmond	EGU	27.75	16.65	11.10	55.50	55.50	55.50	22.64
18	James River Cogeneration Company	Hopewell	EGU	12.65	7.59	5.06	25.30	24.54	24.54	10.01
20	Dominion - Clover Power Station	Halifax	EGU	8.34	5.00	3.34	16.68	190.08	77.55	77.55
26	Cogentrix Virginia Leasing Corp	Portsmouth	EGU	5.85	3.51	2.34	11.70	19.19	19.19	7.83
46	Birchwood Power Partners, L.P.	King George	EGU	1.41	2.05	0.13	3.59	38.57	38.57	15.74
51	Dominion - Altavista Power Station	Campbell	EGU	1.09	0.65	0.44	2.18	11.07	4.52	4.52
57	Dominion - Mecklenburg Power Station	Mecklenburg	EGU	0.84	0.25	0.03	1.11	25.74	15.56	10.50

4. Summary of Recent Mercury Studies

This section summarizes information that may be relevant to the current study from recent papers and presentations on data collection and analysis, modeling, and emissions and controls studies of mercury deposition. Note that all of the references given in this section can be found in the bibliography provided in the appendix. They are also available on the Virginia DEQ Mercury Study web page: http://www.deq.virginia.gov/air/vamercury/vamercurystudy.html

4.1. General Mercury Deposition and Data Analysis Studies

Numerous reports and papers discuss the state-of-the science of mercury deposition, with emphasis on the sources of airborne mercury, mercury chemistry, global and regional transport, mercury deposition mechanisms, and mercury effects on aquatic ecosystems. Several studies focus on the analysis of collected mercury deposition data for specific locations. A few recent studies examine the relationships between meteorology and mercury deposition.

General Studies

Nearly all of the papers and reports examined discussed the **sources of mercury** in the atmosphere. It is widely understood that mercury is emitted to the atmosphere from both natural and anthropogenic sources.

Certain soils, rocks, and other geologic structures naturally contain mercury and therefore represent natural or geogenic sources of mercury emissions. Volcanic activity is thought to be an important but variable source of naturally occurring airborne mercury (Niagru and Becker, 2003). Within North America, most natural mercury emissions are associated with land types found in the western part of the continent. In addition to the land masses, the oceans are also a source of natural mercury emissions. Emissions fluxes from the ocean are thought to be greatest near the equator and to decrease toward the poles (Seigneur et al., 2003; Kim and Fitzgerald, 1986).

Anthropogenic sources of mercury include coal-fired power plants and other industrial coal-burning facilities, municipal, medical, industrial and hazardous waste incinerators, chlor-alkali and other chemical manufacturing plants, taconite and other metallurgical processing facilities, pulp and paper manufacturing facilities, mining operations, cement plants, mobile sources, and a wide variety of other industrial and residential sources (EPA, 2005).

It is also widely understood that re-emission of both natural and anthropogenic emissions from both land and water areas is an important part of the global mercury budget. Over land, prescribed burning and wild fires can increase the rate of re-emission.

Driscoll et al. (2007) estimates that approximately one-third of the emissions are direct anthropogenic emissions. Valente et al. (2007) summarizes the results of numerous studies in estimating that global mercury emissions are equally apportioned among natural emissions, direct anthropogenic emissions, and re-emission of previously deposited natural and anthropogenic emissions.

Understanding the **mercury chemistry** is an active area of research. Bullock et al. (2007) summarizes the three forms of airborne mercury (Hg) as follows: elemental mercury (Hg(0)), reactive gaseous mercury (RGM), and particulate mercury (Hg(p)). RGM is known to be comprised almost entirely of divalent mercury (Hg^{2+} or Hg(II)), since mercury compounds at other valence states tend to be chemically unstable in the atmosphere. Hg(p) is also primarily comprised of divalent mercury, but may also include elemental mercury.

Valente et al. (2007) and others offer that elemental mercury is the dominant atmospheric species and comprises about 99 percent of the total mercury in the atmosphere. Hg(0) is characterized by low reactivity and low solubility in water and has a long atmospheric lifetime. RGM represents less than one percent of atmospheric mercury. It is highly reactive and highly soluble and can be actively removed from the atmosphere through both wet and dry deposition processes. Hg(p) also represents less than one percent of atmospheric mercury. It is moderately reactive and highly soluble in water. It is removed from the atmosphere primarily through wet deposition

Seigneur et al. (2003) discuss the chemical transformations that transfer mercury mass from one of these states to another. Several gas phase and aqueous phase reactions and equilibrium processes are expected to be important.

The **global and regional transport** of mercury is the topic of much discussion in the current literature, especially in explaining deposition observed at remote locations and in the context of mercury deposition modeling. With an atmospheric lifetime that may be on the order of months to years, Hg(0) is dispersed and transported globally by atmospheric circulation systems and regionally by large-scale weather systems. Similarly, with atmospheric lifetimes on the order of a week, RGM and Hg(p) may also be subject to regional-scale transport.

With regard to **deposition mechanisms**, a key area of interest is the re-emission of mercury from both land and water surfaces (e.g., Sofiev and Galperin (2000)). Prescribed burning and wild fires may account for some of the re-emissions. Other natural processes, including microbial activity, may also account for some of the re-emission (Syrakov, 1998). Re-emission of mercury is mainly in the form of Hg(0) (Schluter, 2000).

Of primary interest for states and EPA is the **impact of mercury deposition on aquatic ecosystems**. In the U.S., more than 8,500 individual bodies of water have been identified as mercury impaired and the primary source of mercury to these water bodies is believed to be atmospheric deposition. For example, the South Florida Mercury Science Program found that atmospheric deposition of mercury accounts for more than 95 percent of the new mercury entering the Everglades each year (Fink et al., 1998).

Based on the network of mercury deposition measurements for the Northeast, Driscoll et al. (2007) concludes that mercury can be directly deposited onto surface waters or deposited in forest and wetland areas and then transported through the watershed to accumulate in the surface waters.

In certain bodies of water such as those with low dissolved oxygen, high organic matter content, and low acidity, mercury deposition can lead to the formation and build up of the highly bio-accumulative form of mercury (methyl mercury, CH_3Hg^+ or $MeHg^+$). Human exposure to mercury is linked with the consumption of contaminated fish from such water bodies.

Analysis of Mercury Deposition Data for Specific Locations

Numerous analyses of mercury deposition data (e.g., Seigneur et al. (2003) indicate that there are spatial patterns in the data and that these can vary from year to year. While the patterns are clearly related to rainfall amount, some studies (for example, Keeler et al. (2006)) suggest that there are spatial patterns in the wet deposition data that are not fully accounted for by the rainfall patterns. This suggests the potential for impact from local and regional sources.

An analysis of wet mercury deposition for two rural, coastal sites in North Carolina (Haywood et al., 2000 and others) revealed both a spatial pattern as well as a seasonal pattern of wet

mercury deposition when the data are separated into summer (April – September) and winter (October–March) months.

While most monitoring of mercury is of wet deposition, several studies have also examined mercury air concentrations and dry deposition.

Haywood et al. (2000) also found that both mercury concentration and wet deposition rates are consistently higher at Lake Waccamaw than Pettigrew State Park (both located in coastal North Carolina) and surmised that the pattern could be a result of local source influences.

The National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (NOAA, 2007) conducted a monitoring study during the summer of 2005 at the Harcum site in coastal Virginia which revealed that dry deposition was significant and was dominated by RGM.

Relationships between Meteorology and Mercury Deposition

It is recognized that in addition to the location of sources and the chemical species of mercury emitted, climate and meteorology are key factors in mercury deposition. The relationship between precipitation and deposition is well established. Scavenging by wet deposition is an important mechanism for wet deposition. Few studies, however, address the potentially more complex relationships between meteorology and mercury deposition. EPA (1997) reported that, in general, humid locations have higher deposition rates than arid locations. Keeler et al. (2006) found the annual amount of precipitation to be related to annual mercury deposition. They also found that individual precipitation events can contribute significantly to the annual mercury deposition totals.

4.2. Mercury Air Modeling Studies

Current literature focuses on the development of mercury capabilities in air quality modeling and some national- and regional-scale applications.

Bullock and Brehme (2006) present a description of the methodology for modeling mercury using CMAQ Version 4.5.1. This paper provides a description of the mercury treatment in the CMAQ model that will be used in this study (although the version that will be used for this study is 4.6, the mercury treatment is effectively unchanged). Note that the Particle and Precursor Tagging Methodology (PPTM) has been added to version 4.6.

Several areas of potential uncertainty that may be useful in designing and conducting sensitivity analysis with CMAQ are pointed out in this paper. These include:

- Rates of chemical reactions.
- Deposition of elemental mercury.
- Natural emission and re-emission of mercury.

The presentation of Vijayaraghavan et al. (2005) provides a potential reference/comparison for model performance for the VDEQ study. The authors add the following to the list of potential sources of uncertainty for CMAQ:

- Global emissions.
- Input meteorology, specifically rainfall.
- Dispersion of plumes.

- Chemistry in plumes.

The authors also suggest that the lifetime of mercury in the atmosphere as 1.2 years.

Lin et al. (2004) suggest that the lifetime of mercury in the atmosphere is 0.5 to 2 years and also present some potential implementation issues regarding simulation of mercury with CMAQ. These include:

- Specific uncertainties in gas phase chemistry and in deposition
- Potential for much more rapid oxidation of Hg(0) by halogens in coastal areas

Areas of potential improvement in CMAQ are presented by Lin et al. (2005). Of interest here is the sensitivity to possible improvements in CMAQ algorithms. Some of these improvements have been addressed in Version 4.6 of CMAQ. These include natural emissions and dry deposition of elemental mercury. Additional improvements noted by Lin et al. may be considered during the selection of sensitivity simulations.

Pongprueksa and Lin (2006) conducted sensitivity simulations for mercury using CMAQ. They specifically explored the sensitivity of the simulation results to additional Hg(II) reduction reactions.

Several related papers present information on natural emissions and sensitivity to the CMAQ system to changes in emissions (Wen, 2006; Gbor et al., 2006; Gbor et al., 2004). Topics addressed in these papers include:

- A methodology for estimating natural emissions.
- Deposition vs. evasion of Hg.
- Sensitivity of simulation results to changes in emissions of Hg, NOx, VOC, etc.

To the extent possible, we may qualitatively compare the results of these sensitivity tests to the VDEQ modeling results.

A comparison of model-based and observation-based estimates of dry deposition is made in Marsik et al. (2007). The authors compare the direct measurement of dry deposition to estimates from a resistance model, such as that employed by CMAQ. This gives us some insight into the quality of the CMAQ dry deposition estimates.

A presentation by Braverman (2005) provides some information on EPA's regulatory modeling related to mercury. This presentation gives some background on the Clean Air Mercury Rule (CAMR) modeling and a summary of CMAQ model performance in CAMR. Again, this provides a potential source of comparison for model performance for the VDEQ study.

Discussions of plume models vs. grid model treatments for mercury are discussed in Karamchandani et al. (2006) and Seigneur et al. (2006). The authors present some expected benefits of a plume-in-grid treatment for point sources, with an emphasis on power plant plumes. Comparisons of Hg deposition estimates from grid models and a Gaussian model are provided. Of interest for the VDEQ modeling study is a description of a methodology for estimating deposition using a Gaussian model.

Regional modeling with the SARMAP Air Quality Model (SAQM) studies mercury concentrations in Connecticut (Xu et al., 2000a; Xu et al., 2000b). This study is limited to a small section of the

northeastern U.S. around Connecticut and uses the SAQM model with simple and probably outdated Hg chemistry. The authors include estimates of natural emissions and re-emissions, which may be of some interest for the VDEQ study.

A project update by Walcek (2005) provides information on a modeling study in New York State. It is possible that the estimates of in-state vs. out-of-state contributions to deposition in New York from this study could provide a check on the estimates obtained from the VDEQ study.

A brief project update by Seigneur (2005) summarizes estimates of global and regional contributions to mercury deposition in New York State. This work includes a modeling sensitivity analysis and estimates of deposition contributions to New York State for various emissions sectors. A key finding is that the greatest contributor is U.S. emissions sources (non-New York emissions).

Several reports present the results of national- and regional-scale mercury deposition modeling conducted for the EPA Office of Water (OW), as well as background on and results from the Particle and Precursor Tagging Methodology (PPTM). Modeling of mercury deposition in Wisconsin is reported by Myers et al. (2006a). This report was intended as a peer-reviewed prototype for mercury tagging using the REMSAD model and includes:

- PPTM results for Wisconsin sources with deposition estimates for mercury.
- An estimate of potential year-to-year variability in Hg deposition for several sites in Wisconsin.

Similar modeling in support of the Maryland TMDL is reported by Myers et al. (2004a). This study included:

- Hg tagging simulations using REMSAD for Maryland and surroundings to estimate deposition of Hg.
- An estimate of potential year-to-year variability in Hg deposition for several sites in Maryland.

Additional modeling in support of a Louisiana TMDL is reported by Myers et al. (2004b). This study included:

- Hg tagging simulations for Louisiana and surroundings using REMSAD.
- Estimates of mercury deposition loading from tagged Louisiana sources for Louisiana estuaries.

Simulation results for the entire U.S. are reported by Myers et al. (2006b). In this study, PPTM was applied for approximately 300 sources located throughout the U.S. The study results include estimates of mercury deposition contributions for some Virginia sources. These results may provide a check on similar estimates obtained from the VDEQ study.

Attribution of global emissions to mercury deposition is treated by Seigneur et al. (2004). This paper provides

- Global simulation results using the Chemical Transport Model (CTM).
- Estimates of contributions of various regions of the world to deposition in U.S.

The potential influence of Asian mercury emissions on the U.S. is examined by Lin et al. (2006). Direct deposition of Asian emissions to Virginia should be small, but their contribution to global background may be important.

As an alternative to grid-based modeling, use of the HYSPLIT model is discussed in Cohen et al. (2004) and in Cohen (2004). The authors estimate contributors to mercury deposition to Great Lakes and the Chesapeake Bay using HYSPLIT model. The results tend to differ from other modeling estimates in that very distant sources may contribute to deposition loading. The use of trajectory modeling over long periods of time adds considerable uncertainty to the HYSLPIT modeling approach.

A combination of statistical and modeling techniques is used by Michaels et al. to examine the possible link between local power plant emissions and impaired bodies of water in Virginia. This study relied on HYSPLIT trajectory modeling of Virginia power plants. The authors were not able to establish a statistical link between elevated Hg in fish tissue with power plant emissions.

4.3. Mercury Emissions and Control Studies

As noted above, mercury in the atmosphere originates from a wide variety of anthropogenic, biogenic, and geogenic sources. As mercury deposition and contamination issues have become more important in many areas of the country in the last decade, efforts have been made to prepare more accurate estimates of emissions from mercury sources. Like the criteria pollutant inventories maintained by each state, the mercury emissions inventories are used by EPA and states to assess long term trends in emissions and for rule compliance. In addition, these inventories are used in air quality modeling studies to assess deposition for a base year and as a means of evaluating changes in mercury deposition in a future year. As part of its ongoing development work with the CMAQ modeling system, EPA has developed a methodology to estimate mercury emissions from biogenic sources (Lin, et al., 2004). This methodology will be evaluated for potential use in the Virginia mercury modeling analysis. Other researchers have investigated mercury emissions from soils as a contributor to atmospheric loading. Schluter (2000) found that mercury evaporation rates from non-contaminated soils are small, but do contribute to overall emissions of both elemental and methyl mercury.

Controlling anthropogenic sources of mercury has been the focus of a number of studies conducted in recent years by EPA, the Department of Energy (DOE), and a number of state agencies, with research in control technology ranging from those placed on large industrial combustion sources (e.g., EGU's) to ensuring the proper recycling and disposal of fluorescent light bulbs. The DOE conducted a study evaluating the control efficiencies and effects of selective catalytic reduction (SCR) and fluidized gas desulfurization (FGD) on mercury speciation and removal (Withum, et al, 2006). The study found that the combination of the SCR with FGD removed a substantial amount of mercury from the flue gas. A similar study by Lee, et al. (2004) investigated the effects of SCR on mercury speciation using three different types of coal, and concluded that the effects of SCR in promoting elemental mercury oxidation and removal is highly dependent on the sulfur and chlorine content of the coal.

A number of state agencies have evaluated a list of potential mercury control technologies, including North Carolina (2005), Minnesota (2005), and NESCAUM (2004). The North Carolina and NESCAUM studies primarily focus on controls for EGU's and include various updates of control technology information, cost/benefit information, and recommendations for reducing emissions from such sources. The Minnesota report provides the 2005 annual summary for the Minnesota Legislature of efforts underway to meet the state standards. The report indicates that much of the reduction in mercury air emissions in Minnesota since 1990 has been the result of significant changes in "product use and disposal" category, which includes such items as the elimination of mercury as a preservative in paint products, the use of mercury in electric

switches, and the use of mercury in batteries. These studies provide good references for activities and controls other states have evaluated and undertaken to reduce mercury air emissions from a variety of source sectors.

4.4. Summary of Findings and Implications for Mercury Modeling Analysis

The tools and methods that will be applied for the Virginia mercury deposition modeling represent the current state-of-the-science in regulatory mercury deposition modeling. Similar approaches were used by EPA in the Clean Air Mercury Rule (CAMR) modeling. Ongoing research in the areas of mercury data collection and analysis, deposition modeling, and control technology assessment offers some possibilities for enhancing the VDEQ modeling effort, especially with regard to designing and conducting modeling sensitivity analyses, evaluating model performance, and assessing the effectiveness of local controls. Specific implications and action items for the VDEQ modeling study include:

- Qualitatively compare the modeled results for mercury concentration, wet deposition, and dry deposition with the findings from monitoring studies in North Carolina and Virginia (Harcum) regarding the observed spatial and temporal distributions and relationships among these parameters and with other modeling studies.
- As time and budget allow, conduct model-based sensitivity tests to examine the following key issues:
  - Sensitivity of the modeling results to meteorological inputs, and specifically precipitation amounts.
  - Uncertainties in the mercury chemistry and deposition algorithms.
  - Role of natural emissions.
- Ensure that future-year emissions controls are consistent with recent studies regarding effects on speciation of emissions and the overall effectiveness of control measures.
- To the extent possible, obtain and utilize future-year national emission inventories that reflect planned mercury control technologies/measures prepared by other states.

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National Energy Technology Laboratory

This list server is produced by the National Energy Technology Laboratory (NETL) to provide monthly updates on recent events, publications, presentations, and technical reports related to mercury. For further information, please visit the Environmental & Water Resource (E&WR) website at http://www.netl.doe.gov/technologies/coalpower/ewr/index.html.

The following are new mercury project reports that have been recently added to the E&WR website. Each link will take you directly to the report.

- A report, "The Economics of Powder River Basin Coalbed Methane Development," prepared by Advanced Resources International, Inc., January 2006, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/netl%20Cost%20of%20Produced%20Water%20Treatment%200106.pdf.

- A quarterly progress report, "Field Testing of Activated Carbon Injection Options for Mercury Control at TXU's Big Brown Station," prepared by University of North Dakota Energy & Environmental Research Center for the period of October 1–December 31, 2005, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/JP-ACI%20at%20BB-42305-Dec05.pdf.

- A quarterly progress report, "Evaluation of MerCAP™ for Power Plant Mercury Control," prepared by URS Group, Inc. for the period of October 1–December 31, 2005, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/41993_Q123105.PDF.

- A quarterly progress report, "Pilot Testing of Mercury Oxidation Catalysts for Upstream of Wet FGD Systems," prepared by URS Corporation for the period of October–1 December 31, 2005, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/GRE-CPS123105.pdf.

- A quarterly progress report, "Pilot Testing of Mercury Oxidation Catalysts for Upstream of Wet FGD Systems," prepared by URS Corporation for the period of October 1–December 31, 2005, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/TXU-Duke-SCC123105.pdf.

- A final site report for testing conducted at the Laramie River Station for the project entitled "Evaluation of Sorbent Injection for Mercury Control," prepared by ADA-ES, Inc., for the period of October 1, 2003 through December 31, 2005 has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/toprpt_laramie_river_station.pdf.

- Two quarterly progress reports for the project entitled "Field Test Program for Long-Term Operation of a COHPAC® System for Removing Mercury from Coal-Fired Flue Gas," prepared by ADA-ES, Inc., have been posted:

  1. Quarterly period of July 1–September 30, 2005: http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/41591%20Q093005.pdf.

  2. Quarterly period of October 1–December 31, 2005, has been posted: http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/41591%20Q123105.pdf.

- Three quarterly progress reports for the project entitled "Low-Cost Options for Moderate Levels of Mercury Control," prepared by ADA-ES, Inc., have been posted:

  1. Quarterly period of April 1–June 30, 2005: http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/42307%20Q063005.pdf.

  2. Quarterly period of July 1–September 30, 2005: http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/42307%20Q093005.pdf.

  3. Quarterly period of October 1–December 31, 2005: http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/42307%20Q123105.pdf

- A quarterly progress report, "Amended Silicates for Mercury Control," prepared by Amended Silicates, LLC for the period of July 1–September 30, 2005 has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/41988%20Q093005.pdf.

- A quarterly progress report, "Large-Scale Mercury Control Technology Testing For Lignite-Fired Utilities Oxidation Systems for Wet FGD," prepared by University of North Dakota Energy & Environmental Research Center for the period of July 1–September 30, 2005, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/41991%20Q093005.pdf.

- A quarterly progress report, "Evaluation of Sorbent Injection for Mercury Control," prepared by ADA-ES, Inc. for the period of October 1 December 31, 2005, has been posted at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/control-tech/pubs/41986%20Q123105.pdf.

- For additional information on NETL mercury related activities, please visit the Environmental & Water Resources' Mercury site located at http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/index.html.

Appendix B- VCU-CES report

Fish Consumption and Human Health Risks

September 2008

Prepared for the Virginia Department of Environmental Quality by:

Rachel Bullene and Dr. Peter deFur
Center for Environmental Studies
Virginia Commonwealth University
1000 Cary St.
Richmond, VA 23219

Executive Summary

Methylmercury contamination of fish has become a problem of national significance. Methylmercury can cause a variety of health effects, including cardiovascular disease and neurological impairment in fetuses and neonates. The Virginia General Assembly recognized the seriousness of mercury contamination and directed the Department of Environmental Quality (VA DEQ) to collect additional information on the problem. VA DEQ investigated methylmercury contamination of fish in certain waters of eastern Virginia because monitoring data indicate that catfish, large mouth bass and several other predatory fish have the highest methylmercury levels. VA DEQ contracted with Virginia Commonwealth University (VCU), Center for Environmental Studies (CES) to conduct fish consumption surveys in the affected waters and estimate the associated health risks from resulting methylmercury exposures. CES developed a fish consumption survey, and worked with VA DEQ staff to identify the launching and fishing locations where anglers could be surveyed. The survey was designed to obtain information on fishing behaviors, fish consumption, and demographic data on the anglers and families. During the summer of 2007, a team from CES administered the survey to 158 anglers at boat launching and fishing sites. Surveys were completed for anglers who were fishing at 17 locations on 5 rivers: the James River below Richmond, the Chickahominy, Pamunkey, Mattaponi, and upper Piankatank Rivers. These rivers are affected by methylmercury contamination, have been surveyed in previous similar investigations and are used by anglers for recreational fishing.

The surveys were administered to anglers from all 17 locations on all 5 rivers, predominantly on Friday, Saturday or Sunday. Approximately 44% of all respondents and their families consume the fish that they catch from these waters. Half (50%) of the anglers only, not family members consume some fish that they catch, and more men (54%) than women (43%) were reported to consume the fish with elevated MeHg levels. The most commonly consumed fish were catfish, spot or croaker, sunfish and largemouth bass; catfish and largemouth bass are

two of the species on the fish consumption advisory. Catfish also represented the largest number of meals and total amount of self-caught fish consumed per year. The data on fish consumption were analyzed with VA DEQ data on methylmercury concentrations in fish that had been collected in previous years to estimate the amount of methylmercury consumed in fish yearly. In order to estimate total methylmercury from all fish consumption, canned tuna and purchased fish consumption were added to mercury exposures from self-caught fish. Mercury levels in tuna and purchased fish were taken from national data.

The methylmercury exposures determined from survey data and VA DEQ fish tissue levels were compared to the dose of mercury exposure that the Environmental Protection Agency has set (and Virginia Department of Health uses) as the dose without appreciable health risks, based on the reference dose or RfD.

The analysis of the fish consumption and fish tissue concentrations was performed using a probabilistic computer program that is used for risk assessments. This program randomly selects certain values, as defined, to use in the equations for determining total mercury from all fish consumed. The analysis indicates that a significant number of anglers who regularly catch and consume significant amounts of catfish and large mouth bass from the affected waters are exposed to methylmercury at levels above the U.S. EPA reference dose of 0.1 ug/kg-day.

The present investigation highlighted several areas that are unknown or have very little data and additional data gathering would close significant gaps in our current understanding of the situation in Virginia. These areas include:

- This survey only obtained data from a few women and no family members and further surveys would be needed to obtain direct fish consumption information on women and children in angler's families.
- Fish consumption patterns of Spanish speaking anglers especially in the Richmond area
- the Native American tribes in the area could be contacted to request their participation

- Other waterbodies could not be surveyed in this investigation and additional survey efforts are needed to provide site specific data outside the rivers surveyed
- The risks of combined exposures to multiple contaminants in fish are unknown
- The population of anglers who consume fish from the affected waters experience cumulative risks that could be examined.

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ACKNOWLEDMENTS

The investigators appreciate the cooperation of staff from the Virginia Department of Health who provided information on the fish advisories. We thank Dr. Edward Boone of VCU Department of Statistics and Operations Research who provided assistance in writing the VBA programming used in the Crystal Ball ® models. We also appreciate the assistance of several graduate students in the Center for Environmental Studies who assisted in administering the fish surveys and data entry: Kyle Newman, Srijeeta Ganguli and Jackie Rickards.

INTRODUCTION AND BACKGROUND

Mercury (Hg) can be found in the environment in elemental, inorganic, and organic forms. Methylmercury (MeHg), one of the organic forms of mercury, is of concern because it bioaccumulates in the aquatic food chain and humans can be exposed via consumption of contaminated fish (NRC 2000). While Hg comes from both natural and anthropogenic sources, the largest identified source of Hg emissions are coal fired power plants (U.S. EPA 1997a). Particles of inorganic Hg are emitted into the air and can deposit onto the land or into waterbodies where microorganisms can convert the inorganic Hg into MeHg. The methylated form of mercury is easily absorbed by living organisms and accumulates in the food chain (ATSDR 1999).

MeHg is known to be highly toxic, as noted from the mercury poisonings in Minnamata, Japan and in Iraq. Health effects of these poisoning episodes included sensory and motor impairment in adults and mental retardation, cerebral palsy, deafness, blindness, and slurred speech (dysarthria) in children exposed in-utero (NRC 2000).

The potential for a toxic substance like methylmercury to cause adverse health effects is assessed by comparing the level of exposure an individual experiences to a risk assessment benchmark value known as a reference dose (RfD). The RfD is a numerical estimate of an allowable daily oral exposure to the human population that is not likely to cause harmful effects during a lifetime. If the exposure remains below the RfD, there is little likelihood of adverse effects. The possibility of toxic effects increases as the exposure level increases above the RfD (see NRC 2000). In 1995, the U.S. EPA set the reference dose (RfD) of 0.1 µg/kg-day based upon a poisoning episode in Iraq from grain contaminated with a MeHg fungicide (see U.S. EPA 2005). However, most of the U.S. population is more likely to be exposed to chronic-low dose MeHg exposure through the consumption of MeHg contaminated fish, U.S. EPA wanted the RfD based on a braoder array of investigations. U.S. EPA contracted with the National Research Council to re-evaluate the RfD based on larger epidemiological studies from the Seychelles,

Faroe Islands, and New Zealand. The NRC recommended consideration of the 95% lower confidence limit for the benchmark doses for a number of neurological endpoints based upon the performance on neuropsychological tests. As a result of the NRC analysis, U.S. EPA reviewed the RfD in 2001, basing the RfD on the results of the Faroe Islands study. On these grounds, U.S. EPA kept the current RfD the same at 0.1 µg/kg-day (U.S. EPA 2005).

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1.1 SITUATION IN VIRGINIA

In 1999, the fish tissue monitoring program of the VA Department of Environmental Quality found fish with high levels of mercury in the Dragon Run Swamp. The fish tissue monitoring program had been monitoring mercury and organic chemicals in fish tissues from a number of waterways owing to past contamination from specific sites. The results in Dragon Run Swamp, however, were unexpected, because this region has very little human activity, is free of industry and intensive farming, and is considered “pristine.” There were no obvious point-sources of mercury in the swamp, so it was hypothesized that the mercury was coming from air deposition, as described in national investigations conducted by U.S. EPA. As a result of the results in Dragon Run Swamp, VA DEQ extended the mercury sampling effort to a larger group of rivers.

When fish were sampled from other waterbodies in the Coastal Plain with similar characteristics to the Dragon Run (slow-moving, acidic water), similarly elevated concentrations of Hg were found in the fish. The program has now reported elevated mercury levels in fish from a number of rivers and lakes (Table 1). The rivers with elevated MeHg in fish tissues are shown in Figures 2.1 and 2.2.

Table 1.1 Waterbodies with mercury fish consumption advisories:
From: http://www.vdh.state.va.us/epidemiology/DEE/PublicHealthToxicology/Advisories/index.htm

Watershed	Waterbody	Location	Species Associated with Hg Advisory
Chesapeake Bay and Small Coastal Basin	Lake Trashmore	Virginia Beach City	Large Mouth Bass
	Lake Whitehurst	Norfolk City	Carp
	Blackwater River	Surry County, Southampton County, Isle of Wight County, Franklin City, and Suffolk City, Sussex County, Prince George County, and Petersburg City	Largemouth Bass Chain Pickerel Bowfin Redear Sunfish White Catfish Redhorse Sucker Longnose Gar
Watershed (cont.)	**Waterbody (cont.)**	**Location (cont.)**	**Species Associated with Hg Advisory (cont.)**
Chowan and Dismal Swamp Basin	Great Dismal Swamp Canal	Chesapeake City and Suffolk City	Bowfin Chain Pickerel
	Nottoway River	Greensville County, Sussex County and Southampton County	Largemouth Bass Smallmouth Bass Bowfin Chain Pickerel Redhorse Sucker Spp. Longnose Gar Channel Catfish Sunfish Spp.
	Dragon Run Swamp/ Piankatank River	Essex County, Middlesex County, King and Queen County, and Gloucester County	Large Mouth Bass
James River Basin	Harrison Lake	Charles City County	Redear Sunfish Largemouth Bass Chain Pickerel Bowfin
	Chickahominy River	Charles City County New Kent County	Largemouth Bass Chain Pickerel Bowfin
York River Basin	Lake Gordonsville	Louisa County	Large Mouth Bass
	Pamunkey River	Hanover County, King William County, and New Kent County	Blue Catfish
	Mattaponi River	King William County and King and Queen County	Large Mouth Bass
	Herring Creek	King William County	Bluegill Sunfish Yellow Bullhead Catfish

The fish tissue monitoring results raised concern for several reasons. First, there are no known point sources of mercury in most of the waterbodies that are affected. The only explanation seemed to be the atmospheric deposition of mercury, with subsequent transformation into methylmercury, uptake and accumulation in fish. The sources of mercury emission into the atmosphere were not known precisely and may well include long-range transport. Second, mercury, specifically methylmercury, is highly toxic, especially to the developing nervous system, causing I.Q deficits in children. Third, the developing fetus seems to be the most sensitive to the effects of methylmercury. Fourth, the affected waters are used for both recreational fishers and fishers who rely on their catch for food, although the exact extent of the use was not well known. Fifth, methylmercury was found in several types of fish, both catfish and top predators such as bass. Finally, methylmercury contamination of the coastal plain rivers could be a long term condition that would require a more complex solution than if the source were a direct discharge into the waters.

The impacts on Virginia from mercury contaminated fish could include health consequences for the people who consumed fish from these waters, in spite of warnings to limit or eliminate such consumption. The health effects of MeHg poisoning are primarily neurological damage that is likely to be permanent for children, the most sensitive members of the population. Adults may also suffer from neurological damage at high MeHg doses and an increased risk of cardiovascular disease. Fish advisories on the rivers and lakes may also cause a reduction in recreational uses, with the possibility of some, as yet undescribed economic consequences. The total economic impact of methylmercury contamination is unknown.

1.2 SOURCES OF MERCURY

Mercury is generally found in three forms: elemental (metallic) mercury, inorganic mercury, and organic mercury. Mercury can enter a waterbody either through atmospheric

deposition or through point source discharges. Although metallic mercury (used in thermometer, switches, etc.) can volatize into the air, most of the air born mercury comes from burning hazardous waste and burning coal. According to the U.S. EPA, “coal-burning power plants are the largest human-caused source of mercury emissions to the air in the United States, accounting for over 40 percent of all domestic human-caused mercury emissions” (U.S. EPA 1997a).

1.3 FATE AND TRANSPORT OF MERCURY

The atmospheric particles of elemental or inorganic mercury eventually settle into a water body or onto land where the particles wash into the water. Mercury particles can then be transformed by microorganisms into methymercury, which is easily absorbed by plants and animals, and is a more toxic form of mercury. The methylation process is enhanced under anaerobic conditions (such as a swamp) where the types of bacteria capable of producing methylmercury are likely to flourish (ATSDR 1999).

1.4 BIOACCUMULATION OF MERCURY

Because methylmercury can bioconcentrate, bioaccumulate, and biomagnify, even small environmental concentrations of mercury in water can readily accumulate to potentially harmful concentrations in fish (U.S. EPA 1997b). The ratio of concentration of methylmercury in fish tissue to that in water is usually between 10,000 and 100,000 (U.S. EPA 1978). MeHg in fish tissue is dependent on the chemistry of water body and the trophic level of the fish, with the higher trophic level fishes generally having higher mercury concentrations in their tissues. Mercury binds to protein, and in fish mercury bioaccumulates in the muscle tissue, meaning that the larger and older fish generally have higher mercury concentrations than younger, smaller fish.

1.5 HUMAN EXPOSURE TO MERCURY

Toxicokinetics of MeHg

Absorption

Unlike dimethylmercury, methylmercury is not easily absorbed through the skin. Methylmercury vapors in the air at room temperature are easily absorbed through the lungs (ATSDR 1999); however, route of human exposure to methylmercury is primarily oral. Methylmercury is the form of mercury that is most easily absorbed through the digestive tract, and it is estimated that 90% to 95% of the methylmercury ingested will be absorbed into the bloodstream (NRC 2000, ATSDR 1999). Additionally, animal studies indicate that gastrointestinal absorption is in excess of 90% of the oral dose, and that age (including neonatal stage) has no effect on the absorption rate (Walsh, 1982).

Distribution

Once in the blood, methylmercury is easily transported to other organs including the brain, and in the case of pregnant women, methylmercury enters the fetus's blood, organs, and developing brain (ATSDR 1999). Both inorganic mercury and methylmercury can be passed into a nursing woman's breast milk. Distribution of methylmercury to all tissues is complete within about 4 days in humans, and at this time the brain contains approximately 6% of the dose (Kershaw et al., 1980).

Biotransformation/ Excretion (MeHg half-life)

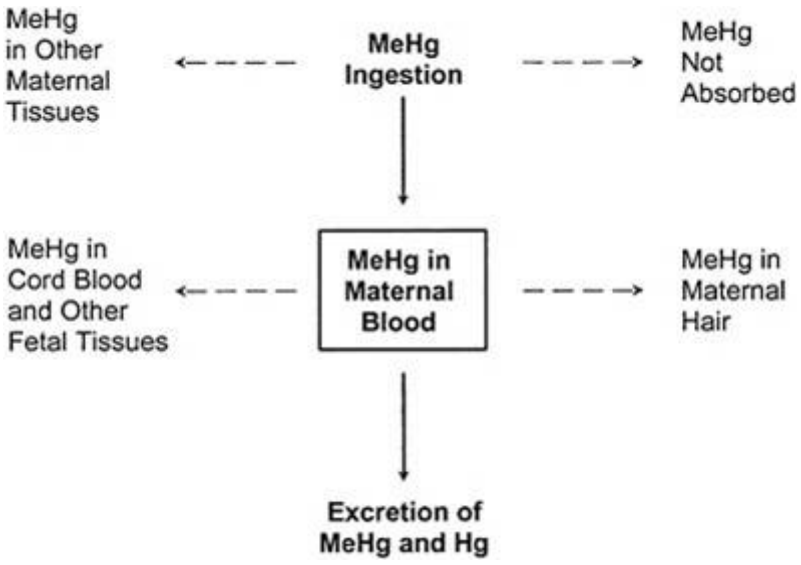
Over time, most of the methylmercury is transformed in the body to inorganic mercury and is then excreted in the urine and feces. Small amounts of the inorganic mercury can further be transformed in the body to metallic mercury and exhaled through the lungs as mercury vapor

(ATSDR 1999). The excretion rate is approximately 1% of the total body burden per day, with the half-life in blood of 48-53 days and the whole body half-life of 70-80 days (Kershaw et al. 1980, U.S. EPA 1997b, NRC 2000). However, the methlymercury converted to inorganic mercury in the brain has a much longer half-life, in the range of years.

Biomarkers and Pharmacokinetic models

In the determination of the dose-response relationship, biomarkers of methylmercury exposure can be used as surrogates when the ingested dose is unknown. The commonly used biomarkers are total mercury blood concentration, fetal-cord-blood concentration, and hair concentration. Using the mercury concentrations in these biomarkers, the ingested dose can be estimated using either a physiologically based pharmacokinetic (PBPK) model or by a simplified one-compartment model (Fig. 1.1 from NRC, 2000).

Figure 1.1 One-Compartment Model



source: NRC 2000

The one-compartment model used by International Programme on Chemical Safety (1990) and the US Environmental Protection Agency (1997)) collapse the distribution and redistribution of methylmercury among several body compartments into one compartment that assumes the blood concentration to be at a steady state. Under this assumption, the steady state dose can be calculated by the following equation:

$$D = \frac{C \times b \times V}{W \times A \times F}$$

Where D = steady state dose
C = concentration of MeHg in the blood (µg/L)
b = elimination rate constant (fraction of the concentration eliminated per day (day^{-1})
V = blood volume (L)
W = body weight (kg)
A = fraction of ingested MeHg that is absorbed
F = fraction of absorbed MeHg that is distributed in the blood

When the biomarker of exposure is hair concentration or fetal-cord-blood concentration, these factors can be substituted for C in the above equation as C = (1/R) x Z, where R is either the hair-to-blood concentration ratio (µg/g)/(µg/L) or the cord-blood to maternal-blood ratio and Z is the hair concentration or fetal-cord-blood concentration. These equations can be used either to calculate the ingested dose from a given blood concentration, hair concentration, or fetal-cord-concentration, or conversely to calculate these biomarker levels from a given ingested dose.

Inter-individual Toxicokinetic Variability

The relationship between ingested dose and the concentration of MeHg in hair or cord blood depends on physiological factors that vary among individuals in the population. Therefore, there is no single conversion factor to translate an ingested dose into a biomarker concentration (or vice-versa, from a biomarker concentration to an ingested dose.) Based upon recommendations from the NRC report (2000), the U.S. EPA used the central tendency for each physiological parameter when reconstructing the ingested dose from the biomarker when deriving the revised RfD. An alternative to using the central tendency estimate is to use the

distribution of each parameter in a Monte Carlo simulation as Stern did in 1997 and 2005. In 1997, Stern used distributions for each parameter from the literature that were relevant to women of childbearing age (18 – 45). In 2005 Stern revised his analysis to use empirical or parametric distributions appropriate for third-trimester pregnancy specific values. A comparison of the values used in these three analyses can be seen in Table 1.2 below:

Table 1.2 Comparison of Physiological Parameters. Ingestion, absorption, transfer factors and relevant ratios for calculating methylmercury in humans

Parameter	U.S. EPA (1995)	Stern (1999)	Stern (2005)
$\mathbf{R_h}$ (hair to blood ratio)	0.25	Cumulative probability distribution[1]: min: 0.073 10%: 0.224 25%: 0.265 50%: 0.292 75%: 0.307 90%: 0.41 max: 0.535	(not used in analysis)
$\mathbf{R_c}$ (cord blood to maternal blood ratio)	1	(not used in analysis)	lognormal (μ: 1.7, σ: 0.9)[10]
b (elimination rate)	0.014/day	lognormal (μ: 0.011, σ: 0.0037)[2] ---------- lognormal l(μ: 0.014, σ: 0.0026)[3]	empirical probability distribution[11]: min: 0.009/day max: 0.046/day
V (blood volume)	5 L	lognormal (μ: 3.57, σ: 0.443), rank order correlation with **W**, r=0.63 [4] ---------- = 0.037 L/kg x **W** + 1.43 [5]	cumulative probability distribution[12]: min: 3.707 L max: 7.902 L correlated with W, r=0.49
A (fraction of ingested MeHg that is absorbed)	0.95	normal (μ: 0.94, σ: 0.016)[6]	cumulative probability distribution[13]: min: 0.940 max: 0.999
F (fraction of absorbed MeHg that is distributed in the blood)	0.05	lognormal (μ: 0.077, σ: 0.008)[7] ---------- lognormal l(μ: 0.067, σ: 0.019)[8]	normal (μ: 0.052, σ: 0.0095)[14]
W (body weight)	60 kg	Cumulative probability distribution[9]: min: 34.75 kg max: 153.3 kg	lognormal (μ: 80.9 kg, σ: 16.3 kg)[15]

[1] combined data set from Kershaw et al. (1980) and Birke et al. (1972)
[2] from Al-Sharistani (1974)
[3] average of Kershaw et al. (1980), Smith et al. (1994), Sherlock et al. (1984), Al-Sharistani et al. (1974), and Miettinen et al. (1971)
[4] combined data set from Brown et al. (1962), Retzlaff et al. (1969), Huff and Feller (1956)
[5] combined data set from Brown et al. (1962), Retzlaff et al. (1969), Huff and Feller (1956)
[6] from Miettinen et al. (1971)
[7] from Smith et al. (1994)

[8] average of Smith et al. (1994) and Kershaw et al. (1980)
[9] from NHANES III (1996)
[10] from Stern and Smith (2003)
[11] from Cox et al. (1989)
[12] from Thomson et al. (1938) and Caton et al. (1951)
[13] from Miettinen et al. (1971)
[14] from Sherlock et al. (1984) and Kershaw et al. (1980)
[15] from CDC (2004)

The principal target organ of oral exposure to methylmercury is the central nervous system. Methylmercury is rapidly transported across the blood-brain barrier and accumulates in the brain where it slowly demethylates to inorganic (mercuric) mercury. Both the adult and fetal brains are damaged by methylmercury (and the oxidized inorganic mercury), but the fetal brain is more sensitive.

1.6 HEALTH EFFECTS OF MERCURY

Health Effects:

The danger posed by methylmercury was first elucidated by several tragic poisoning episodes. In the 1950s, outbreaks of a severe neurological disease were first noted in Minamata City, Japan. The cause of the epidemic was eventually traced to the consumption of fish and shellfish from Minamata Bay that were contaminated with methylmercury that came from the wastewater discharge from the local chemical plant. Both adults and children exhibited adverse health effects; however, children exposed in-utero were more sensitive, suffering from mental retardation, cerebral palsy, and other central nervous system defects (NRC 2000). Similar epidemics of neurological disorders occurred in Iraq in 1960, 1965, and 1971-72; however, in Iraq the poisoning was a result of the handling and consumption of grain treated with ethyl or methylmercury fungicides (ATSDR 1999). The results from these high-dose poisoning episodes were similar: adults suffered from loss of sensation in the hands, feet, and around the mouth (paresthesia), uncoordinated walking (ataxia), slurred speech (dysarthria), diminution or loss of sight, loss of hearing, and death. Infants exposed to the highest doses either in utero or through their mother's milk suffered severe brain damage (Bakir et al. 1973). The high dose exposures

have served to inform the health and medical communities on the health effects from MeHg poisoning, the mechanism of action and the most sensitive populations.

Because both the poisoning episodes in Japan and Iraq were studied retrospectively, exposure doses had to be estimated in adults through blood concentrations and in infants exposed *in utero* through maternal hair concentrations. Using hair as a biomarker of exposure has the advantage of being able to reconstruct a timeline of exposure in both duration and magnitude. Using pharmokinetic models, maternal hair mercury concentration can be used as a surrogate for the dose of mercury received by the fetal brain and hair mercury concentration can also be used to estimate the ingested dose (NRC 2000).

While dose response functions can be estimated from the data from the poisoning episodes in Japan and Iraq, these exposure scenarios are not comparable to chronic low-dose exposure from the consumption of fish or other seafood. To better understand the effects of chronic low-dose exposure, several prospective epidemiological studies have been carried out on populations around the world. The developing central nervous system is assumed to be the most sensitive to chronic low-dose exposure, therefore status on neurological examination, age at reaching developmental milestones, and performance on neurobehavioral tests, and other endpoints in children were examined in these studies (NRC 2000).

Finally, animal studies have shown that high level, long term exposure to methylmercury produces adverse effects including: damage to the nervous system; damage to the kidneys and the digestive tract (stomach and large intestine); changes in blood pressure and heart rate; damage to the developing fetus; adverse effects on the male reproductive organs and sperm; increases in spontaneous abortions and still births. Of all the adverse effects, damage to the nervous system occurred at the lowest doses (ATSDR 1999).

The following is a summary of effects of methylmercury on the different organ systems. The concern of this study is exposure to methylmercury through the consumption of

contaminated fish; therefore, the health effects discussed are associated with the oral route of exposure as opposed to inhalation or dermal exposure.

Gastrointestinal effects:

Gastrointestinal effects were noted in an ethylmercury poisoning episode in Iraq in the form of abdominal pain, vomiting, diarrhea or constipation (Jalili and Abbasi 1961). Long-term exposure of rats to 4.2 mg Hg/kg/day resulted in necrosis and ulceration of the cecum, and long-term exposure of mice to 0.1 mg Hg/kg/day resulted in ulceration of the glandular stomach (ATSDR 1999).

Hepatic effects:

In the Iraqi poisoning episode, autopsies of four adults and four infants who died as a result of methylmercury poisoning showed fatty changes in the liver in most cases. (Al-Saleem & the Clinical Committee on Mercury Poisoning 1976).

Renal effects:

The kidney is the critical organ of toxicity from the ingestion of inorganic mercury (mercuric salts) (ATSDR 1999), and several case studies and animal studies have demonstrated renal toxicity from the ingestion of organic mercury as well. In an ethylmercury induced poisoning episode in Iraq, affect individuals exhibited excessive urination (polyuria), excessive thirst (polydipsia), and protein in the urine (albuminuria) (Jalili and Abbasi 1961). In the case of the family poisoned from consuming ethylmercury contaminated pork, the two boys that died also exhibited albuminaria, increased blood urea, and urinary sediment (Cinca et al. 1979). A study of residents of an area of Minamata Japan that had the highest incidence of Minamata disease (caused by the consumption of methylmercury contaminated fish) revealed a

higher than expected death rate attributed to nephritic disease among women but not among men (Tamashiro et al. 1986). NRC's Toxicological Effects of Methylmercury (2000) cites eight studies of rodents that described methylmercury induced renal toxicity.

Hematological effects:

ATSDR noted that no human studies of hematological effects from the oral ingestion of organic mercury were located in their 1999 Toxicological Profile of Mercury (ATSDR 1999); however, they noted that long them exposure of rats to 4.2 mg Hg/kg/day resulted in anemia, but that may have been a secondary effect of gastrointestinal bleeding.

Respiratory effects:

In autopsies of four adults and four infants who died as a result of methylmercury poisoning in Iraq, in all four adults and one of the infants bronchopneumonia was considered the immediate cause of death (Al-Saleem & the Clinical Committee on Mercury Poisoning 1976). According to ATSDR, however, it is unclear if this was a direct effect on the respiratory system or a secondary effect of the poisoning (ATSDR 1999). One animal study reviewed by the ATSDR showed no "treatment related histopathological lesions" in rats from long term exposure to 0.1 mg Hg/kg/day. (ATSDR 1999)

Cardiovascular effects:

The cardiovascular effects such as changes in blood pressure and cardiac function were first noted in both inorganic and organic poisoning episodes; however, recent epidemiological studies have also found associations between low level exposure to methylmercury and increased risk of myocardial infarction, hypertension, and changes in heart rate variability.

Heart-rhythm abnormalities were observed in at least two of the organic mercury poisoning incidents: in the 1956 Iraqi ethylmercury poisoning episode (Jalili and Abbasi 1961) and from a family that consumed a hog that had eaten ethylmercuric contaminated seed (Cinca et al. 1979).

In a prospective epidemiological study, Salonen et al. studied the relationship between the dietary intake of fish, the estimated dose of mercury, the measured mercury hair content, and the amount of mercury excreted in the urine, to the risk of acute myocardial infarction and death from coronary heart disease or cardiovascular disease. The study group was made up of 1833 Finnish men aged 42 to 60 years with no prior history of heart disease, heart attacks, or strokes. The cohort was initially followed for an average of 5 years for acute myocardial infarction and an average of 6 years for death. Salonen et al. (1995) found that dietary intake of fish and hair mercury concentrations were associated with significant increases in the risk of acute myocardial infarction and death from coronary heart disease, cardiovascular disease, or any cause. Men in the highest tertile (2.0 μg/g) of hair mercury concentration had a 2.0-fold (95% confidence interval, 1.2 to 3.1; P=.005) higher risk of acute myocardial infarction and a 2.9-fold (95% CI, 1.2 to 6.6; P=.014) adjusted risk of cardiovascular death compared with those with hair mercury content < 2.0 μg/g. The authors suggested that the mercury could be causing lipid peroxidation, thereby antagonizing the beneficial effects of the n-3 fatty acids found in fish. In a follow up study, Rissanen et al. (2000) extended the study time for the same cohort of Finnish men to 10 years and also measured the blood levels of docosapentaenoic acid (DPA), docosahexaenoic acid (DHA), and eicosapentanoic acid (U.S. EPA) (all end product n-3 fatty acids from fish). This study confirmed the hypothesis that fish oil derived fatty acids reduce the risk of acute coronary events in the study population (middle age men from Eastern Finland), but high levels of mercury (as measured in hair content) reduced the beneficial effects of the fatty acids. Virtanen et al. did a similar analysis from the same study (Kuopio Ischaemic Heart Disease Risk Factor Study) and found that men with greater than 2.03 ug/g hair mercury

concentration had an adjusted 1.6 fold increase in risk of an acute coronary event, 1.68 fold risk of cardiovascular death, 1.56 fold increase risk of coronary heart disease, and 1.38 fold risk of any death (Virtanen et al. 2005)

Prenatal exposure to low levels of methylmercury has also been associated with changes in cardiovascular function. In a prospective study a cohort of 1000 children from the Faroe Islands, Sorenson et al. (1999) found an association between prenatal exposure to methylmercury and cardiovascular function at age 7. In this study, Sorenson et al. (1999) found that blood pressures and the cord blood mercury concentration showed a linear relationship, with diastolic blood pressure increasing by 13.9 mmHg (95% CL – 7.4, 20.4) and systolic pressure increasing by 14.6 mmHg (95% CL = 8.3, 20.8) as cord blood Hg levels increased from 1 to 10 µg/liter. Above 10 µg/liter no relationship was seen between cord blood level and blood pressure.

Central Nervous System Effects:

Developing nervous system

High-dose in utero exposure to methylmercury can result in congenital Minamata disease (CND – caused by the maternal consumption of heavily contaminated fish and shellfish in Japan) characterized by mental retardation, primitive reflexes, cerebellar ataxia (loss of muscle coordination), disturbances in physical growth, dysarthria (slurred speech), and limb deformities (NRC 2000). The most severely affected children exposed in utero in Iraq had similar symptoms: blindness, deafness, paralysis, hyperactive reflexes, cerebral palsy, and mental retardation (NRC 2000).

Low-dose but chronic exposure to methylmercury was examined in epidemiological studies in the Faroe Islands, the Seychelles Islands, New Zealand, and others for more subtle neurological effects. The Faroe Island study used the mercury content in maternal hair, cord

blood, and cord tissue as biomarkers for exposure and examined a cohort of 1010 children at age 7 (917 children examined) and age 14 (878 children examined). The children were given a battery of neuropsychological tests; significant associations between higher prenatal methylmercury exposure and lower finger tapping speed, increased reaction time on a continued performance task, and lower cued naming scores were found at age seven and again at age 14 (Debes et al., 2006).

The New Zealand study matched children of mothers who had hair-mercury levels above 6 ppm during pregnancy with 3 control children of mothers who had lower hair mercury levels. One group of control children came from mothers who had hair mercury concentrations between 3 and 6 ppm, and the other 2 control children had mothers who's mercury hair concentrations during pregnancy was 0-3 ppm; one mother being a high fish consumer, the other being a low fish consumer. When the children were 6 to 7 years old they were assessed on 26 psychological and scholastic tests. Kjellstrom et al (1989) found a significant relationship between higher prenatal methylmercury exposure and decreased performance on five of the tests based upon the category of mercury exposure. Crump et al. 1989 reanalyzed the data by performing a regression analysis of the actual maternal hair mercury levels. When one highly influential point was omitted, Crump et al. found a significant relationship (α=0.1) between maternal hair mercury levels and scores on six of the psychological and scholastic tests (Crump et al. 1998). The regression coefficients for the significant tests (especially the Wechsler Intelligence Scale for Children-Revised (WISC-R)) can be used as a dose response function.

The Seychelles study followed 779 mother-infant pairs from a primarily fish-eating population. The children in this study were assessed at various ages between birth and 5.5 years on a number of standardized neuropsychological endpoints. No significant associations were found between cord-blood mercury or maternal hair mercury and the children's performance on the neuropsychological tests. (Davidson et al. 1998, Davidson et al. 2006)

Dose-response functions:

Reference Dose

The reference dose "is is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime" (U.S. EPA 2001). U.S. EPA chose a benchmark dose analysis (and the quantitative analysis done by the NRC (2000)) to derive a dose-response relationship from the three studies mentioned above. U.S. EPA considered any score at or below the 5th percentile of the populations' distribution of scores as an abnormal response. Thus for the methylmercury RfD analysis U.S. EPA set the benchmark response to 0.05, which in this case would double the number of children who scored at the the population's 5th percentile. The benchmark dose lower limit (the lower 95% confidence limit of the BMD_{05}) was then calculated from the significant test results in all three studies: the Faroe Islands, Seychelles, and New Zealand studies. For the RfD U.S. EPA used the $BMDL_{05}$s (quantified in mercury cord blood) from several scores for the Faroe Islands study and converted those doses into maternal ingested doses using the one-compartment model. The RfDs were then derived by dividing the ingested doses by an uncertainty factor of 10; the values of the RfDs for a number of endpoints in all three studies converged around 0.1 ug.kg.day (NRC, 2000; U.S. EPA 2001).

Table 1.3 Reference Dose and Virginia Consumption Advisories

Threshold	**directed at/ protective of**	**compare consumption to:**
RfD	sensitive subgroups	oral dose of 0.1 ug/kg/day
VA consumption advisory	Women of childbearing age and children	No meals of certain species of fish
VA consumption advisory	all anglers	No more than 2 meals/month of certain species of fish

Table 1.4 Cardiovascular Health Effects Dose/Response Functions

Group	**outcome**	**relative risk**	**source**
adult males with hair conc. over 2 ppm	relative risk for non-fatal and fatal myocardial infarctions	1.69 compared to lower hair concentrations	Salonen et al. (1995)

adult males	relative risk for non-fatal and fatal myocardial infarctions	1.068 per 1 ppm hair Hg concentration over 2 ppm	Salonen et al. (1995)
adult males with hair conc. over 2 ppm	Relative risk for all-cause mortality	1.93 compared to lower hair concentrations	Salonen et al. (1995)
adult males	relative risk for all-cause mortality	1.09 per 1 ppm hair Hg concentration over 2ppm	Salonen et al. (1995)

Table 1.5 Neurological Health Effects Dose/ Response Functions

based on:	outcome	Dose/Response	source
Seychelles, Faroe Islands, NZ cohorts	change in IQ points per 1 ppm increase in maternal hair Hg concentration	-0.7 (plausible values ranging from 0 to 1.5)	Cohen et al. (2005)
Cohen et al. and Crump et al. (1998)	change in IQ points per 1 ppm increase in maternal hair Hg concentration	-0.6	Rice and Hammitt (2005)
Seychelles, Faroe Islands, NZ cohorts	change in IQ points per 1 ppm increase in maternal hair Hg concentration	-0.18 (95% CI: -0.378,-0.009)	Axelrad et al. (2007)

1.7 PURPOSE OF THE VIRGINIA STUDY

The purpose of this study was to obtain Virginia-specific fish consumption information and combine that with information from VA DEQ's fish tissue database to assess the range of exposures for the population of Virginia anglers (and their household members) that eat fish from Virginia's freshwater-tidal rivers. This distribution of exposures was then used to construct a distribution of adverse health effects based upon the dose response functions described in the literature. A second objective of this survey was to obtain demographic information from the target population to characterize the sub-populations at greatest risk.

The concentration of methylmercury in fish tissue obtained from VA DEQ's fish tissue database was combined with information derived from the consumption survey to produce baseline estimates of ingested doses. Dose-response functions from the literature were then

applied to these doses to estimate the probability of health impacts to the anglers and the household members who consume contaminated fish from the study area. In addition to estimating risks under present exposure conditions, risks were estimated for lower mercury contamination conditions. VA DEQ estimated mercury air-deposition across Virginia after 2010 and 2018 in response to planned regulatory controls. These estimates were used to estimate the potential changes in fish contamination levels and the resulting possible changes in health risks. These estimates of risks to human health will be analyzed by VA DEQ to predict economic benefits and costs due to current levels of mercury versus potential future reductions.

2 METHODS

2.1 FISH CONSUMPTION SURVEY OF POPULATION OF INTEREST

To acquire the Virginia-specific fish consumption information, a survey was designed to obtain recreationally-caught freshwater fish and total fish consumption information from the population of freshwater anglers that fish in Virginia's coastal plain. Personal interviews of anglers were conducted from June 2007 until September 2007, at 17 fishing access points in the region of interest. The survey locations were chosen by VCU and DEQ staff as the most likely places to find both anglers fishing by boat or by shore within the range of the areas under a fish consumption advisory for mercury. The original proposal also included a plan to interview the Native American tribes that live in Virginia's coastal plain; however, they declined to participate.

2.1.1 SURVEY INSTRUMENT DESIGN

The sampling method for the recreational freshwater anglers was a creel survey at 17 selected fishing access points. The survey instrument was based upon previously used survey instruments (Jones 2002), and was designed to minimize the time burden (estimated at 10 minutes) upon the participating subjects.

Target populations and sampling strategy

The target populations for this survey were recreational freshwater anglers and their household members who fish in Virginia's coastal plain and Native Americans who live in Virginia's coastal plain. To sample the population of recreational freshwater anglers, 17 fishing access points in the region of interest were visited multiple times on different days of the week and at different times of day over a four month period (June – September). All adult anglers present (either boat fishing or shore fishing) at the survey times were approached and asked to participate in the survey. Subjects were asked if they have been interviewed before, and those who had previously completed the survey were not re-interviewed. With this method we assumed that the population of anglers who fish at least once from June – September have an equal probability of being interviewed and as such we did not assign a sampling weight based upon the subject's fishing frequency.[1]

Specific data obtained from the survey:

- fishing behavior information: frequency of recreational freshwater fishing, average distance traveled to fishing locations, range of fishing locations;
- motivation for fishing: recreation, food, both;
- the species of recreational freshwater fish most frequently consumed;
- the average meal size and frequency of self-caught fish meals consumed by anglers;
- the average meal size and frequency of purchased fresh or frozen fish or shellfish meals consumed by anglers;
- the average meal size, frequency and type of canned tuna fish consumed by anglers;
- household make-up: number of children under five, the number of children six to 15 years old, the number of women 16 to 49 years old, the number of men 16 to 49 years

[1] I n the Exposure Factors Handbook (U.S. EPA, 1997), the U.S. EPA noted that a weakness of the creel survey was the possibility of overestimating the target population distribution if the sampling time was limited in duration.

old, the number of people over the age of 50, and the number of people in each age group that eat fish that the angler catches;

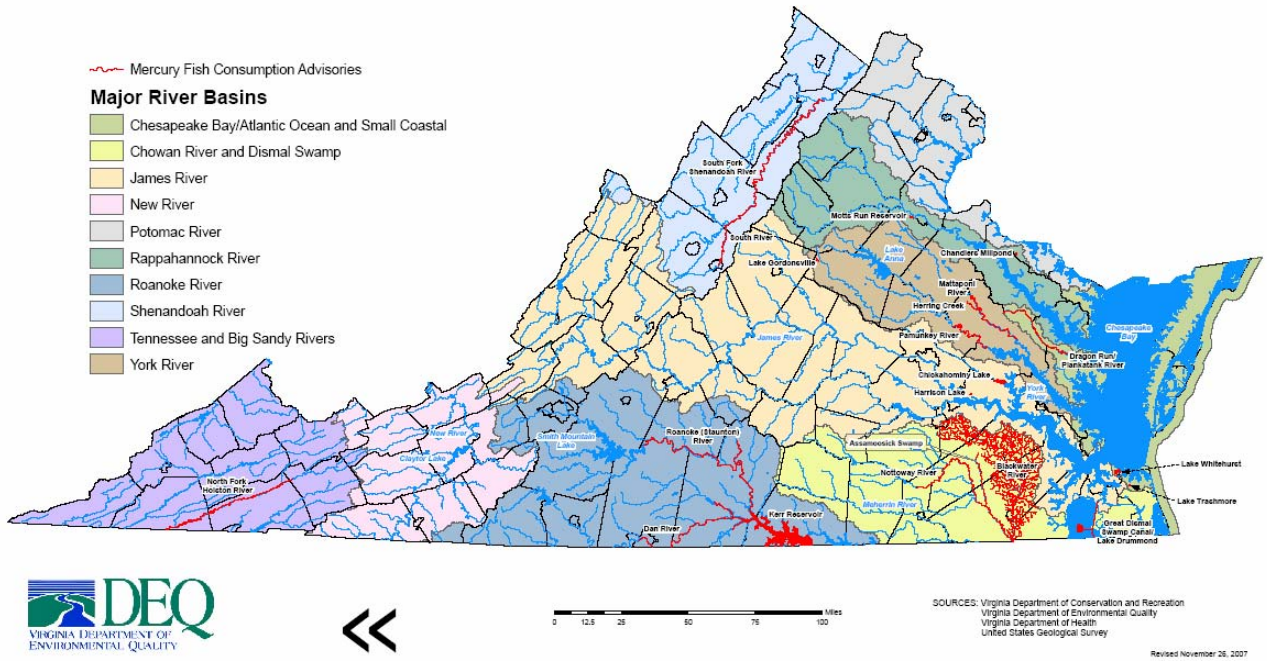
- demographic information: race, age, education level, income level, zip code

2.1.2 SURVEY LOCATIONS

The survey locations were chosen in consultation with VA DEQ to provide a good sample from the area of interest (Eastern rivers under fish consumption advisories for mercury). Survey locations were chosen where we believed we would find the most anglers, so that we could maximize the sample number with the surveying effort. Thirteen survey sites were initially identified; however, five additional sites (2 on the Pamunkey, 2 on the Chickahominy, and one on the Piankatank) were added. These new survey locations were all mentioned by several anglers during interviews as “good places to find anglers.” The addition of these new sites was necessary because of problems encountered with the some of the survey sites initially identified for the Piankatank and Chickahominy rivers.

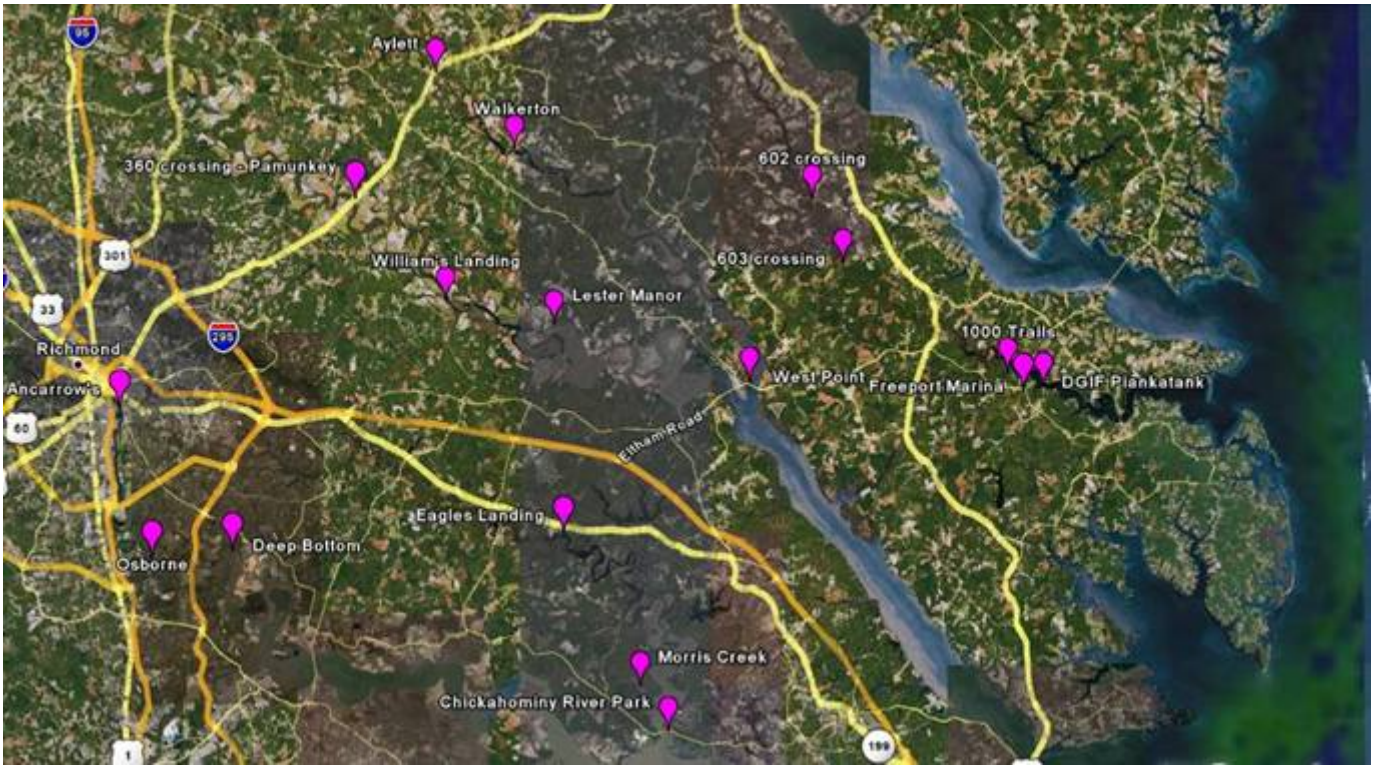
Two of the sites originally identified: 1000 Trails and Rockahock campgrounds have been problematic. Rockahock campground was chosen for its proximity to Walkers Dam, but because of the concerts held at that location in the early summer, surveys were not able to be completed on the dates that the survey team visited. Chickahominy Lake in general has been difficult to survey in part because of the lack of public access, but also because Walkers Dam was partially breached in the late spring, causing the lake level to drop. We were advised by anglers interviewed on other rivers who said they fished Chickahominy Lake that Ed Allens Campground and Eagles Landing were more heavily used by anglers. The survey team was invited by Jill O’Brien-Jones, the owner of Eagles Landing, to interview anglers at that location; however, she advised the team that because of the low lake level, boat access (and the likelihood of meeting anglers) was best at high tide. 1000 Trails Campground was chosen as

Figure 2.1 Waters Under VDH Fish Consumption Advisories For Mercury



one of the few boat ramps on the Upper Piankatank River. Two survey visits were completed before the boat ramp closed in late June. At that time the survey team was advised to try Freeport Marina a few miles down river.

Figure 2.2 Map of Survey Locations



map from Google Earth

2.2 FISH TISSUE MERCURY CONCENTRATIONS

As part of the VA DEQ Fish Tissue and Sediment Monitoring Program, fish are collected by the VA DEQ each summer. Fish are weighed, measured, and a 1 g sample of muscle tissue is analyzed for total Hg (among other contaminants). Since previous studies indicated that 90% of the Hg found in fish tissue was MeHg, the VA DEQ assumes that all mercury is MeHg. (Barron 2007). By assuming 100% of the mercury is MeHg, VA DEQ is protective of those cases in which all the mercury is MeHg and accounts for variation around the 90% value. The assumption of 100% v 90% has a small effect on the results of this prediction and on setting health advisories. Over 3,000 fish tissue samples with mercury concentrations are listed in VA DEQ's fish tissue database for the years 1999-2006. For the risk assessment, we only used the samples that corresponded to our survey areas. The sample was further reduced by only

including the fish that the anglers reported eating. Fish such as carp, longnose gar, bowfin, and gizzard shad were excluded because these species were never or rarely reported consumed. The values of each species/class of fish were then grouped from the 5 rivers to create distributions of mercury concentrations for each species. The distribution was constructed so that the frequency of each observation was equal to 1/n.

Distributions for fish tissue concentrations projected in 2010 and 2018 were constructed by multiplying each observation by the corresponding reduction factor for the river. Reduction factors were determined by VA DEQ based upon projected reductions in air deposition provided by an air- modeling study that estimated reductions in air-deposition rates of total mercury across Virginia in future years 2010 and 2018. The modeled reductions in total mercury deposited into the individual river watersheds were used to estimate future mercury deposition in comparison with the base line mercury deposition rates estimated for the year 2002. The modeled deposition rates for the base year of 2002 is considered representative of the conditions that were responsible for the fish-mercury concentrations that were detected during the VA DEQ fish monitoring between 1998-2006. This information was used to calculate a "reduction factor" for future years, representing the remaining air–deposited mercury compared to the rates of 2002. For example; the air model predicted the rate for 2010 of air-deposition of total mercury onto the watershed of the Dragon Run swamp to be 82.01% of the mercury deposition rate in 2002. This amount represents an estimated 17.9% reduction in the air deposition rate for total mercury in 2010 compared to the deposition rate of 2002. This procedure yields a "reduction factor" of 0.8201 modeled for this watershed based on projected 2010 deposition levels. The reduction factor for the river basin can be used to estimate future fish –mercury concentrations levels in response to reduced mercury deposition.

It was assumed by VA DEQ that the fish-mercury-concentrations in an ecosystem are in dynamic equilibrium with mercury inputs to that watershed and that a reduction in mercury deposition will result in a proportional reduction in fish-mercury concentrations after the

ecosystem re-equilibrates to the lowered inputs of mercury. Under this scenario, the reduction factor for the watershed can be multiplied times the fish-mercury concentrations seen in previous monitoring (which are assumed to be a result of deposition rates reprsented by the 2002 base year) to estimate future mercury-fish concentrations after the projected reductions in mercury deposition rates have occurred. For example; if previous samples of largemouth bass from the Dragon Run contained an average concentration of mercury of 1.0 part per million, then after the projected 2010 reductions in air deposition rates take effect we can estimate that future concentrations in this species may average 1.0 ppm x 0.8201 (the river-specific reduction factor) = 0.8201 parts per million mercury.

The reduction factors calculated for 2010 and 2018 are shown in table 2.1 for the specific river basins important to this fish consumption and risk assessment study.

Table 2.1 Modeled Reduction Ratios in Hg-Air Deposition

Ratio (unitless) of projected mercury deposition in future years, following emission reductions, compared to base year 2002

Modeled Year:	2010	2018
Dragon Run / Swamp:	0.8201	0.7972
Mattaponi River:	0.8120	0.7853
Pamunkey River:	0.8063	0.7830
Chickahominy River:	0.8096	0.7885
James River (Richmond-Hopewell):	0.7186	0.6850

The values used to estimate the current (2008), 2010, and 2018 fish tissue mercury concentrations of fish caught in the survey area are presented in the appendix.

Purchased fish tissue mercury concentrations were taken from Carrington et al. (2004). Using data from the U.S Food and Drug Administration and the National Marine Fisheries Service, Carrington et al. (2004) determined the market share and mean mercury concentration

for the 42 most consumed species. These data accounted for 99% of all seafood eaten and were used to simulate the types and mercury concentrations of purchased fresh or frozen fish or shellfish in the model. The data were modified to remove canned tuna as we asked about this type of purchased meal separately. Once the canned tuna had been removed, the market shares were converted into a cumulative probability distribution. Albacore and light canned tuna had their own empirical distributions where the frequency of each observation =1/n. No adjustments were made in purchased fish tissue concentrations for 2010 and 2018. The values used to model the current fish tissue mercury concentrations of purchased fresh or frozen fish or shellfish and canned tuna are presented in the appendix.

2.3 STATISTICAL ANALYSIS

Data were entered into a MS Access database and then exported to MS excel and SAS version 9.1 for analysis. Data were assessed for normality, and because the quantitative variables were not normally distributed, non-parametric tests were used. Comparisons of fish consumption patterns (frequency, amount consumed) grouped by subject characteristics were made by using one-way nonparametric analysis (SAS procedure NPAR1WAY WILCOXON). The p-values reported are from the Kruskal-Wallis test (one-way ANOVA statistic). Spearman correlation coefficients were used to analyze the relationship between continuous variables, and the relationship between categorical variables was assessed with Pearson chi-square analysis. Multiple linear regression analysis was used to evaluate the contribution of the independent variables (age, race, education level, income level, zip code) and the dependent fish consumption variables (frequency, amount consumed). For all test statistics the level of significance was $\alpha = 0.05$.

2.4 RISK ASSESSMENT MODEL

The risk assessment models were designed to evaluate three outcomes: exceeding the reference dose, the loss of IQ points from prenatal exposure to MeHg through the maternal diet, and the change in the relative risk of myocardial infarction in adults over 50. The models simulated the baseline outcomes using the most recent (1999 – 2006) fish tissue Hg concentrations from VA DEQ, and future outcomes using the projected decreases in fish tissue Hg concentration in 2010 and 2018 as predicted by the deposition models.

The sample of 75 anglers who eat self-caught fish was expanded to 222 by including all the household members who were reported to eat the fish caught by the anglers. The gender and age group of all household members was recorded, but the meal frequency and meal size of household members was not asked, so assumptions had to be made for those parameters. It was assumed that household members would eat equally as frequently as the angler, and that adult household members would have the same meal size. Both assumptions increase the uncertainty of estimating MeHg exposure for the household members. These assumptions overestimate exposures for those who consume smaller fish portions and/or less often, and underestimate exposures for those who consume larger meal sizes more often. The meal size and meal frequency of the household members is a source of uncertainty in the analysis that could be improved with a more detailed survey (and possibly different type) for the population of interest.

To model the loss of IQ points from prenatal exposure to MeHg through the maternal diet, the population of interest is women of childbearing age. To approximate this group, the survey results were divided by gender and age group and the subsample from women 16 to 49 years old (n=52) was used for the simulation. Two of the survey results used were from female anglers who had been interviewed; the remaining 50 survey results used were from anglers who reported women 16 to 49 living in their households who ate fish that the angler caught from the river where interviewed. Again, because we did not have the fish meal frequency and meal size for family members, it was assumed that these 50 women had the same meal frequency and

size as their angler. Using the survey results and fish mercury concentrations from VA DEQ's fish tissue database a probability distribution of ingested doses was created through a Monte Carlo simulation.

Instead of using single point estimates of each parameter in a model, Monte Carlo simulations use probability distributions for each parameter. Thousands of trials are run and each time a random value for each parameter is sampled from its probability distribution. Thus, instead of the model resulting in a single value, the simulation produces thousands of possible values. These resulting values can then in turn be described by a probability distribution.

The simulation was done in two loops. The outer variability loop accounted for differences between individuals in terms of eating habits and body weights. The outer loop began by choosing an individual from the subsample (for models 1 and 2 this was women 16 to 49) at random and looking up her reported meals per year of self-caught, purchased, and canned tuna fish, and her corresponding meal sizes reported for each type of fish meal. The number of meals of each type of fish eaten became the number of iterations through the inner loops. For each meal, a mercury concentration was sampled from the fish tissue concentration distribution for the corresponding type of fish, and then multiplied by the individual's reported meal size to get the dose of mercury (in ug) for that meal. The doses for all fish meals were summed to obtain the annual dose (ug/year), and this value was then divided by a bodyweight (kg) chosen from a probability distribution, and averaging time (365 days) to arrive at the average daily intake (ADI). (see equation 1). This average daily intake can then be compared to U.S. EPA's reference dose (0.1 ug/kg/year) which "is an estimate of the amount of a chemical that a person can be exposed to on a daily basis that is not anticipated to cause adverse health effects over a person's lifetime" (U.S. EPA, 2001). The value for the ADI was stored and the outer loop began again with the next individual.

Equation 1: Average Daily Intake ($\mu g/kg\ day^{-1}$):

$$D = \frac{\sum_{i}^{n} (c_i \times s_i \times f_i)}{W \times a}$$

Where n = number of types (species) of fish eaten
c_i = MeHg concentration for the i^{th} species (ug/g)
s_i = meal size for the i^{th} species (g/meal)
f_i = meal frequency for the i^{th} species (meals/year)
W = body weight (kg)
a = averaging time (365 days)

The next step in the model was to convert ADI into blood concentration levels using the one-compartment model (NRC 2000, U.S. EPA 2001). The parameters of the one-compartment model (see equation 2) became assumptions in the Monte Carlo simulation. The simulation was run with two sets of assumptions: point estimates from U.S. EPA's Integrated Risk Information System (model 1), and distributions from Stern 1998 and Stern 2005 (model 2). The assumptions for the two models are shown in table 2.2. Whereas the U.S. EPA point estimates of these parameters are not necessarily gender or pregnancy specific, the distributions used by Stern were chosen to better approximate the values of the parameters for women of childbearing age in the third semester of pregnancy.

Table 2.2 Model Assumptions for Physiological Parameters

Parameter	Model 1 Assumptions: Point Estimates (U.S. EPA 2001)	Model 2 Assumptions: Distributions (Stern 1998, Stern 2005)
$\mathbf{R_h}$ (hair to blood ratio)	0.25	cumulative probability distribution: min: 0.073 max: 0.535
$\mathbf{R_c}$ (cord blood to maternal blood ratio)	1	lognormal (μ: 1.7, σ: 0.9)
b (elimination rate)	0.014 days $^{-1}$	empirical probability distribution: min: 0.009 days $^{-1}$ max: 0.046 days $^{-1}$
V (blood volume)	5 L	cumulative probability distribution: min: 3.707 L max: 7.902 L correlated with W, r=0.49
A (fraction of ingested MeHg that is absorbed)	.95 (unitless)	cumulative probability distribution: min: 0.940 max: 0.999

F (fraction of absorbed MeHg that is distributed in the blood)	0.059 (unitless)	normal (μ: 0.052, σ: 0.0095)
W (body weight)	67 kg	lognormal (μ: 80.9 kg, σ: 16.3 kg)

Equation 2: Blood concentration (μg/L):

$$C = \frac{D \times W \times A \times F}{b \times v}$$

Where D = average daily intake (μg/kg day $^{-1}$)
W = body weight (kg)
A = fraction of ingested MeHg that is absorbed (unitless)
F = fraction of absorbed MeHg that is distributed in the blood (unitless)
b = elimination rate constant (fraction of the concentration eliminated per day (day $^{-1}$)
v = blood volume (L)

The distribution of maternal blood concentrations was then converted into hair concentrations using Equation 3. For model 1 (point estimate model), the value of R was set to 0.25 (or 250:1 hair to blood ratio) as used in U.S. EPA 2001. For model 2, the assumption for R was a cumulative probability distribution; min: 0.073, max: 0.535 (Stern 1998).

Equation 3: Hair Concentration (μg/g):

$$H = C \times R$$

Where C = blood concentration
R = conversion ratio ((μg/g)/(μg/L))

The dose response functions found in the literature result from the analysis of the Faroe Islands study, the Seychelles study, the New Zealand study, or a combination of all three. Results of these analyses are reported as decrease in IQ points per ppm increase in maternal hair mercury.

The distribution of fish tissue concentrations was created from VA DEQ's fish tissue database. Only fish tissue samples that came from the portions of the rivers that roughly corresponded to the area covered by the survey were included; the samples were further filtered

to only include the types of fish reported as being consumed in the survey. It was assumed that the fish caught by VA DEQ were similar to the fish caught by the anglers.

2.5 OUTCOMES TO BE EVALUATED

The present investigation was intended to provide estimates of the fishing behaviors of anglers from Virginia and estimate fish consumption patterns for the purpose of estimating risks from methyl mercury. The fish consumption data were then used with VA DEQ data on fish tissue mercury data to estimate the probability that anglers and family members would be exposed to mercury levels exceeding the U.S. EPA's RfD or VDH recommended safe level. The health outcomes were based on neurological deficit measures as a function of the amount of mercury in hair or in blood, as reported in the literature. The target population was all the people who consumed fish caught recreationally from the eastern rivers targetted because of excess methyl mercury in fish.

3 RESULTS

3.1 SURVEY RESULTS

Quantitative variables of interest (fishing frequency, years fishing, travel distance, number of purchased fresh or frozen meals eaten per year, meal size of purchased fresh or frozen fish, number of canned tuna meals eaten per year, meal size of canned tuna meals, number of meals of self-caught fish eaten per year, and meal size of self-caught meals) were tested for normality. The only quantitative variable that was normally distributed was age – the rest of the variables did not follow a normal distribution, so non-parametric tests were used to test correlations and to test for differences between means.

The overall response rate was 86% completion. Counting against the response rate are 19 anglers who declined to do the survey and 3 anglers who could not complete the survey because of a language barrier (Spanish). Not counted towards response rates:

- 10 people who said it was their first time fishing (ever or on that river)
- people who had already been interviewed
- people who were not fishing on the target river (such as those anglers encountered at West Point who only saltwater fish in the York River)

Fishing frequency:

Fishing frequency was significantly negatively correlated with travel distance ($r = -0.31$, $p<0.0001$) and marginally and negatively correlated with income ($r = -0.16$, $p=0.05$). The mean number of days fishing per year (on the river where interviewed) was 44.13 (n=158, standard deviation = 61.42), ranging from 1 to 364 days per year. There was no difference in fishing effort by race, gender, income level, or whether or not the angler ate his/her catch. There was a significant difference in fishing effort between the rivers ($p=0.005$) and by knowledge of consumption advisories ($p=0.02$). Anglers with knowledge of a consumption advisory (n=83) reported fishing an average of 57.36 days per year, whereas those without knowledge of advisories (n=73) reported fishing an average of 29.06 days per year. The average number of days anglers reported fishing on the river where interviewed can be seen in table 3.1 below:

Table 3.1 Mean Number of Days Fishing per Year

River	N	Mean
Chickahominy	19	42
James	60	66
Mattaponi	39	22
Pamunkey	19	48
Piankatank	21	22

Years fishing:

The number of years the angler reported fishing on the river where interviewed was significantly and positively correlated with his or her age ($r = 0.27$, $p=0.0008$), significantly and negatively correlated with travel distance ($r = -0.25$, $p = 0.001$), and marginally and negatively correlated with his or her education level ($r = -0.16$, $p=0.05$). The overall mean number of years fishing on the river where interviewed was 16 years (n=156, standard deviation = 14.94) with a

range of 0.83 (I month) to 70 years. There was no difference in years fishing by race, gender, income level, river, or whether or not the angler ate his/her catch. There was a significant difference (p=0.02) in years fishing by knowledge of advisory, with those with knowledge of advisories (n=83) fishing having fished an average of 18.26 years on the river, and those without knowledge of the advisory (n=73) having fished an average of 12.49 years on the river.

Travel Distance:

The distance the angler reported having traveled to reach the location where interviewed was significantly and negatively correlated with years fishing (r = -0.25, p = 0.001), but only marginally (p=0.06) and positively correlated with both income level and education level (r = 0.18 and r = 0.15 respectively). The overall mean distance traveled was 18.9 miles (n= 158, standard deviation = 19.39) and ranged from <1 mile to 90 miles. There was no difference in travel distance by race, gender, income level, knowledge of advisory, or whether or not the angler ate his/her catch. There was a significant difference (p=0.04) in travel distance between the rivers, with those anglers fishing on the James having traveled significantly fewer miles. The average travel distances for the five rivers can be seen in table 3.2 below. By looking at the frequency of anglers by their zip code (figure 3.1) is clear that most of the anglers came from the eastern part of Metro Richmond and Gloucester County

Table 3.2 Mean Travel Distance

River	N	Mean travel distance (miles)
Chickahominy	19	27.5
James	60	10.8
Mattaponi	39	20.7
Pamunkey	19	23.9
Piankatank	21	26.6

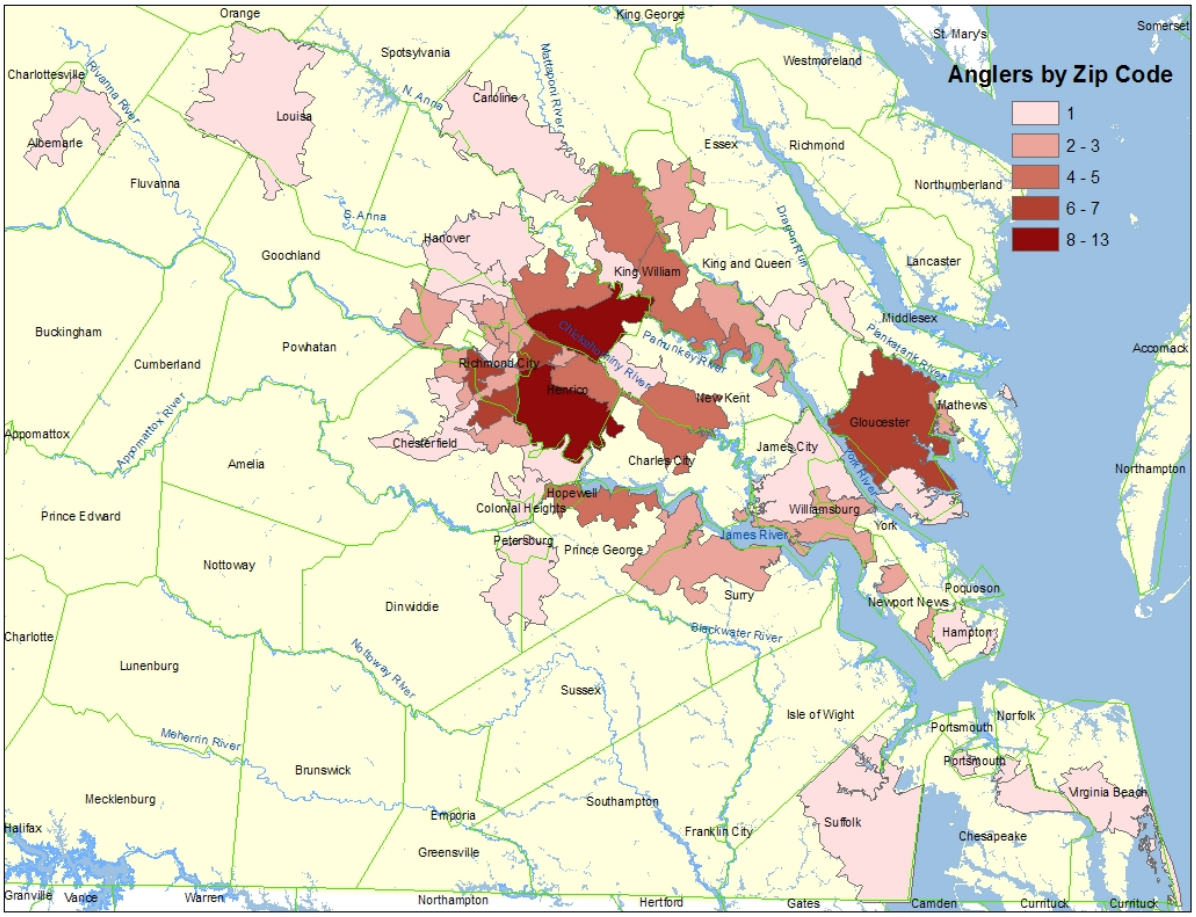


Figure 3. 1. Distribution of anglers by zip code- given as number of anglers in the response group

Consumption of purchased fresh or frozen fish:

The number of meals consumed of purchased fresh or frozen fish significantly and positively correlated with education level when non-consumers were included ($r = 0.20$, $p = 0.01$), but not significantly correlated ($p=0.17$) when the non-consumers were excluded from the analysis. The overall mean number of purchase fresh or frozen meals consumed per year (including non-consumers) was 35 ($n = 155$, standard deviation = 49.04). However, 18 of the 155 respondents to this question (11.6%) reported never eating purchased fresh or frozen fish; when the non-consumers are excluded, the average meals per year of fresh or frozen fish

consumed is 39.85 meals per year (n=137, standard deviation = 50.37). There was no difference in number of purchased meals consumed by race, gender, income level, education level, knowledge of advisory, or whether or not the angler ate his/her catch. There was a significant difference (p=0.04) between the rivers; the number of meals of fresh or frozen fish eaten per year by anglers on the different rivers is shown in table 3.3 below:

Table 3.3 Mean Number of Meals of Purchased Fresh or Frozen Fish or Shellfish per Year

River	N (including non-consumers)	Mean number of meals	N (consumers only)	Mean number of meals
Chickahominy	19	32	16	38
James	58	43	51	49
Mattaponi	38	44	35	48
Pamunkey	19	23	16	27
Piankatank	21	12	19	14

The average meal sizes reported for purchased fresh or frozen fish was 241.8 g per meal (n=138, standard deviation = 161.14). There was no difference in purchased meal size by race, income level, education level, knowledge of advisory, river, or whether or not the angler ate his/her catch. There was a significant (p=0.004) difference in the meal sizes of men (249.08 g, n=126) and women (165.38 g, n=12); however, the small sample size of the women might make this result questionable.

Consumption of canned tuna:

The meals of canned tuna consumed per year was significantly and positively correlated with education level (r = 0.20, p = 0.02) when non-consumers of canned tuna were included, but not significant when the non-consumers of canned tuna were excluded (r = 0.17, p = 0.06). The overall mean number of canned tuna meals eaten per year (including non-consumers of canned tuna) was 29.15 (n = 156, standard deviation = 53.10). Thirty-five anglers (22.4%) reported that they never ate canned tuna fish; when the non-consumers were excluded, the mean number of meals per year was 37.54 (n=121, standard deviation = 57.54) When non-consumers of tuna were included in the analysis, there was a marginally significant (p=0.05) difference tuna consumption between those anglers who ate the fish they caught and those who did not; 24.31

meals per year and 33.92 meals per year respectively; however, this difference was not significant when non-consumers were excluded. There was no difference in tuna consumption by race, income level, gender, knowledge of advisory, or river. The mean canned tuna meal size was reported to be 163.19 g (n=122, standard deviation = 105.59). There was no difference in canned tuna meal size by race or river. Women reported significantly (p=0.02) smaller meal sizes for canned tuna fish (117.45 g, n=14) than men (169.04 g), but again because of the small sample size for women, there is uncertainty with this result. Those anglers who reported knowledge of fish consumption advisories had significantly larger meal sizes of canned tuna: 165.15 g (n=63) versus those who did not know of fish consumption advisories: 160.79 g (n=58).

Consumption of fish caught on the river where interviewed:

While 79 (50%) anglers responded that they "eat fish caught in this river," four of the anglers reported that they had not caught any fish this year; however, they intended to eat the fish when they caught them. Because meal frequency and meal size were not available for these four anglers, the actual number of anglers who eat self-caught fish used in the analysis was 75. Of the anglers who reported eating at least one meal of self-caught fish (n=75), 69 were male (92%) and 6 were female (8%). Of the six females, four reported being over the age of 50, and two were in the 16 – 49 age group.

Percentages of anglers that eat the fish they catch by gender, race, household income, education level, river, fishing mode, and knowledge of advisory

There was no significant difference in the percentage of male and female anglers who reported eating self-caught fish. However, there was a significant difference (p=0.003) based upon the self-reported race of the angler, with 44.41% of white anglers, 66.67% of black anglers, and 78.57% of "other" anglers (Hispanic, Asian, and Native American – grouped for analysis because of their small sample size) eating the fish they caught on the river where

interviewed. For the validity of the chi-square test some of the categories for household income and education level had to be combined. With fewer categories, there was a significant difference in the percent of anglers who ate their catch based upon income (p=0.04) and education level (p=0.02), given in Tables 3.4 and 3.5. Anglers with lower income and lower education levels were more likely to consume fish from the affected waters.

Table 3.4 Percent of Anglers Who Eat Their Catch by Household Income

	Household Income			
Eat fish caught in the river?	**Less than $24,999**	**$25,000 to $49,000**	**$50,000 to $75,000**	**more than $75,000**
No	40%	33.33%	50%	63.46%
Yes	60%	66.67%	50%	36.54%

Table 3.5 Percent of Anglers Who Eat Their Catch by Education Level

	Education Level			
Eat fish caught in the river?	**Less than high school**	**graduated high school**	**some college**	**Bachelors or Masters degree**
No	27%	48%	61%	65%
Yes	73%	52%	39%	35%

There was a marginally significant (p=0.05) difference in whether or not the angler ate his/her catch by fishing mode, with 41.89% of anglers fishing by boat, 48.84% of anglers fishing from a pier, and 65.85% of anglers fishing from the shore reporting that they ate the fish caught from the river where interviewed. There was also a significant difference (p=0.04) in the percent of anglers who ate their catch based upon their awareness of fish consumption advisories, with the anglers who are <u>not</u> aware of the advisories being 1.4 times more likely to eat the fish they catch from the river where interviewed than the anglers who are aware of advisories. There was no difference in whether or not the angler ate his/her catch based upon the river where interviewed.

Table 3.6 Percent of Angers Who Eat Their Catch by Awareness of Advisory

	Aware of advisory	
Eat fish?	**No**	**Yes**
No	41%	58%
Yes	59%	42%

Among the anglers who eat the fish they catch, the mean number of meals per year (of fish caught from the river where the angler was interviewed) was 20.37 (n=75, standard deviation=30.68). There was no difference in self-caught meal frequency size by gender, race, education level, knowledge of advisory, or river, There was a significant (p=0.03) difference in the number of meals of self caught fish eaten per year by household income as seen in table 3.7 below:

Table 3.7 Self-Caught Meals per Year by Household Income

Income range	N	mean	standard deviation	range
less than $14,999	5	20.31	20.16	1 – 49
$15,000 to $24,999	7	33.42	33.56	1 – 84
$25,000 to $49,000	21	32.31	45.55	1 – 200.1
$50,000 to $74,999	22	7.52	8.94	1 – 36
above $75,000	18	18.15	24.28	2 – 96

The mean reported meal size for self-caught fish was 276.59 grams (n=75, standard deviation = 188.01), and this was significantly correlated with meal size of purchase fresh or frozen fish or shellfish ($r = 0.5$, $p < 0.0001$). There was no significant difference in self-caught meal size by gender, race, income level, education level, river, or knowledge of advisory.

Species of recreational freshwater fish most frequently consumed:

Table 3.8 Count of Species Named		
Species Name	**Total**	**Percent**
catfish	44	33.33%
spot or croaker	26	19.70%
sunfish	23	17.42%
largemouth bass	16	12.12%
striped bass	9	6.82%
white perch	7	5.30%
perch (yellow)	6	4.55%
sucker	1	0.76%
Total	132	100.00%

The type of fishes consumed by the anglers was recorded on the survey sheets, but for analysis these fishes has to be condensed into groups. The fish species that make up each group can be found in the appendix. Table 3.8 shows the frequency of fish species as named as a type of fish the angler eats. However, when the number of reported meals of each species or the reported total grams eaten of each species (number of meals x meal size) are considered, the percentages change. For example, “spot or croaker” were ranked as the second

most named type of fish eaten, but when the mass of fish consumed is factored, yellow perch are the second most consumed fish in terms of mass.

Table 3.9 Sum of meals per year		
Species Name	**Total no.**	**Percent**
catfish	704	46%
perch (yellow)	261	17%
spot or croaker	200	13%
sunfish	134	9%
largemouth bass	111	7%
striped bass	84	6%
white perch	25	2%
sucker	9	<1%
Total	1528	100.00%

Table 3.10 Sum of grams per year		
Species Name	**Total grams**	**Percent**
catfish	239425	54%
perch (yellow)	65863	15%
spot or croaker	49727	11%
sunfish	34358	8%
striped bass	24826	6%
largemouth bass	23319	5%
white perch	6394	1%
sucker	3062	<1%
Total	446974	100.00%

Household make-up:

From 158 surveys, the reported number of people in each age group living in the household and the number who eat "fish caught from this river" (the river where the survey took place) are reported below. The ages of pregnant women were not asked, but it is assumed that they are a sub-set of the 16 to 49 age group.

Table 3.11 Percent of Household Members Who Eat Fish Caught from the Survey Rivers

Age group	Total reported living in all households	number of age group who eat caught fish	percent of age group who eat caught fish
5 or younger	46	18	39.13%
6 to 15	88	34	38.64%
50 or older	100	37	37.00%
women 16 to 49	127	54	42.52%
(pregnant women)	*11*	*3*	*27.27%*
men 16 to 49	164	88	53.66%
Total	525	231	44.00%

Table 3.12 Consumers of Caught Fish	
Age Group	**% of Consumers**
5 or younger	8%
6 to 15	15%
50 or older	16%

women 16 to 49	23%
pregnant	1%
men 16 to 49	38%
Total	100%

Demographic Information:

47% of the anglers interviewed were fishing from a boat, 28% from a pier or dock, and 26% from the shore. 90.38% of the anglers were men; 9.62% of the anglers were women. Anglers were asked to self-identify their race, and 6 anglers chose two categories to describe themselves (Table 3.13). In table 3.13 these anglers were counted in both categories. Tables 3.14 and 3.15 show the percentages when these 6 anglers are classified as "other."

Table 3.13 Anglers by Race/Ethnicity

Race/Ethnicity	Survey Results	Statewide 2006 Estimates from Census Bureau
White:	73.08 %	73.34%
Black:	23.08%	19.89%
Hispanic:	3.85%	6.37%
Asian:	0.64%	4.75%
Native American:	3.21%	0.07%

"Other"	Number	Percent
White & Black	3	1.92%
White & Native American	2	1.28%
Black & Native American	1	0.64%
Total		**3.85%**

Table 3.14

Race/Ethnicity	Number	Percent
White	109	69.87%
Black	32	20.51%
Asian	1	0.64%
Native American	2	1.28%
Hispanic	6	3.85%
"Other"	6	3.85%
Total	**156**	**100**

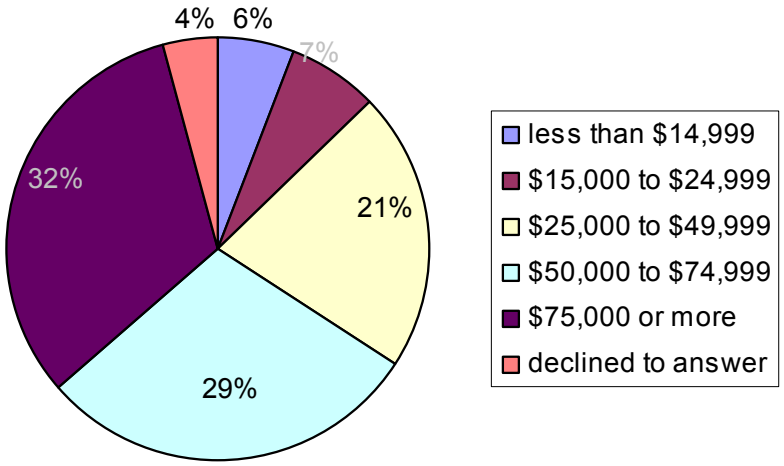
Table 3.15

Because of the low numbers of Hispanic, Asian, and Native American anglers, valid chi-square analysis could not be performed to determine if there is a relationship between race and household income, education level, river, fishing mode, whether or not the angler was fishing for

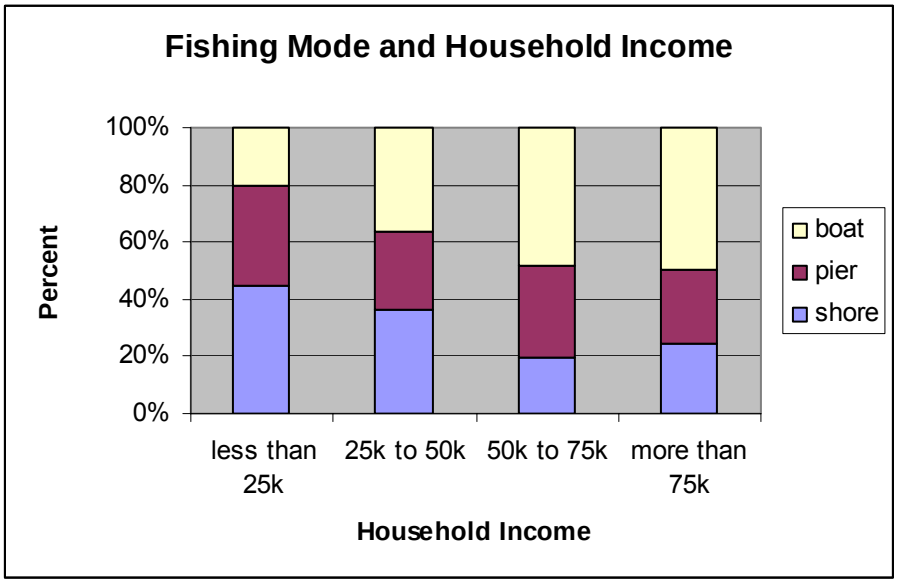
food, or the total number of people living in the household. There was no significant association between race and awareness of consumption advisories, but there was a significant (p=0.003) difference in the races in whether or not the angler gave away any of his/her catch, with 41.28% of white anglers giving away the fish they catch, 53.33% of “other” anglers giving away their catch, and 75% of black anglers giving away their catch.

Household Income: The majority of anglers (61%) self-reported their household income greater than $50,000 (Fig. 3.2). The distribution of household incomes is shown in Fig. 3.2.

Figure 3.2 Household Income



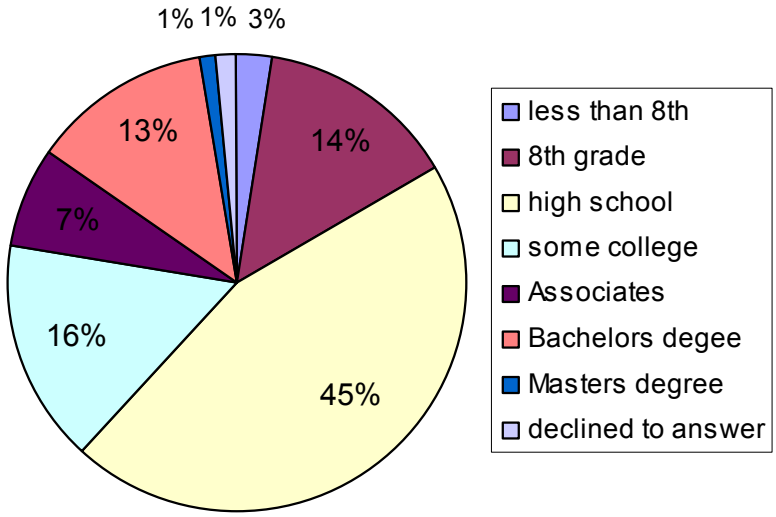
There was a significant difference (p=0.02) in fishing mode by household income, shown in Figure 3.3. The general trend showed that as income increased fishing from the shore decreased and fishing from a boat increased.



There was no significant difference in awareness of advisories or the likelihood of an angler giving fish away by household income.

Education Level: The breakdown in education level can be seen in figure 3.4 below:

Figure 3.4 Education Level



3.2 RESULTS OF RISK ASSESSMENT SIMULATIONS

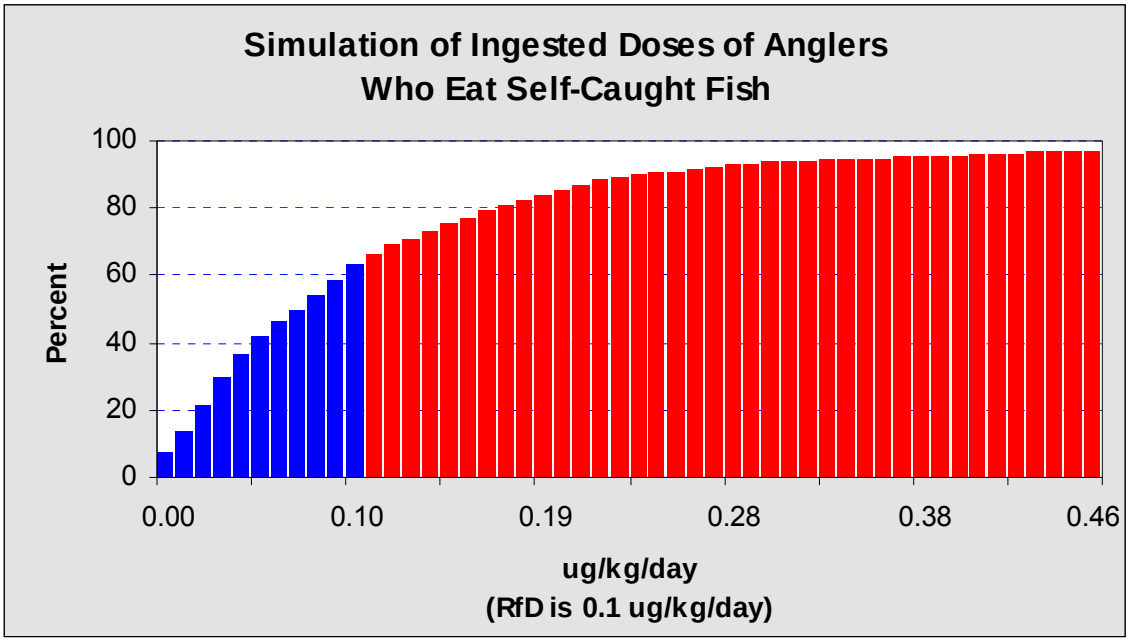
3.2.1 Percent of people exceeding RfD

The total ingested dose (sum of dose from caught fish, purchased fish, and canned tuna fish) can be compared to the reference dose (RfD) of 0.1 ug/kg/day set by the U.S. EPA. The mean values of ingested doses under the baseline scenario and the percent exceeding the RfD in the baseline, 2010, and 2018 scenarios can be seen in table 3.16 below. The distribution of the total ingested doses for all anglers is shown in figure 3.5 (doses above 0.1 ug/kg/day are in red):

Table 3.16 Mean Doses and % Exceeding RfD

Group	Mean Dose (current Hg levels)	% exceeding RfD (current Hg levels)	% exceeding RfD (2010 Hg levels)	% exceeding RfD (2018 Hg levels)
All anglers	0.11	38%	36%	36%
Men 16 to 49	0.10	37%	34%	34%
Women 16 to 49 (model 1)	0.15	49%	45%	44%
Women 16 to 49 (model 2)	0.12	39%	37%	36%
Adults over 50	0.11	39%	37%	36%

Figure 3.5 Distribution of Average Daily Intake of All Anglers



3.2.2 Loss of I.Q. Points

Two models were constructed for the loss of I.Q. points due to in-utero exposure to MeHg from the maternal diet. Model 1 used point estimates for values of the model parameters for body weight, blood volume, fraction of MeHg absorbed, fraction of Hg in blood, elimination rate constant, and blood to hair ratio, and Model 2 used probability distributions for these values. The point estimates are the assumed mean values of these physiological parameters as used by U.S. EPA in the RfD determination (U.S. EPA 2001, NRC 2000). The parameter distributions came from analysis by Alan H. Stern (Stern 1997, 2005). Both models simulated women (16 – 49) who consume fish caught in Virginia's freshwater tidal rivers using the current levels of mercury fish tissue concentrations (baseline scenario), fish tissue levels predicted from mercury deposition in 2010 (scenario 1), and fish tissue levels predicted from mercury deposition in 2018. 10,000 trials were run with forecast set for ingested dose (ug/kg/day), blood concentration (ug/L), hair concentration (ug/g), IQ points lost, and change in IQ points lost.

Blood concentrations were derived from the application of the one-compartment model to the Average Daily Intake Doses derived for comparison with the RfD. For Model 1 (mean values of physiological parameters) in the baseline scenario blood concentrations ranged from 0 to 33 ppm, with the mean concentration being 6 ppm and the median being 4 ppm. Under scenario 1 (2010 fish tissue mercury levels), the mean blood concentration was 5.3 ppm and the median concentration was 3.5 ppm. Under scenario 2 (2018 fish tissue mercury levels), blood concentrations dropped further to a mean of 5.25 ppm and a median of 3.4 ppm.

For Model 2 (probability distributions for values of physiological parameters), in the baseline scenario they ranged from 0 to 47 ppm, with the mean concentration being 5.4 ppm and the median being 3.4 ppm. Under scenario 1 (2010), the mean blood concentration was 4.9 ppm and the median concentration was 3.0 ppm. Under scenario 2 (2018), blood concentrations dropped further to a mean of 4.8 ppm and a median of 2.9 ppm.

Hair concentrations showed a similar decrease in the three scenarios as seen in tables 3.17 and 3.18 below:

Table 3.17 Hair Concentrations from Model 1 (Point Estimates of Parameters)

Hair Concentration (ug/g) from Model 1				
Scenario	**Range**	**Mean**	**Median**	**StDev**
baseline	0 – 8.3	1.49	1.00	1.15
scenario 1	0 – 8.3	1.33	0.87	1.35
scenario 2	0 – 8.3	1.31	0.85	1.33

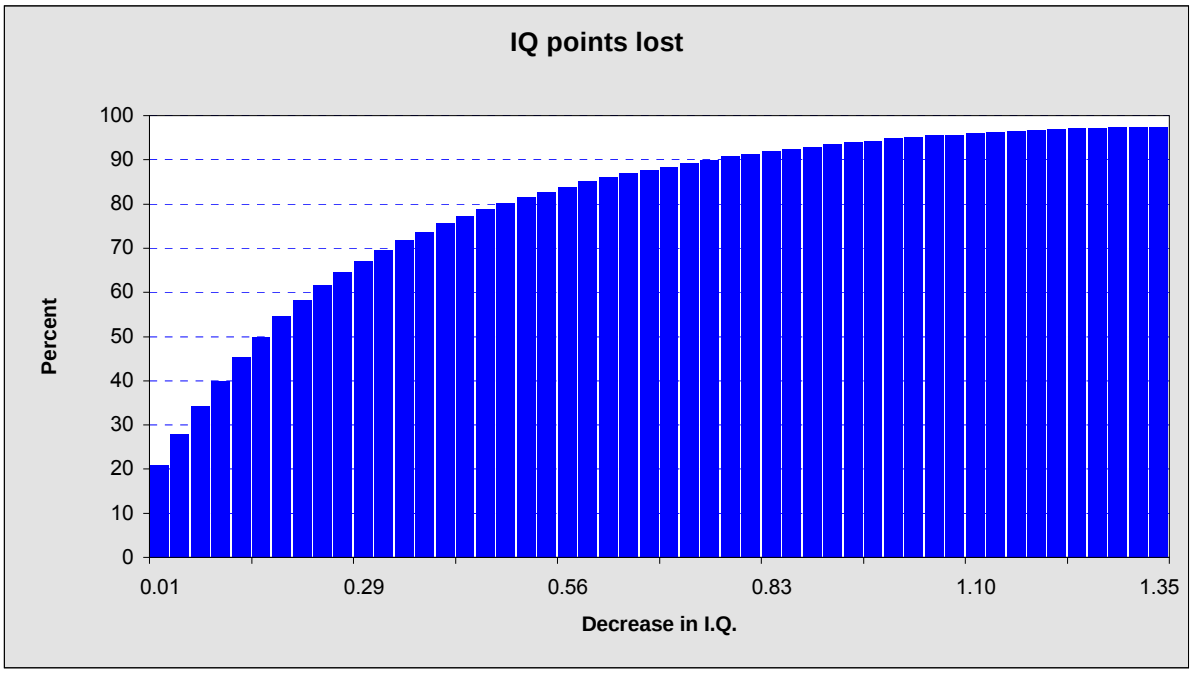
Table 3.18 Hair Concentrations from Model 2 (Distributions of Parameters)

Hair Concentration (ug/g) from Model 2				
Scenario	**Range**	**Mean**	**Median**	**StDev**
baseline	0 – 25	1.77	1.06	2.07
scenario 1	0 – 25	1.59	0.94	1.87
scenario 2	0 – 25	1.56	0.91	1.85

Hair concentrations were then converted into IQ points lost using the dose response function of -0.18 IQ points for each ppm increase in maternal hair mercury (Axelrad et al., 2007). The predicted IQ points lost in model 1 for the baseline scenario ranged from 0 to 1.49, with the

mean IQ points lost predicted to be 0.27 points and the median predicted to be 0.18 points lost. The predicted IQ points lost in model 2 for the baseline scenario ranged from 0 to 4.53, with the mean IQ points lost predicted to be 0.32 points and the median predicted to be 0.19 points lost. The distribution of IQ points lost from the simulation of Model 2 is shown in figure 3.6 below:

Figure 3.6 Distribution of I.Q. Points Lost to Children of Women 16 to 49 Who Consume Fish from the Survey Rivers

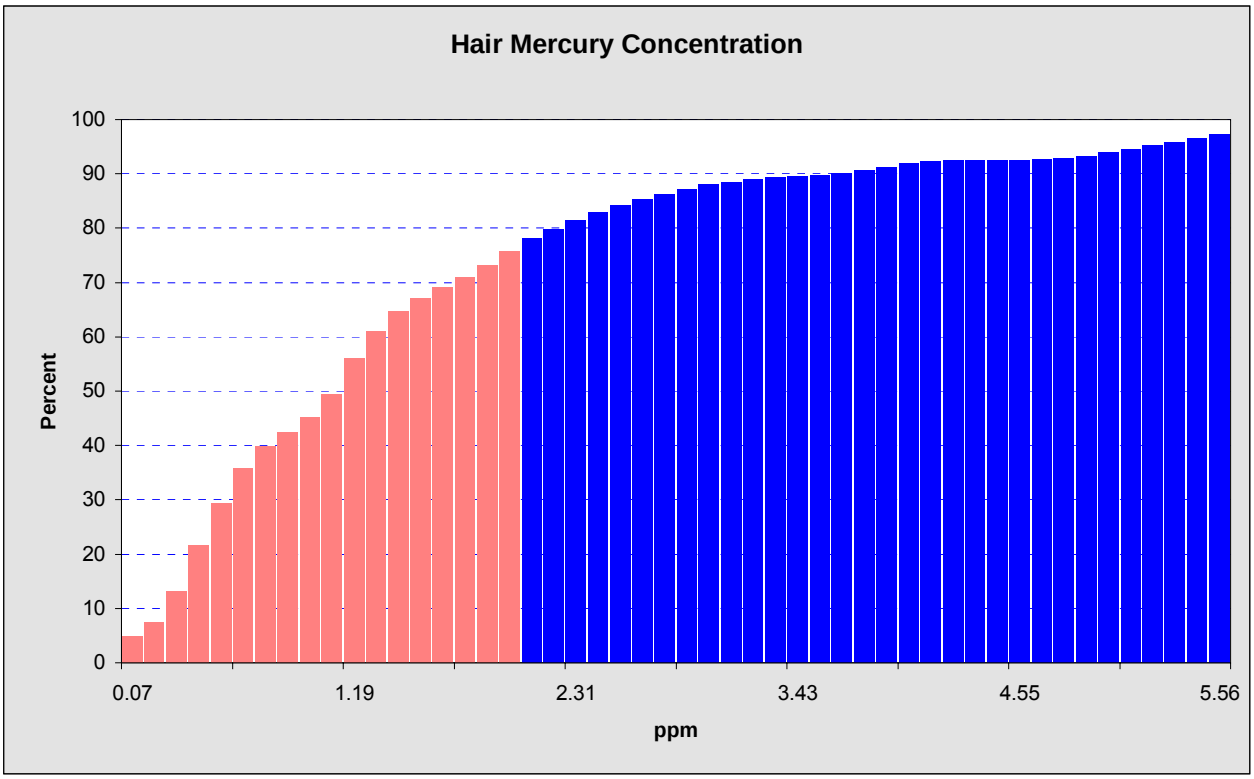


Changes in IQ points lost were then calculated for both models under scenarios 1 and 2. The mean of scenario 1 for both models was an improvement of 0.03 IQ points over the baseline scenario; the median was 0.01 IQ points. Under scenario 2 the mean IQ improvement was 0.03 over the baseline scenario for model 1 and 0.04 for model 2; the median was again 0.01 for both models.

3.2.3 Increased Risk of Acute Myocardial Infarction

To calculate the increased risk of Acute Myocardial Infarction we focused on the percent of adults over 50 that the model predicted would have greater than 2 ppm of hair mercury.

Figure 3.7 Distribution of Mercury Hair Concentrations of People Over 50 Who Consume Fish from the Survey Rivers



Under the baseline scenario, 22% of the adults 50 and over are predicted to have hair mercury concentrations over 2 ppm. This percentage drops by 2% to 20% exceeding 2 ppm with the lower fish tissue mercury concentrations predicted starting in 2010.

3.3 SENSITIVITY ANALYSIS

The sensitivity of the models to the variability of the parameters was tested by setting each parameter value, in turn, to a fixed value (the mean), and then comparing the results of

that run of the model to the results of the full model. The sensitivity analysis was done on the Women 16 to 49 model 2, since it had the largest number of variable model parameters. Sensitivity was determined by calculating the percentage difference in the 99th to 50th percentile ratio of the Improvement in I.Q. points in 2010 between the results with each parameter frozen and with the full model. The self-caught fish meal frequency, meal size, and mercury concentration of Virginia fish contributed most to the variability of the model as seen in table 3.20.

Table 3.20 Sensitivity Analysis

Parameter	Contribution to Variability
blood volume	5.13%
blood fraction	-1.14%
fraction abosorbed	0.46%
elimination rate	2.98%
body weight	10.39%
hair-to-blood ratio	6.96%
caught fish Hg	32.15%
caught meal frequency	76.27%
caught meal size	36.84%
purchased fish Hg	4.57%
purchased fish freq.	-0.15%
purchased meal size	4.43%
tuna Hg	3.71%
tuna meal freq.	-0.37%
tuna meal size	1.82%

4 DISCUSSION

4.1 OBSERVATIONS FROM SURVEY

Several qualitative observations from the survey were not captured in the statistical results or risk assessment results. Although we only recorded 3 anglers who could not complete the survey because of a language barrier, the number of non-English speakers is potentially greater as these men were accompanied by 4 -8 people (women and children) who were assumed to

be family members). At other times at Ancarrows Landing, one member of a group of 4 or more people who were Spanish speakers was able to speak English, and volunteered to translate the survey. In these circumstances we only obtained one survey for the group, as translation was time consuming and the group identified themselves as all living in the same household with one person doing most of the fishing. Awareness of fish consumption advisories was very low among the Spanish-speakers at Ancarrows; we also did not see any consumption advisory signs written in Spanish. Also, during the time that we visited the survey sites (May through September of 2007) we observed that almost all of the posted signs did not have the current fish consumption advisory; the exceptions being the bridge crossings on the Dragon Run and at West Point.

Regardless of whether or not there was a consumption advisory sign posted, many of the anglers had similar comments on their perception of the risk of fish consumption. Several anglers told us that if it were dangerous to eat fish, there would be a sign along the river bank (when in fact, the signs were at the boat ramp or in the parking lot). Also, there was a perception that the "water is dirty in Richmond, but clean downstream," (or on the other rivers). Some anglers acknowledged that the fish may be contaminated, but they were convinced that proper cleaning of the fish would remove the contaminants.

Many of the anglers wanted to talk about other environmental problems, and several (especially at West Point) mentioned that they perceived a decline in the quality and quantity of fish over the last decade. However, other anglers on the James River talked about the great improvements in water quality since they were children.

At least two anglers expressed a concern that the results of the survey could be used to put restrictions on recreational fishing. The survey team responded with a non-committal explanation that repeated the initial information about the purpose of the survey.

Many of the anglers who said they did not eat the fish they caught on the river where the interview was conducted reported that they <u>did</u> eat salt-water fish they caught in salt water

estuaries, the Chesapeake Bay or in the Atlantic Ocean. The survey was not designed to capture information about self-caught fish consumed from other regions. A longer and more detailed survey would be necessary to compare recreationally caught freshwater and salt-water fish.

4.2 UNCERTAINTY

Any risk assessment has areas of uncertainty that include the data, assumptions and equations that make up the quantitative inputs. Uncertainty can be expressed either qualitatively or quantitatively and we present here a qualitative discussion of the uncertainties that complements the preceding sensitivity analysis (section 3.3). The three basic areas of uncertainty in this risk assessment are the empirical data, the equations used to estimate biological processing of MeHg, and the assumptions about mercury processes in the environment.

Empirical data: fish tissue MeHg levels

VA DEQ collects fish tissue samples and has the tissues analyzed for total mercury, Hg. The tissues contain mercury in both the metallic form, Hg, and the organic or methylated form, MeHg. Detailed chemical analysis indicates that on average, more than 90% of the total mercury is in the methylated form, MeHg, and VA DEQ makes the simplifying and conservative assumption that all mercury is MeHg. Some of the samples will actually have more than 90% and other samples less than 90% MeHg. A proportion of the samples will have close to 100% MeHg. The assumption of 100% is a source of uncertainty as a systematic over-estimate of exposure.

The fish sampling effort is able to collect enough fish to provide a general trend for the species and sizes collected. The sampling effort is not able to collect and analyze enough samples for a comprehensive description of the mercury contamination

for all sizes and ages of species in all the rivers of interest. The result of using these empirical data is the inherent uncertainty of the data. One of the areas of uncertainty in the data set is the relationship between fish age and MeHg levels. This uncertainty represents possible changes in both directions- actual MeHg levels may be both higher and lower than the reported values.

Empirical data: fish consumption surveys

The analysis assumes that the women in the household ate as much fish as did the men, yet there were limited direct information from the surveys on women's fish consumption. This assumption is most likely an error of overestimate of exposure. The assumption of all members of the angler families eating the same canned tuna is also likely wrong and the nature of that error is unknown. The fact that the consumption advisory for women of child-bearing age to limit tuna intake has been in place for some time may have changed their behavior and not be reflected in the survey. By the same token, men's consumption of canned tuna may be less than reported. One problem with creel surveys is gathering data on family behaviors based on one member of the group. Most of the anglers were men and the target group of women of child bearing age were not highly represented in the angler group.

Creel surveys also rely on recall of fish consumption over an entire year. There will be some error in these data because of imperfect recall.

Equations:

The equations assume that the processes as described are accurately represented. The equation for MeHg accumulation and distribution assumes steady-

state and a one compartment distribution. Although these assumptions seem to be met for many conditions, both assumptions may not represent actual events in all people in the groups of interest.

Environmental processes:

This analysis assumes that the processes causing MeHg start with elemental mercury emissions that cause deposition into the watersheds of the eastern waters of Virginia. The assessment further assumes that mercury deposited is converted to MeHg under the reducing conditions present in the rivers surveyed. The analysis also ssumes that MeHg is taken up via ingestion of food and water intake and accumulates in tissues of fish and other aquatic animals. The projections of mercury levels in 2010 and 2018 assume that there is a direct relationship between emission reductions and fish tissue concentrations. These assumptions are based on research in other ecosystems that are not identical to those in the eastern Virginia rivers studied here. The mercury in fish tissues may have a larger component from direct discharge sources in the James River, or from legacy sediment accumulation in any of the rivers. The systems may not be as responsive to the emission reductions and greater or lesser fish tissue concentrations may result.

4.3 RECOMMENDATIONS

The Department of Environmental Quality (VA DEQ) may want to consider several efforts to expand and complement the work conducted here on methylmercury in fish from Virginia waters. The areas for VA DEQ to consider include the following:

- This survey had limited direct response from a target group- women of child bearing age and none from children; additional survey data could be obtained directly from these groups.
- Design and conduct a fish consumption survey for non-English speaking anglers, concentrating on the James River below Richmond.
- Extend the survey area to include regions such as near the Blackwater River and the Dismal Swamp and the waters that have more recently come under consumption advisories for methylmercury contamination.
- Contact the appropriate Native American tribes and work cooperatively with their leaders in conducting a fishing survey for tribal members.
- Conduct a cumulative risk assessment for the angler group most at risk from methylmercury contamination. The cumulative risk assessment should include, but not be limited to, the interactions of multiple chemicals in fish, existing health conditions, and socio-economic status.
- There is an advantage to continuing to survey in the regions covered by this study – portions of the James, Chickahominy, Piankatank, Pamunkey, Mattaponi. Additional data could reduce the uncertainties in this investigation as well as increase sample size for the groups and areas with the lowest representation.

The present study was able to survey more than 150 recreational anglers and gather information on their fishing and fish consumption patterns in areas east of Interstate 95 that are under fish advisories for methylmercury. The scope of this investigation did not permit surveying family members, more individuals or a wider range of waters or for a longer period. As a result, it is necessary to estimate fishing efforts and consumption rates for the entire year and for other areas. These estimates are a source of uncertainty in the fish consumption estimates and

subsequent exposures. Additional survey data would reduce the uncertainties resulting from limiting the surveys in time and space.

Family members:

Anglers were predominantly male, and one target group is women of child bearing age. The survey did ask for information on fish consumption by family members, but this information is still second-hand and was not obtained directly from the family members. A modified survey of a different nature (not an intercept survey) would need to be used to obtain information directly from the family members of the anglers who fish the rivers in the area of interest.

Another target group is children of the anglers and there are limited data in the literature on this group. The EPA Exposure Factors Handbook is the most widely used source, but direct data could be obtained through a survey that obtained food consumption information from families of anglers in eastern Virginia.

Non- English speaking anglers:

During the field survey, the investigators identified a number of people fishing who did not speak English, or who spoke English so poorly that the survey instrument could not be administered. These anglers were fishing on the James River at Ancarrow's Landing and their native language was Spanish or a Spanish-based language. Surveyors identified only a few of these anglers who could speak English sufficiently well to administer the questionnaire. Important information could not be collected because of the language barrier and the survey team observed that these anglers seemed to be catching a variety of species. We believe that there is a population of Spanish speaking people who are catching and consuming fish with

higher levels of methylmercury, and an investigation into this group would provide important information to help VA DEQ estimate methylmercury exposure via fish consumption.

Survey Additional Waters:

The present study was able to survey more than 150 recreational anglers and gather information on their fishing and fish consumption patterns in areas east of Interstate 95 that are under fish advisories for methylmercury. The scope of this investigation did not permit surveying more individuals or a wider range of waters or for a longer period. As a result, it is necessary to estimate fishing efforts and consumption rates for the entire year and for other areas. These estimates to other waters and groups are a source of uncertainty in the fish consumption estimates and subsequent exposures. Additional survey data would reduce the uncertainties resulting from limiting the surveys in time and space.

Fish consumption advisories for mercury (specifically methylmercury) are presently in place for the waters survey in this investigation (James, Chickahominy, Pamunkey, Mattaponi and Piankatank Rivers) and several other waters or waters bodies. The other waters include Harrison Lake, Blackwater River, Dismal Swamp/Lake Drummond, Herring Creek, Lake Gordonsville, Lakes Trashmore and Whitehurst and the Nottoway River. The present investigation did not survey these other waters because the warnings were issued only recently or the budget did not permit more survey sites, or both. Further investigations of fishing and fish consumption from these waters would provide a more complete understanding of the nature and extent of the situation in Eastern Virginia.

Native Americans:

Investigators attempted to survey the Native American tribes who reside in the affected areas specifically, in addition to the general survey of anglers on the rivers. This effort was not successful, and only 2 of the survey respondents identified themselves as Native Americans.

Three tribes have historically used local waters for fishing, and the Pamunkey and Mattaponi have reservations on the respective rivers, where the tribal members use of the river is expected to be substantial. The information gained from surveying the tribes would make an important addition to understanding the effects of methylmercury on the health of anglers in eastern Virginia.

Cumulative Risks:

The present assessment was a single chemical, single scenario risk assessment. We used a field survey of fishing behaviors with measurements of methylmercury levels in fish to estimate health risks to people consuming fish caught in waters where we surveyed. This type of risk assessment estimates risks from a single chemical and examines the single exposures pathway- fish consumption. Other factors that influence how methylmercury in fish affects the health of the consumers were not examined. Methylmercury exposures from fish consumption were not examined within the context of other chemical contaminants, life style issues or other existing conditions that affect health (i.e., nutrition).

Risks in the context of how an individual, group or population is affected by aggregate conditions and exposures are classified as cumulative risk, an area that U.S. EPA is presently developing in response to input and comments from the National Academy of Sciences, Congress and the U.S. EPA Science Advisory Board (see U.S. EPA 2003). U.S. EPA published initial processes for examining cumulative risk in the Framework for Cumulative Risk Assessment (U.S. EPA 2003). In the Framework, U.S. EPA (2003) defines cumulative risk as "the combined risks from aggregate exposures to multiple agents or stressors." U.S. EPA further notes that cumulative risk assessment deals with multiple stresses, that all stresses need not be chemical and that the risks from the different stresses are combined. In the context of the present assessment, cumulative risk assessment could include multiple chemical contaminants in the fish caught from Virginia waters, existing disease burden in the group of people

consuming the fish, psycho-social stress of the consumers, and other factors combining to increase the risks to fish consumers. Cumulative risk assessment was outside the scope of the present investigation. VA DEQ could pursue the matter of a cumulative risk assessment for the anglers in the highest risk category- those who are consuming catfish and large mouth bass from the affected areas in Eastern Virginia.

The experience of health risk assessment in the US has demonstrated that some individuals or groups may respond to a given stress with more adverse responses than would ordinarily be anticipated. Some individuals are more sensitive due to their biological/genetic make-up, and other people simply cannot cope or respond to a stress situation. The greater sensitivity is the case for children because of their developmental stage. Taken together, these types of responses are considered vulnerability.

Risk assessment procedures generally account for greater sensitivity in many cases by applying a safety factor that essentially lowers the threshold concentration for effects. In other words, if the general population is protected from effects of methylmercury at a daily dose of 1.0 ug/kg-day, then applying a safety factor of 10 would lower that daily dose to 0.1 ug/kg-day (as done by U.S. EPA). The basis for using this approach has been that sensitive individuals respond with an adverse effect at a lower dose (or at a lower concentration). U.S. EPA-derived reference doses attempt to incorporate safety factors for sensitive individuals as possible, and state criteria likewise include some provision for protecting sensitive individuals and groups.

Vulnerability goes beyond biological or toxicological sensitivity and has four major elements: multiple exposures (i.e., chemical), differential exposures, inability to respond, and inability to recover (Kasperson et al., 1995; see also U.S. EPA 2003.) Multiple and differential exposures are aspects of the environmental conditions to which an individual or group is subjected. Vulnerability is an important element of risk assessment that is exposed. Response and recovery deal with properties of the group or individual and are frequently inherent, such as genetic disposition, immune responsiveness or psychological makeup (see deFur et al., 2007).

Vulnerability is an important element of risk assessment that has not been well investigated for either single chemical or cumulative risk assessments (deFur et al., 2006, Kasperson et al., 1995; see also U.S. EPA 2003). In the present investigation, some groups or individuals may be more vulnerable to the effects of methylmercury as a result of poor nutrition (Chapman and Chan 2000)

Multiple chemical exposures:

This investigation and the resulting estimated risks address only the health consequences from exposure to one chemical, methylmercury via consumption of fish. In this regard, the investigation was simplistic by intentionally limiting the work to a single chemical and a single exposure pathway. Data from VA DEQ's fish tissue monitoring program indicate that other chemicals (http://www.deq.virginia.gov/fishtissue/fishtissue.html) are also found in some fish tissues of some fish. A review of the VA DEQ website that provides data on some chemical contaminants in fish tissues indicates that several other chemicals co-occur with methylmercury in fish in Eastern Virginia. Specifically, specifically PCB's occur in catfish in the James River at levels that warrant fish consumption advisories. Kepone is still found in some James River fish species at low levels and arsenic has been reported in several areas. These results are summarized in the following Table of data from the VA DEQ web site.

Table 4.1 Compounds found in mercury-contaminated fish in southeastern Virginia waterways
Data from http://www.deq.state.va.us/fishtissue/fishtissue.html
Searched data for James, Chickahominy, Mattaponi, Pamunkey, Piankatank, Blackwater Rivers, Harrison Lake, Dismal swamp

Waterbody	Location	Species	Contaminants Co-occuring w/ Hg
James River	I-95 Bridge	Striped Bass Blueback Herring Hickory Shad	Arsenic
		Striped Bass Blueback Herring	PCBs

		Hickory Shad	
	Richmond	White Perch Striped Bass	Kepone
Pamunkey Creek	Lake Anna near State Park	Largemouth Bass	Arsenic
		Channel Catfish Striped Bass	PCBs
Blackwater River	Near VA state-line	Bowfin	Arsenic

In addition, Garman et al. (1998) reported that catfish from the tidal freshwater James River in the vicinity of Hopewell had elevated levels of DDT, PCBs, and TBT, in addition to MeHg. These chemicals all target the nervous system and/or reproductive system in fish, mammals and other animals.

The most significant issue regarding the co-occurrence of multiple chemicals is likely that some of the chemicals act on the same target, especially the developing brain or reproductive system. PCBs (Schantz, Widholm and Rice, 2003) and methylmercury (see discussion above, and NRC 2000), two contaminants found in fish in Eastern Virginia; both affect the developing brain, each causing a reduction in cognitive function. The effects of combined exposure to both PCBs and methylmercury on neurological function, including I.Q. have been investigated in a few laboratory studies and in two epidemiological investigations (Grandjean et al., Stewart et al., 2003). The results suggest but do not confirm the combined exposures add to the impact on the developing brain of young children and fetuses. This exposure scenario likely occurs in Virginia anglers who catch fish from waters with fish advisors for both PCBs and methylmercury. The effects may be additive, synergistic (the combination greater than additive) or one may reduce the effect of the other. Future work could assess the combined effects by considering each option as a possible scenario in estimating health outcomes from such exposures.

Continue 2007 Surveys:

Uncertainties in the present work result from the limited sample size, period over which the surveys were conducted and the few locations that could be surveyed (sampled). Most of the uncertainty is sampling uncertainty, meaning whether the data obtained here are truly able to represent the range of responses and central tendency of the responses (averages). Larger sample sizes could be obtained by using the same survey instrument in subsequent years with the intent of interviewing new anglers who were not survey in 2007 in this investigation.

Another goal of continuing surveys in the same waterbodies next year could be to confirm the data from 2007 by administering a confirmation survey to anglers who had participated in the 2007 survey. Such a confirming survey would be designed differently and would have to be newly designed to ask new questions to obtain information that can act to confirm the 2007 information.

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6 Appendix

6.1 Angler Survey (Example from the Mattaponi River)

Surveyor Name: **SURVEY NUMBER:**
Survey Location: Time Begin:
Date: Time End:
Day of Week: Length of Interview:
Gender: Fishing Mode?
☐Male ☐Female ☐Shore ☐Pier ☐Boat

My name is _____ *(first name).* **I'm with the VCU fishing survey team. We're talking to people who fish here to learn how Virginia's rivers are used for fishing. Can I have about 10 minutes of your time to ask you some questions? All of your answers will be confidential and anonymous.**

Thank you! Before we start, I just want to make sure that you haven't already been interviewed by our team sometime this summer. Have you been interviewed by one of us before?
IF YES, TERMINATE INTERVIEW. IF NO, CONTINUE

FOR ALL QUESTIONS: UNLESS OTHERWISE NOTED, READ RESPONSE OPTIONS ONLY IF RESPONDENT HAS TROUBLE ANSWERING.

1. How many miles did you travel to get here today?

_____ miles

2a. During this season or last season, have you fished on… *(read locations)*

Harrison Lake	☐Yes ☐No
the James River	☐Yes ☐No
the Chickhominy	☐Yes ☐No
the Pamunkey River	☐Yes ☐No
the Dragon Run	☐Yes ☐No
Blackwater River	☐Yes ☐No

b. Where else in Virginia have you fished this season or last season?

_____

3. How often do you fish on the Mattaponi River?

_____ times per ☐week ☐month ☐year

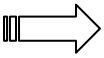
4. Think back to the first time you fished on the Mattaponi River. Can you tell me how many years you have fished on the Mattaponi River?

_____ ☐months ☐years

We are also interested in knowing how much fish you eat. In this survey, when I talk about fish meals I mean any fish that is consumed for breakfast, lunch, dinner, or snacks.

5. Do you eat any of the fish that you catch in the Mattaponi River?

☐Yes ☐No *(skip to question 10)*



6. On average throughout the year, how many of your meals include fish that you catch in the Mattaponi River?

_____ meals per ☐week ☐month ☐year

☐ Don't Know

7. Is the primary reason you come fishing here to get food to eat?

☐Yes ☐No

8. When fishing on the Mattaponi River, what types of fish do you catch and eat most frequently? You can name up to four. I have pictures of some of the fish, but you can name any fish that you catch here and eat frequently. *(show fish species visual aid)*

What fish do you catch and eat most frequently?	**Which months of the year do you catch and eat the *MOST* _____?**	**and how frequently do you eat a meal of _____ during these months?**	**How much_____ do you typically eat during a meal?**
a)	☐Jan ☐Feb ☐Mar ☐Apr ☐May ☐ all the same ☐Jun ☐ don't know ☐ Jul ☐Aug ☐Sep ☐Oct ☐Nov ☐Dec	_____ meals per ☐ week ☐month *(refer to fish species visual aid)*	_____ oz. per meal *(show meal size visual aid)*
b)	☐Jan ☐Feb ☐Mar ☐Apr ☐May ☐ all the same ☐Jun ☐ don't know ☐ Jul ☐Aug ☐Sep ☐Oct ☐Nov ☐Dec	_____ meals per ☐ week ☐month *(refer to fish species visual aid)*	_____ oz. per meal *(show meal size visual aid)*
c)	☐Jan ☐Feb ☐Mar ☐Apr ☐May ☐ all the same ☐Jun ☐ don't know ☐ Jul ☐Aug ☐Sep ☐Oct ☐Nov ☐Dec	_____ meals per ☐ week ☐month *(refer to fish species visual aid)*	_____ oz. per meal *(show meal size visual aid)*

d)

☐Jan
☐Feb
☐Mar
☐Apr
☐May
☐Jun
☐ Jul
☐Aug
☐Sep
☐Oct
☐Nov
☐Dec

_____ meals per

☐ week ☐month

☐ all the same

☐ don't know

_____ oz. per meal *(show meal size visual aid)*

(refer to fish species visual aid)

9. Are there any kinds of fish from this river that you won't eat?

☐Yes *(CONTINUE)* ☐No
If yes, **what kind?**

_____

10. *(Ask about these specific fish if they were not mentioned in the question above and point to their pictures on the visual aid)*

Do you ever eat bowfin? ☐Yes ☐No

…chain pickerel? ☐Yes ☐No

…longnose gar? ☐Yes ☐No

…gizzard shad? ☐Yes ☐No

…alewife? ☐Yes ☐No

11. We also want to know if anyone else in your household eats the fish that you catch in the Mattaponi River, so I am going to ask you how many people are in your household. Please include yourself in this count.

A. How many people in your household are…
B. …and how many eat fish from the Mattaponi River?

	A.	**B.**
a) children 5 or younger?		
b) children between the age of 6 and 15?		
c) adults aged 50 or older?		
d) men between the ages of 16 and 49?		
e) women between the ages of 16 and 49?		
f) women who have been pregnant in the last year?		

13. Do you give away any of the fish that you catch in the Mattaponi River?
☐Yes ☐No

14. We would also like to know how often you eat fish that you buy in a store, a market, or a restaurant.

a. On average throughout the year, how often do you eat a meal of fresh or frozen fish or shellfish that you bought in a store, a market, or a restaurant?

_____ meals per ☐week ☐month ☐year ☐ Don't Know

b. How much fresh or frozen fish or shellfish do you typically eat during a meal? *(show visual aid)*

_____ oz. per meal

15a. On average throughout the year, how often do you eat a meal of canned tuna fish?

_____ meals per ☐week ☐month ☐year ☐ Don't Know

b. Do you eat light tuna or white tuna? White tuna is also called albacore tuna.

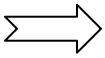
☐light ☐white ☐both ☐ don't know

c. How much canned tuna fish do you typically eat during a meal? *(show visual aid)*

_____ oz. per meal

16. Do you know that there is a fish consumption advisory on this river?

☐Yes ☐No *(skip questions 17 and 18)*



17. How do you know about the advisory?

☐posted signs
☐word of mouth
☐newspaper
☐radio
☐other _____

18. Do you know what the advisory is on this river?

[Because of Mercury No more than two meals/month: Largemouth Bass]

[Because of PCBs] No more than two meals/month: Anadromous (coastal) Striped Bass, White perch, Gizzard Shad]

[High risk individuals such as women who are pregnant or may become pregnant, nursing mothers, and young children are advised not to eat any fish contaminated either with polychlorinated biphenyls (PCBs) or mercury from the respective advisory areas.]

☐Answered correctly ☐Answered incorrectly

⇨ **We are almost done with the survey, but we would like to get information to classify your answers. Remember that all your answers are entirely confidential and anonymous.**

19. What is your zip code? _____

20. How old are you? _____

21. How would you describe your race or ethnicity? *(check all boxes respondent says)*

- ☐ White/Caucasian
- ☐ Black/ African American
- ☐ Asian
- ☐ American Indian/ Native American
- ☐ Other:
- ☐ Hispanic/ Latino

22. What is the highest degree or level of school that you have completed?

- ☐ Less than high school
  if yes **Did you leave school after the eight grade?**
  ☐ Yes ☐ No
- ☐ High School
- ☐ Some College
- ☐ Associates degree
- ☐ Bachelor's degree
- ☐ Master's degree
- ☐ PhD, M.D., or professional degree

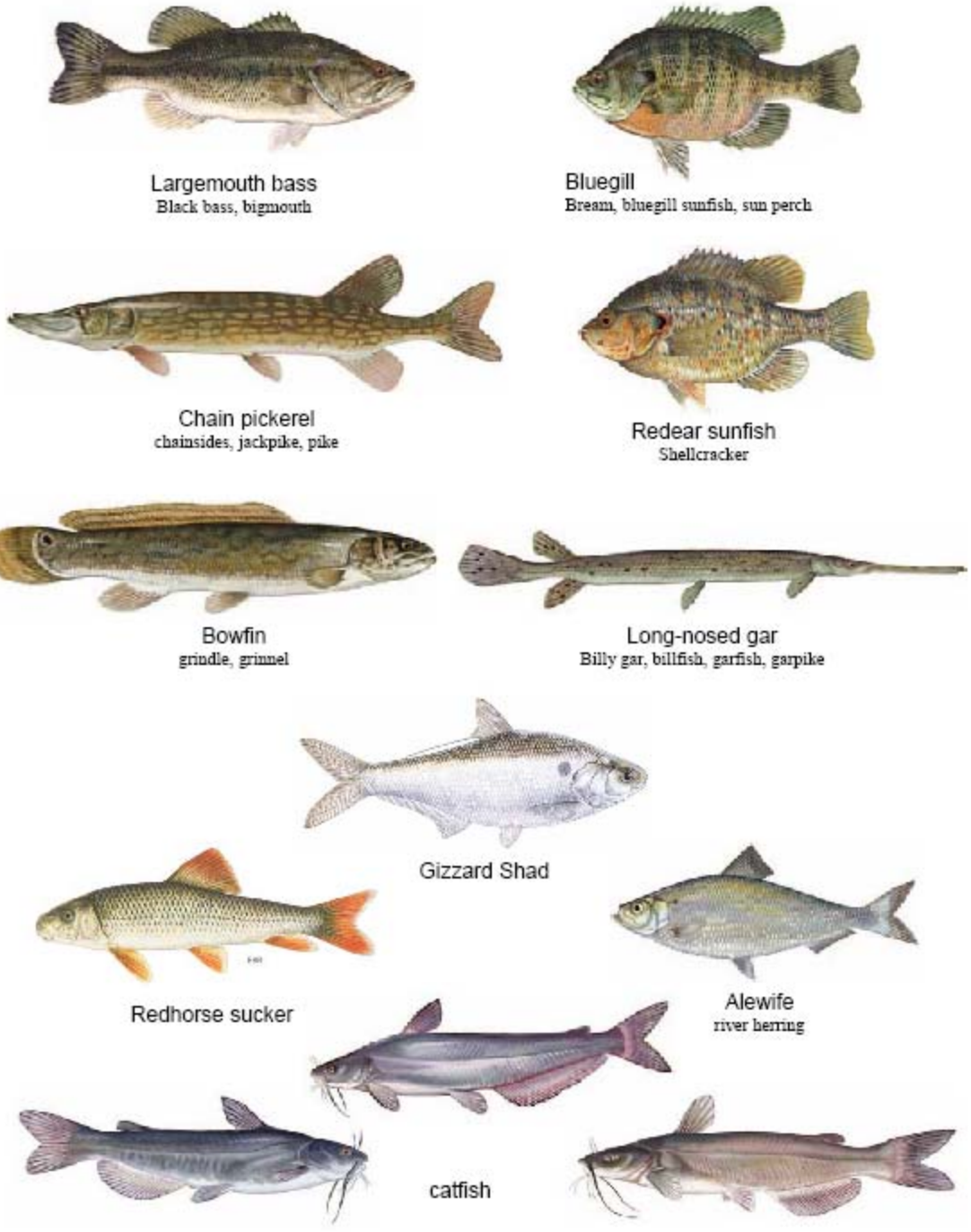
23. What was the total income of your household before taxes last year? Please count all sources, such as wages, salaries, dividends, rents, royalties, etc. If it makes you feel more comfortable, you can look at our categories and indicate what range your household falls in. *(show the page to the respondent)*

- ☐ less than $14,999
- ☐ $15,000 to $24,999
- ☐ $25,000 to $49,999
- ☐ $50,000 to $74,999
- ☐ $75,000 or more

Thank you for participating in the survey.

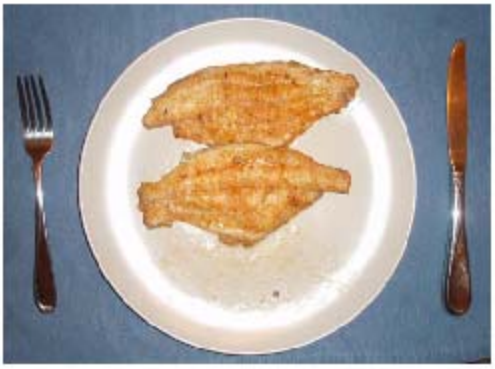
***END OF INTERVIEW*.**

6.2 Fish Species Visual Aid



6.3 Fish Meal Visual Aid

4 oz.



8 oz.

12 oz.

6.4 FORMULAS USED IN ANALYSIS:

Average Daily Intake (µg/kg day $^{-1}$):

$$D = \frac{\sum_{i}^{n} (c_i \times s_i \times f_i)}{W \times a}$$

Where n = number of types (species) of fish eaten
c_i = MeHg concentration for the i^{th} species (ug/g)
s_i = meal size for the i^{th} species (g/meal)
f_i = meal frequency for the i^{th} species (meals/year)
W = body weight (kg)
a = averaging time (365 days)

Blood concentration (µg/L):

$$C = \frac{D \times W \times A \times F}{b \times v}$$

Where D = average daily intake (µg/kg day $^{-1}$)
W = body weight (kg)
A = fraction of ingested MeHg that is absorbed (unitless)
F = fraction of absorbed MeHg that is distributed in the blood (unitless)
b = elimination rate constant (fraction of the concentration eliminated per day (day $^{-1}$)
v = blood volume (L)

Hair Concentration (µg/g):

$$H = C \; x \; R$$

Where C = blood concentration
R = conversion ratio ((µg/g)/(µg/L))

IQ points lost:

$$IQ = \beta \times H_{m0}$$

Where β = slope of the dose response function
H_{m0} = maternal hair concentrations in time 0 (baseline)

Change in IQ points:

$$\Delta IQ = \beta \times \left(H_{m1} - H_{m0}\right)$$

Where β = slope of the dose response function
H_{m1} = maternal hair concentrations in time 1(future)
H_{m0} = maternal hair concentrations in time 0

Conversion Factors:
1 ounce = 28.35 grams
1 month = 4.35 weeks
1 month = 30.44 days
1 year = 365 days

6.5 FISH GROUPINGS USED IN ANALYSIS

Entered Name	Group Name
bass	largemouth bass
blue gill	sunfish
bluegill	sunfish
brim	sunfish
catfish	catfish
crab	blue crab
crappie	sunfish
croaker	spot or croaker
large mouth bass	largemouth bass
largemouth bass	largemouth bass
largemouth small bass	largemouth bass
perch	yellow perch
redear	sunfish
Redhorse sucker	sucker
rockfish	striped bass
sea trout	spot or croaker
spot	spot or croaker
stiffback perch	white perch
striped bass	striped bass
striper	striped bass
sunfish family	sunfish
white perch	white perch

6.6 FISH TISSUE MERCURY CONCENTRATIONS

River	Fish	Hg	2010	2018
James	catfish	0.223	0.16	0.153
James	catfish	0.411	0.295	0.282
James	catfish	0.261	0.188	0.179
James	catfish	0.01	0.007	0.007
James	catfish	0.04	0.029	0.027
James	catfish	0.02	0.014	0.014
James	catfish	0.143	0.103	0.098
James	catfish	0.11	0.079	0.075
James	catfish	0.21	0.151	0.144
James	catfish	0.06	0.043	0.041
James	catfish	0.16	0.115	0.11
James	catfish	0.12	0.086	0.082
James	catfish	0.02	0.014	0.014
James	catfish	0.737	0.53	0.505
James	catfish	0.07	0.05	0.048
James	catfish	0.09	0.065	0.062
James	catfish	0.13	0.093	0.089
James	catfish	0.12	0.086	0.082
James	catfish	0.1	0.072	0.069
James	catfish	0.08	0.057	0.055
James	catfish	0.08	0.057	0.055
James	catfish	0.06	0.043	0.041
James	catfish	0.16	0.115	0.11
James	catfish	0.05	0.036	0.034
James	catfish	0.05	0.036	0.034
Chickahominy	catfish	0.73	0.591	0.576
Chickahominy	catfish	0.05	0.04	0.039
Chickahominy	catfish	0.05	0.04	0.039
Pamunkey	catfish	0.01	0.008	0.008
Pamunkey	catfish	0.1	0.081	0.078
Pamunkey	catfish	0.73	0.589	0.572
Pamunkey	catfish	0.01	0.008	0.008
Pamunkey	catfish	0.063	0.051	0.049
Pamunkey	catfish	0.483	0.389	0.378
Pamunkey	catfish	0.01	0.008	0.008
Pamunkey	catfish	0.256	0.206	0.2
Pamunkey	catfish	0.038	0.031	0.03
Pamunkey	catfish	0.233	0.188	0.182
Mattaponi	catfish	0.013	0.011	0.01
Mattaponi	catfish	0.376	0.305	0.295
Mattaponi	catfish	0.077	0.063	0.06
Mattaponi	catfish	0.142	0.115	0.112
Mattaponi	catfish	0.143	0.116	0.112
Dragon-Piank	catfish	0.06	0.049	0.048
Dragon-Piank	catfish	0.22	0.18	0.175
Dragon-Piank	catfish	0.3	0.246	0.239
Dragon-Piank	catfish	0.047	0.039	0.037
Dragon-Piank	catfish	0.01	0.008	0.008
Dragon-Piank	catfish	0.26	0.213	0.207
Dragon-Piank	catfish	0.31	0.254	0.247
Dragon-Piank	catfish	0.078	0.064	0.062
Dragon-Piank	catfish	0.21	0.172	0.167
Dragon-Piank	catfish	0.1	0.082	0.08
Dragon-Piank	catfish	0.288	0.236	0.23
Dragon-Piank	catfish	0.209	0.171	0.167
Dragon-Piank	catfish	0.211	0.173	0.168

River	Fish	Hg	2010	2018
James	largemouth bass	0.102	0.073	0.07
James	largemouth bass	0.06	0.043	0.041
James	largemouth bass	0.44	0.316	0.301
James	largemouth bass	0.52	0.374	0.356
Chickahominy	largemouth bass	0.08	0.065	0.063
Chickahominy	largemouth bass	0.72	0.583	0.568
Chickahominy	largemouth bass	0.56	0.453	0.442
Chickahominy	largemouth bass	0.72	0.583	0.568
Chickahominy	largemouth bass	0.14	0.113	0.11
Chickahominy	largemouth bass	0.17	0.138	0.134
Chickahominy	largemouth bass	0.7	0.567	0.552
Chickahominy	largemouth bass	0.58	0.47	0.457
Chickahominy	largemouth bass	0.03	0.024	0.024
Chickahominy	largemouth bass	0.14	0.113	0.11
Pamunkey	largemouth bass	0.211	0.17	0.165
Pamunkey	largemouth bass	0.303	0.244	0.237
Pamunkey	largemouth bass	0.088	0.071	0.069
Pamunkey	largemouth bass	0.477	0.385	0.373
Pamunkey	largemouth bass	0.925	0.746	0.724
Mattaponi	largemouth bass	1.47	1.194	1.154
Mattaponi	largemouth bass	0.577	0.469	0.453
Mattaponi	largemouth bass	0.896	0.728	0.704
Dragon-Piank	largemouth bass	0.34	0.279	0.271
Dragon-Piank	largemouth bass	0.7	0.574	0.558
Dragon-Piank	largemouth bass	0.72	0.59	0.574
Dragon-Piank	largemouth bass	0.54	0.443	0.43
Dragon-Piank	largemouth bass	0.16	0.131	0.128
Dragon-Piank	largemouth bass	0.79	0.648	0.63
Dragon-Piank	largemouth bass	0.71	0.582	0.566
Dragon-Piank	largemouth bass	0.53	0.435	0.423
Dragon-Piank	largemouth bass	0.08	0.066	0.064
Dragon-Piank	largemouth bass	0.91	0.746	0.725
Dragon-Piank	largemouth bass	0.58	0.476	0.462
Dragon-Piank	largemouth bass	0.15	0.123	0.12
Dragon-Piank	largemouth bass	1.9	1.558	1.515
Dragon-Piank	largemouth bass	0.59	0.484	0.47
Dragon-Piank	largemouth bass	0.57	0.467	0.454
Dragon-Piank	largemouth bass	0.1	0.082	0.08
Dragon-Piank	largemouth bass	0.047	0.039	0.037
Dragon-Piank	largemouth bass	0.09	0.074	0.072
Dragon-Piank	largemouth bass	0.71	0.582	0.566
Dragon-Piank	largemouth bass	0.05	0.041	0.04
Dragon-Piank	largemouth bass	0.7	0.574	0.558
Dragon-Piank	largemouth bass	0.14	0.115	0.112
Dragon-Piank	largemouth bass	0.37	0.303	0.295
Dragon-Piank	largemouth bass	0.41	0.336	0.327
Dragon-Piank	largemouth bass	0.29	0.238	0.231
Dragon-Piank	largemouth bass	0.35	0.287	0.279
Dragon-Piank	largemouth bass	0.72	0.59	0.574
Dragon-Piank	largemouth bass	0.21	0.172	0.167
Dragon-Piank	largemouth bass	0.48	0.394	0.383
Dragon-Piank	largemouth bass	0.14	0.115	0.112
Dragon-Piank	largemouth bass	0.25	0.205	0.199
Dragon-Piank	largemouth bass	0.1	0.082	0.08
Dragon-Piank	largemouth bass	0.48	0.394	0.383
Dragon-Piank	largemouth bass	0.31	0.254	0.247
Dragon-Piank	largemouth bass	0.08	0.066	0.064
Dragon-Piank	largemouth bass	0.06	0.049	0.048
Dragon-Piank	largemouth bass	0.149	0.122	0.119

River	Fish	Hg	2010	2018
Pamunkey	spot-croaker	0.246	0.198	0.193
Mattaponi	spot-croaker	0.024	0.019	0.019
Mattaponi	spot-croaker	0.022	0.018	0.017
Mattaponi	spot-croaker	0.062	0.051	0.049
Mattaponi	spot-croaker	0.131	0.106	0.102
Mattaponi	spot-croaker	0.051	0.041	0.04

River	Fish	Hg	2010	2018
James	sucker	0.13	0.093	0.089
James	sucker	0.284	0.204	0.195
James	sucker	0.169	0.121	0.116
James	sucker	0.159	0.114	0.109
Chickahominy	sucker	0.25	0.202	0.197
Chickahominy	sucker	0.21	0.17	0.166
Pamunkey	sucker	0.02	0.016	0.016
Dragon-Piank	sucker	0.17	0.139	0.136
Dragon-Piank	sucker	0.27	0.221	0.215
Dragon-Piank	sucker	0.07	0.057	0.056
Dragon-Piank	sucker	0.15	0.123	0.12

River	Fish	Hg	2010	2018
James	sunfish	0.087	0.063	0.06
James	sunfish	0.01	0.007	0.007
James	sunfish	0.01	0.007	0.007
James	sunfish	0.04	0.029	0.027
James	sunfish	0.01	0.007	0.007
James	sunfish	0.01	0.007	0.007
Chickahominy	sunfish	0.13	0.105	0.103
Chickahominy	sunfish	0.31	0.251	0.244
Chickahominy	sunfish	0.09	0.073	0.071
Chickahominy	sunfish	0.1	0.081	0.079
Chickahominy	sunfish	0.08	0.065	0.063
Chickahominy	sunfish	0.36	0.291	0.284
Chickahominy	sunfish	0.01	0.008	0.008
Chickahominy	sunfish	0.05	0.04	0.039
Pamunkey	sunfish	0.01	0.008	0.008
Pamunkey	sunfish	0.367	0.296	0.287
Pamunkey	sunfish	0.01	0.008	0.008
Pamunkey	sunfish	0.013	0.01	0.01
Pamunkey	sunfish	0.038	0.031	0.03
Pamunkey	sunfish	0.109	0.088	0.085
Mattaponi	sunfish	0.24	0.195	0.188
Mattaponi	sunfish	0.21	0.171	0.165
Dragon-Piank	sunfish	0.39	0.32	0.311
Dragon-Piank	sunfish	0.2	0.164	0.159
Dragon-Piank	sunfish	0.42	0.344	0.335
Dragon-Piank	sunfish	0.27	0.221	0.215
Dragon-Piank	sunfish	0.31	0.254	0.247
Dragon-Piank	sunfish	0.089	0.073	0.071
Dragon-Piank	sunfish	0.082	0.067	0.065
Dragon-Piank	sunfish	0.14	0.115	0.112
Dragon-Piank	sunfish	0.21	0.172	0.167
Dragon-Piank	sunfish	0.17	0.139	0.136
Dragon-Piank	sunfish	0.07	0.057	0.056
Dragon-Piank	sunfish	0.01	0.008	0.008
Dragon-Piank	sunfish	0.155	0.127	0.124

River	Fish	Hg	2010	2018
James	striped bass	0.435	0.313	0.298
James	striped bass	0.314	0.226	0.215
James	striped bass	0.284	0.204	0.195
James	striped bass	0.147	0.106	0.101
James	striped bass	0.11	0.079	0.075
James	striped bass	0.09	0.065	0.062
James	striped bass	0.18	0.129	0.123
James	striped bass	0.21	0.151	0.144
James	striped bass	0.43	0.309	0.295
James	striped bass	0.01	0.007	0.007
James	striped bass	0.01	0.007	0.007
James	striped bass	0.64	0.46	0.438
James	striped bass	0.11	0.079	0.075
James	striped bass	0.09	0.065	0.062
James	striped bass	0.07	0.05	0.048
James	striped bass	0.13	0.093	0.089
James	striped bass	0.1	0.072	0.069
James	striped bass	0.09	0.065	0.062
James	striped bass	0.15	0.108	0.103
James	striped bass	0.14	0.101	0.096
James	striped bass	0.09	0.065	0.062
James	striped bass	0.11	0.079	0.075
James	striped bass	0.24	0.172	0.164
James	striped bass	0.09	0.065	0.062
James	striped bass	0.14	0.101	0.096
James	striped bass	0.12	0.086	0.082
James	striped bass	0.16	0.115	0.11
James	striped bass	0.04	0.029	0.027
James	striped bass	0.12	0.086	0.082
James	striped bass	0.12	0.086	0.082
James	striped bass	0.12	0.086	0.082
James	striped bass	0.15	0.108	0.103
James	striped bass	0.19	0.137	0.13
James	striped bass	0.11	0.079	0.075
James	striped bass	0.19	0.137	0.13
James	striped bass	0.07	0.05	0.048
James	striped bass	0.17	0.122	0.116
James	striped bass	0.08	0.057	0.055
James	striped bass	0.27	0.194	0.185
James	striped bass	0.09	0.065	0.062
James	striped bass	0.09	0.065	0.062
James	striped bass	0.07	0.05	0.048
James	striped bass	0.09	0.065	0.062
James	striped bass	0.08	0.057	0.055
James	striped bass	0.05	0.036	0.034
James	striped bass	0.04	0.029	0.027
James	striped bass	0.04	0.029	0.027
James	striped bass	0.04	0.029	0.027
James	striped bass	0.08	0.057	0.055
Chickahominy	striped bass	0.06	0.049	0.047
Chickahominy	striped bass	0.15	0.121	0.118
Chickahominy	striped bass	0.12	0.097	0.095
Chickahominy	striped bass	0.07	0.057	0.055
Chickahominy	striped bass	0.08	0.065	0.063
Mattaponi	striped bass	0.144	0.117	0.113
Mattaponi	striped bass	0.01	0.008	0.008

River	Fish	Hg	2010	2018
James	white perch	0.01	0.01	0.01
James	white perch	0.03	0.02	0.02
Pamunkey	white perch	0.02	0.02	0.02
Pamunkey	white perch	0.02	0.01	0.01
Pamunkey	white perch	0.01	0.01	0.01
Pamunkey	white perch	0.35	0.28	0.27
Mattaponi	white perch	0.03	0.02	0.02
Mattaponi	white perch	0.16	0.13	0.13
Dragon-Piank	white perch	0.05	0.04	0.04
Dragon-Piank	white perch	0.36	0.3	0.29
Dragon-Piank	white perch	0.22	0.18	0.18
Dragon-Piank	white perch	0.01	0.01	0.01
Dragon-Piank	white perch	0.09	0.07	0.07
Dragon-Piank	white perch	0.22	0.18	0.17

River	Fish	Hg	2010	2018
Mattaponi	yellow perch	0.375	0.3045	0.294
Dragon-Piank	yellow perch	0.2	0.164	0.159
Dragon-Piank	yellow perch	0.21	0.1722	0.167
Dragon-Piank	yellow perch	0.26	0.2132	0.207
Dragon-Piank	yellow perch	0.269	0.2206	0.214

Tuna Concentrations

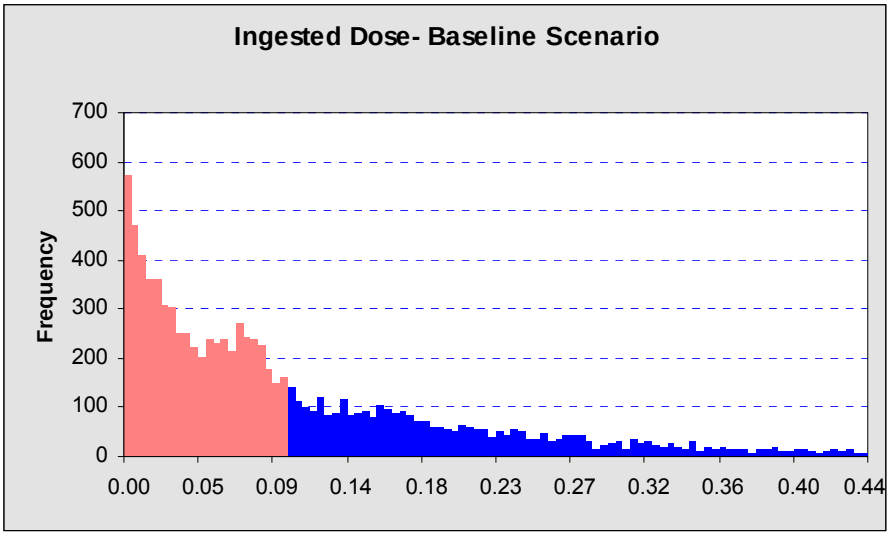
light	albacore
0.007	0.015
0.007	0.015
0.007	0.030
0.007	0.035
0.007	0.046
0.013	0.070
0.028	0.090
0.030	0.090
0.032	0.100
0.035	0.169
0.040	0.172
0.040	0.188
0.040	0.190
0.040	0.207
0.040	0.216
0.040	0.220
0.043	0.229
0.043	0.230
0.043	0.231
0.044	0.232
0.044	0.236
0.045	0.240
0.048	0.240
0.048	0.250
0.048	0.250
0.050	0.250
0.050	0.252
0.050	0.258
0.050	0.260
0.050	0.260
0.050	0.260
0.050	0.260
0.050	0.260
0.050	0.260
0.051	0.260
0.052	0.263
0.052	0.264
0.053	0.265
0.053	0.267
0.054	0.268
0.057	0.269
0.059	0.270
0.059	0.270
0.060	0.270
0.060	0.272
0.060	0.273
0.060	0.274
0.060	0.280
0.060	0.280
0.060	0.280
0.061	0.280
0.061	0.282
0.062	0.285
0.069	0.286
0.070	0.288
0.070	0.289
0.070	0.290
0.070	0.290
0.070	0.290
0.070	0.290
0.070	0.290
0.070	0.294
0.071	0.296
0.073	0.296
0.076	0.298
0.077	0.300
0.080	0.300
0.080	0.300
0.080	0.300
0.080	0.300
0.080	0.308
0.080	0.310
0.080	0.310
0.080	0.314

MARKET SHARE AND MERCURY CONCENTRATION OF PURCHASED FISH

SPECIES	% OF SEAFOOD MARKET	cumulative frequency	MEAN HG CONC PPM
Shrimp	0.18610	0.186096	0.012
Pollock	0.13582	0.321919	0.067
Salmon	0.10128	0.423202	0.028
Haddock, Hake, and Monkfish	0.06576	0.488963	0.17
Catfish	0.05863	0.547594	0.066
Cod	0.05789	0.605488	0.143
Crabs	0.05777	0.663258	0.063
Flatfish	0.04437	0.707631	0.059
Anchovies, Herring, and Shad	0.03761	0.745244	0.05
Tilapia	0.02299	0.768229	0.02
Tuna, Fresh	0.02200	0.790231	0.378
Clams	0.02077	0.811004	0.017
Lobsters, American	0.01586	0.826861	0.31
Oysters and Mussels	0.01524	0.842102	0.017
Sardines	0.01512	0.857221	0.016
Squid	0.01266	0.869881	0.07
Other	0.01192	0.881804	0.085
Lingcod and Scorpionfish	0.01131	0.893113	0.286
Halibut	0.01106	0.904175	0.217
Lobsters, Spiny	0.01008	0.914254	0.121
Scallops	0.00983	0.924088	0.017
Perch, Ocean and Mullet	0.00848	0.932569	0.04
Trout, Freshwater	0.00848	0.941050	0.030
Bass, Saltwater	0.00750	0.948548	0.263
Crawfish	0.00688	0.955431	0.027
Snapper, Porgy, and Sheepshead	0.00664	0.962069	0.141
Swordfish	0.00516	0.967231	0.969
Skate	0.00418	0.971411	0.137
Croaker, Atlantic	0.00369	0.975098	0.055
Mackerel, Atlantic	0.00350	0.978601	0.049
Sablefish	0.00307	0.981674	0.273
Whitefish	0.00270	0.984378	0.068
Orange Roughy	0.00246	0.986837	0.540
Grouper	0.00209	0.988926	0.549
Mackerel, Chub	0.00207	0.990991	0.088
Butterfish	0.00172	0.992712	0.0580
Shark	0.00160	0.994310	0.988
Pike	0.00123	0.995539	0.056
Bluefish	0.00111	0.996645	0.324
Trout, Saltwater	0.00074	0.997383	0.269
Mackerel, King	0.00061	0.997997	0.73
Mackerel, Spanish	0.00058	0.998575	0.368
Perch, Freshwater	0.00049	0.999067	0.162
Tilefish, Atlantic	0.00032	0.999386	0.123
Marlin	0.00025	0.999632	0.489
Carp and Buffalofish	0.00025	0.999878	0.203
Tilefish, Gulf	0.00007	0.999951	1.450
Croaker, Pacific	0.00002	0.999975	0.303
Bass, Freshwater	0.00001	0.999988	0.318
Smelt	0.00001	1.000000	0.092

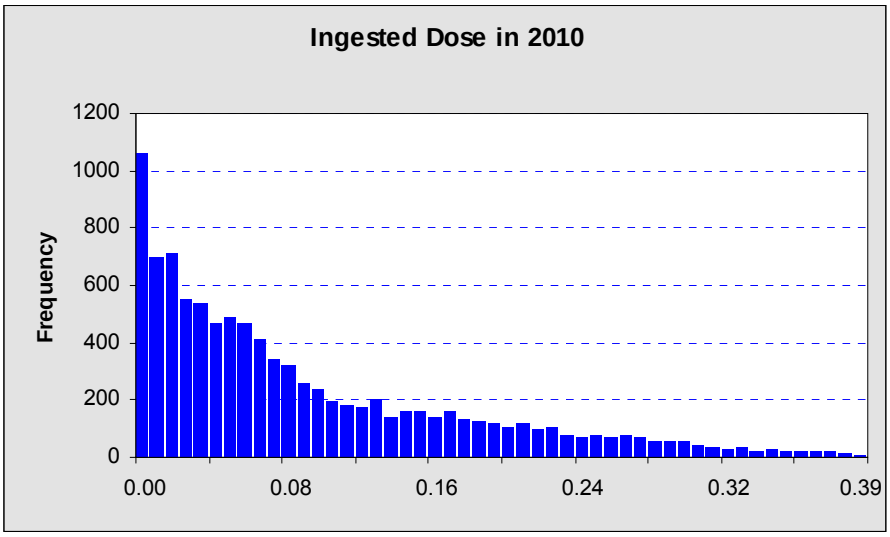
6.7 EXAMPLE OF DISTRIBUTIONS FROM CRYSTAL BALL ®

Results for Model 2:
Women 16 – 49, assumptions from Stern 2005, Outcome = Loss of IQ points



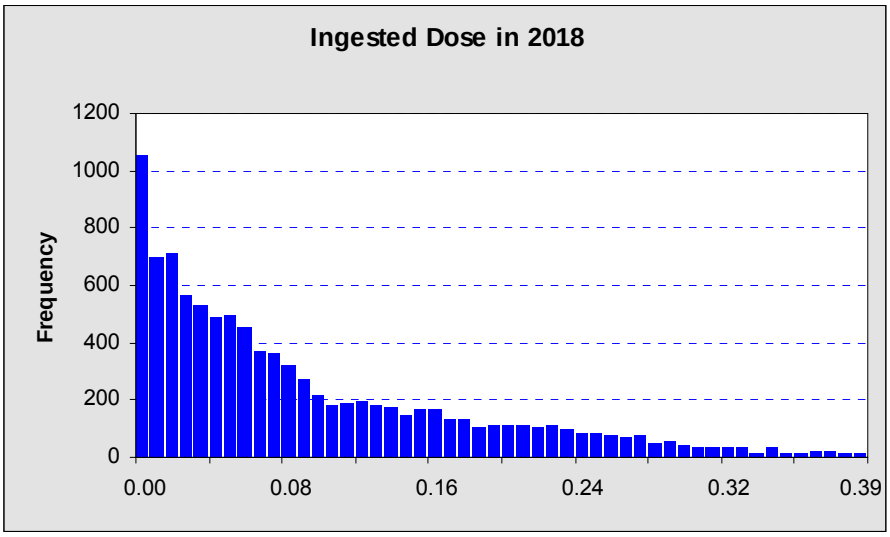
Statistics:	Forecast values
Trials	10,000
Mean	0.11
Median	0.07
Mode	---
Standard Deviation	0.12
Variance	0.01
Skewness	1.78
Kurtosis	6.56
Coeff. of Variability	1.06
Minimum	0.00
Maximum	0.92
Range Width	0.92
Mean Std. Error	0.00

Percentiles:	Forecast values
0%	0.00
10%	0.01
20%	0.02
30%	0.03
40%	0.05
50%	0.07
60%	0.10
70%	0.13
80%	0.19
90%	0.28
100%	0.92



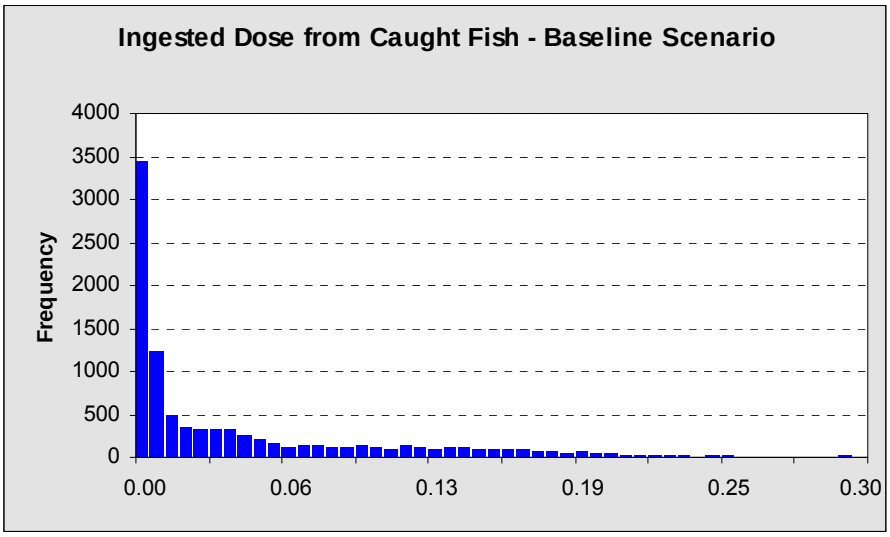
Statistics:	Forecast values
Trials	10,000
Mean	0.10
Median	0.06
Mode	---
Standard Deviation	0.11
Variance	0.01
Skewness	1.90
Kurtosis	7.83
Coeff. of Variability	1.05
Minimum	0.00
Maximum	0.91
Range Width	0.91
Mean Std. Error	0.00

Percentiles:	Forecast values
0%	0.00
10%	0.01
20%	0.02
30%	0.03
40%	0.05
50%	0.06
60%	0.09
70%	0.12
80%	0.17
90%	0.24
100%	0.91



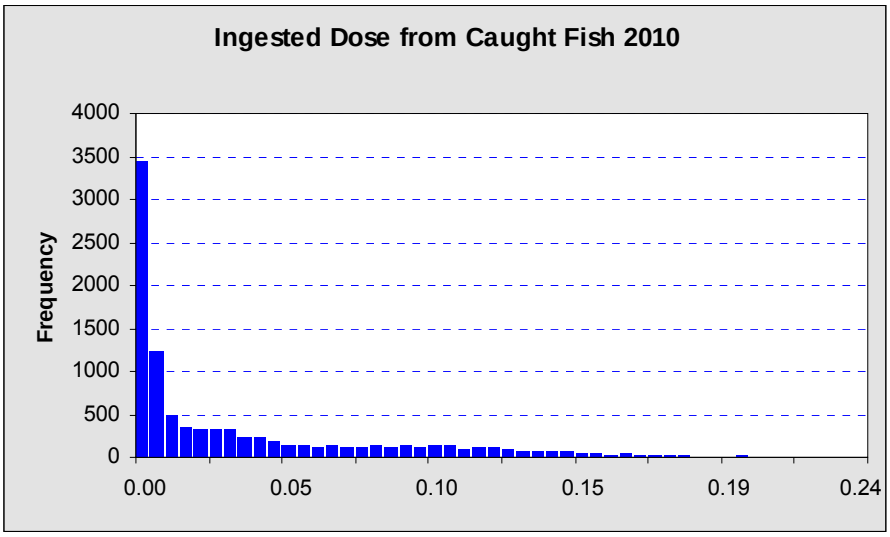
Statistics:	Forecast values
Trials	10,000
Mean	0.10
Median	0.06
Mode	---
Standard Deviation	0.10
Variance	0.01
Skewness	1.92
Kurtosis	8.08
Coeff. of Variability	1.05
Minimum	0.00
Maximum	0.91
Range Width	0.91
Mean Std. Error	0.00

Percentiles:	Forecast values
0%	0.00
10%	0.01
20%	0.02
30%	0.03
40%	0.05
50%	0.06
60%	0.09
70%	0.12
80%	0.17
90%	0.24
100%	0.91



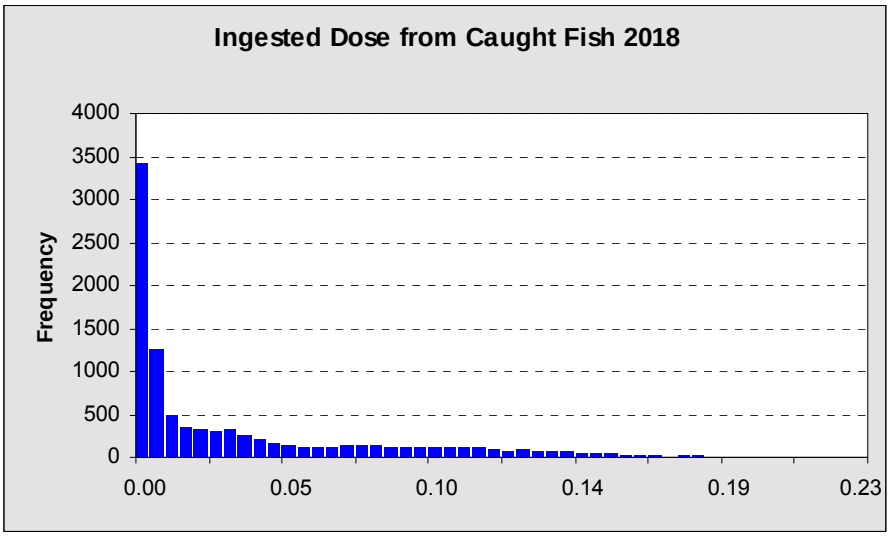
Statistics:	Forecast values
Trials	10,000
Mean	0.06
Median	0.02
Mode	---
Standard Deviation	0.09
Variance	0.01
Skewness	2.74
Kurtosis	12.17
Coeff. of Variability	1.57
Minimum	0.00
Maximum	0.73
Range Width	0.73
Mean Std. Error	0.00

Percentiles:	Forecast values
0%	0.00
10%	0.00
20%	0.00
30%	0.01
40%	0.01
50%	0.02
60%	0.03
70%	0.06
80%	0.10
90%	0.16
100%	0.73



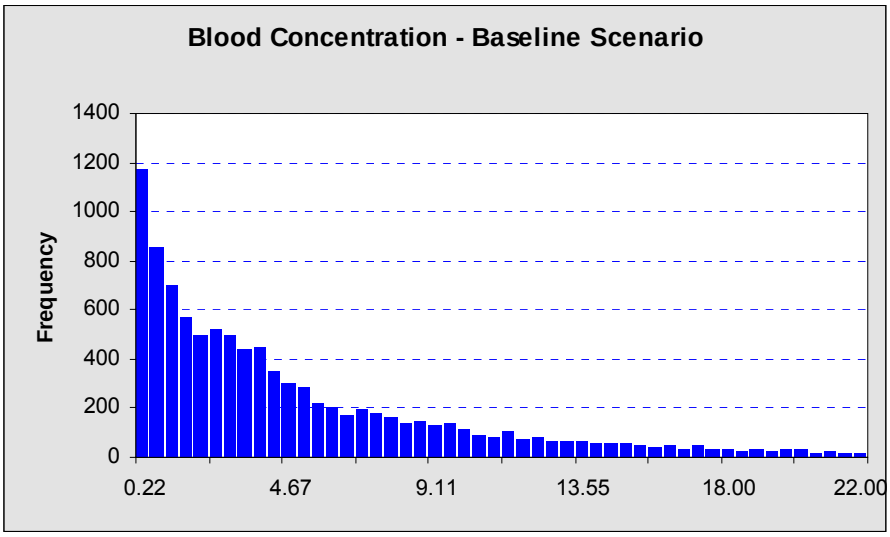
	Forecast values
Trials	10,000
Mean	0.04
Median	0.01
Mode	---
Standard Deviation	0.07
Variance	0.00
Skewness	2.76
Kurtosis	12.28
Coeff. of Variability	1.56
Minimum	0.00
Maximum	0.55
Range Width	0.55
Mean Std. Error	0.00

	Forecast values
0%	0.00
10%	0.00
20%	0.00
30%	0.00
40%	0.01
50%	0.01
60%	0.03
70%	0.04
80%	0.08
90%	0.12
100%	0.55



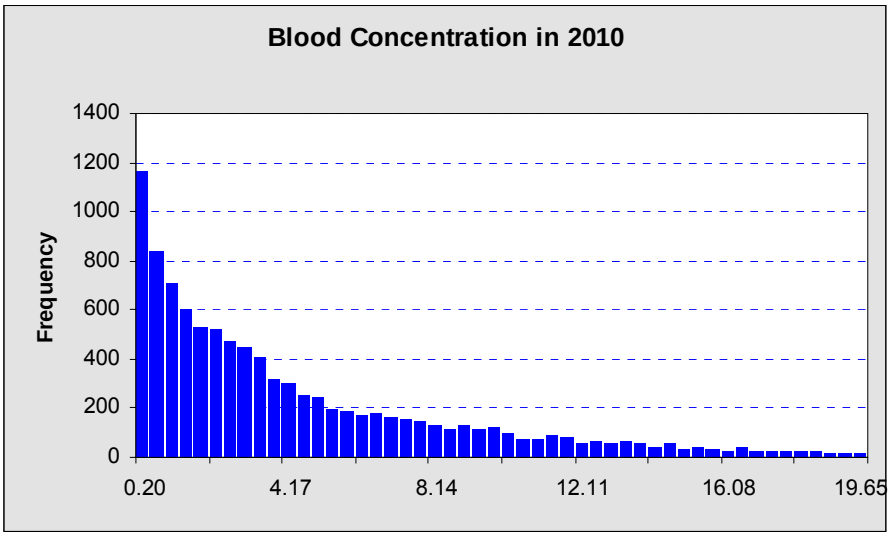
	Forecast values
Trials	10,000
Mean	0.04
Median	0.01
Mode	---
Standard Deviation	0.07
Variance	0.00
Skewness	2.74
Kurtosis	12.20
Coeff. of Variability	1.56
Minimum	0.00
Maximum	0.53
Range Width	0.53
Mean Std. Error	0.00

	Forecast values
0%	0.00
10%	0.00
20%	0.00
30%	0.00
40%	0.01
50%	0.01
60%	0.03
70%	0.04
80%	0.08
90%	0.12
100%	0.53



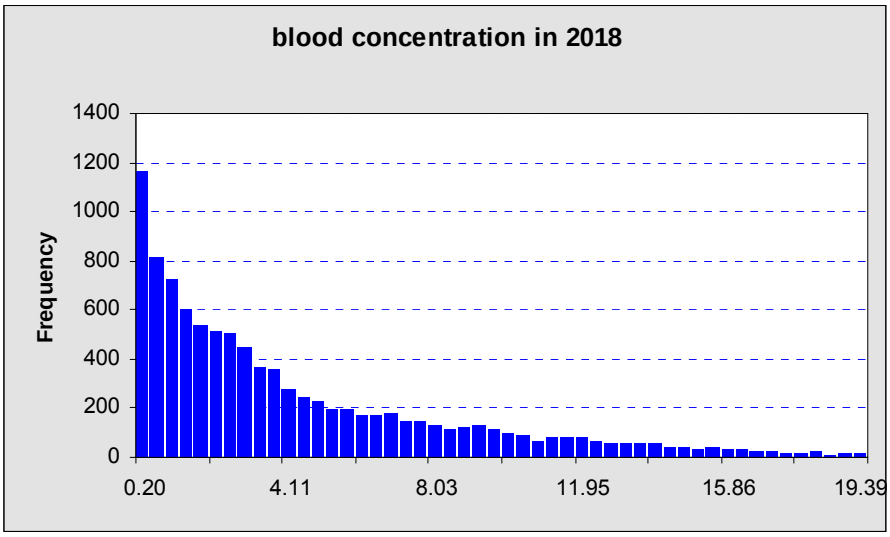
	Forecast values
Trials	10,000
Mean	5.34
Median	3.31
Mode	---
Standard Deviation	6.03
Variance	36.32
Skewness	2.11
Kurtosis	8.74
Coeff. of Variability	1.13
Minimum	0.00
Maximum	54.07
Range Width	54.07
Mean Std. Error	0.06

	Forecast values
0%	0.00
10%	0.37
20%	0.88
30%	1.55
40%	2.39
50%	3.31
60%	4.35
70%	6.07
80%	8.71
90%	13.31
100%	54.07



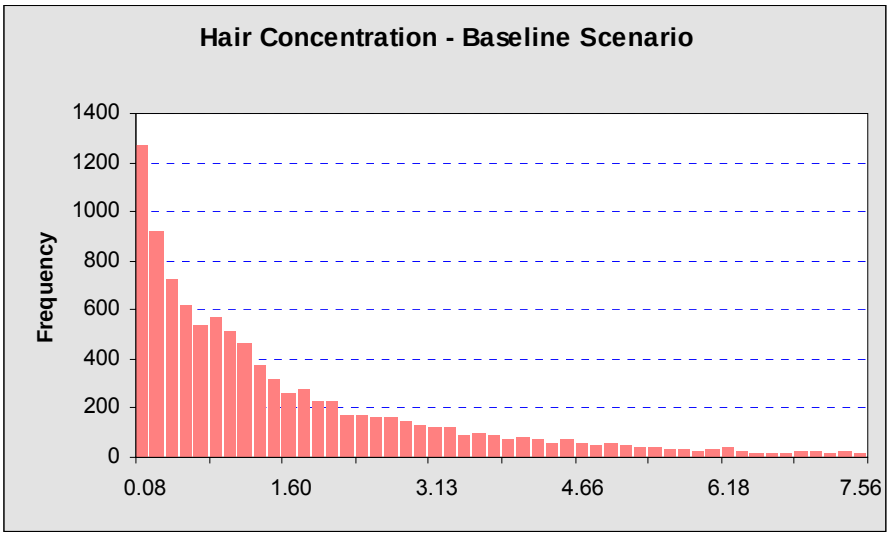
	Forecast values
Trials	10,000
Mean	4.77
Median	2.92
Mode	---
Standard Deviation	5.39
Variance	29.01
Skewness	2.28
Kurtosis	10.73
Coeff. of Variability	1.13
Minimum	0.00
Maximum	54.33
Range Width	54.32
Mean Std. Error	0.05

	Forecast values
0%	0.00
10%	0.32
20%	0.80
30%	1.39
40%	2.09
50%	2.92
60%	3.96
70%	5.54
80%	7.92
90%	11.79
100%	54.33



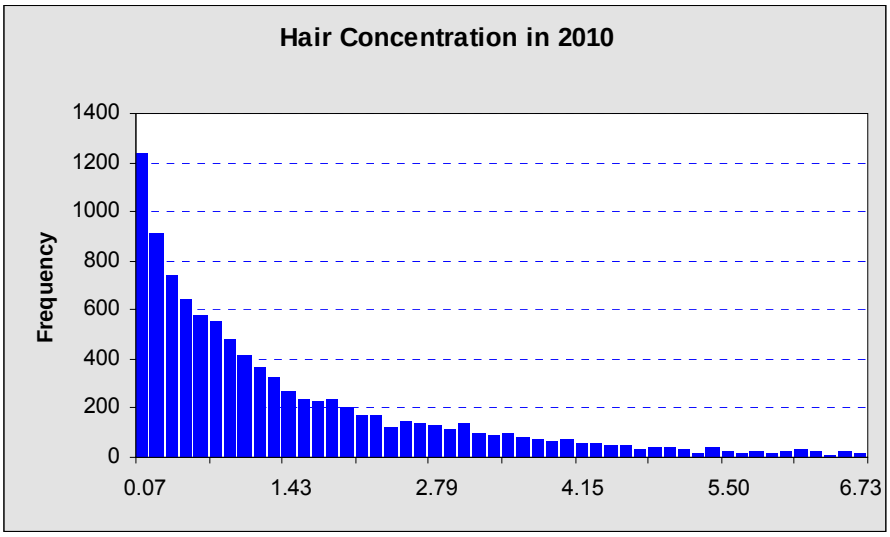
	Forecast values
Trials	10,000
Mean	4.71
Median	2.86
Mode	---
Standard Deviation	5.31
Variance	28.23
Skewness	2.30
Kurtosis	10.94
Coeff. of Variability	1.13
Minimum	0.00
Maximum	54.09
Range Width	54.09
Mean Std. Error	0.05

	Forecast values
0%	0.00
10%	0.32
20%	0.79
30%	1.36
40%	2.09
50%	2.86
60%	3.89
70%	5.51
80%	7.83
90%	11.59
100%	54.09



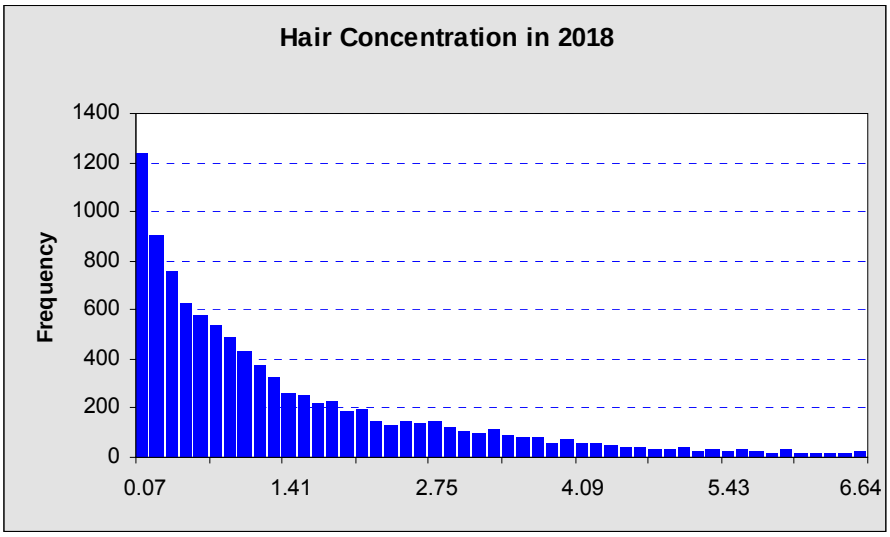
	Forecast values
Trials	10,000
Mean	1.75
Median	1.03
Mode	---
Standard Deviation	2.10
Variance	4.41
Skewness	2.54
Kurtosis	12.52
Coeff. of Variability	1.20
Minimum	0.00
Maximum	22.08
Range Width	22.08
Mean Std. Error	0.02

	Forecast values
0%	0.00
10%	0.11
20%	0.27
30%	0.48
40%	0.74
50%	1.03
60%	1.39
70%	1.94
80%	2.80
90%	4.34
100%	22.08



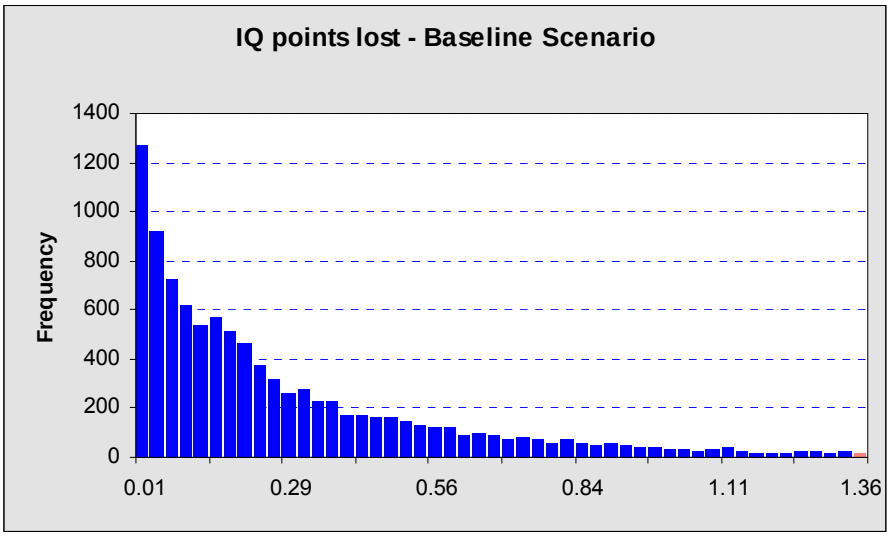
	Forecast values
Trials	10,000
Mean	1.56
Median	0.91
Mode	---
Standard Deviation	1.87
Variance	3.49
Skewness	2.65
Kurtosis	14.05
Coeff. of Variability	1.20
Minimum	0.00
Maximum	21.99
Range Width	21.99
Mean Std. Error	0.02

	Forecast values
0%	0.00
10%	0.10
20%	0.25
30%	0.43
40%	0.65
50%	0.91
60%	1.25
70%	1.78
80%	2.55
90%	3.83
100%	21.99



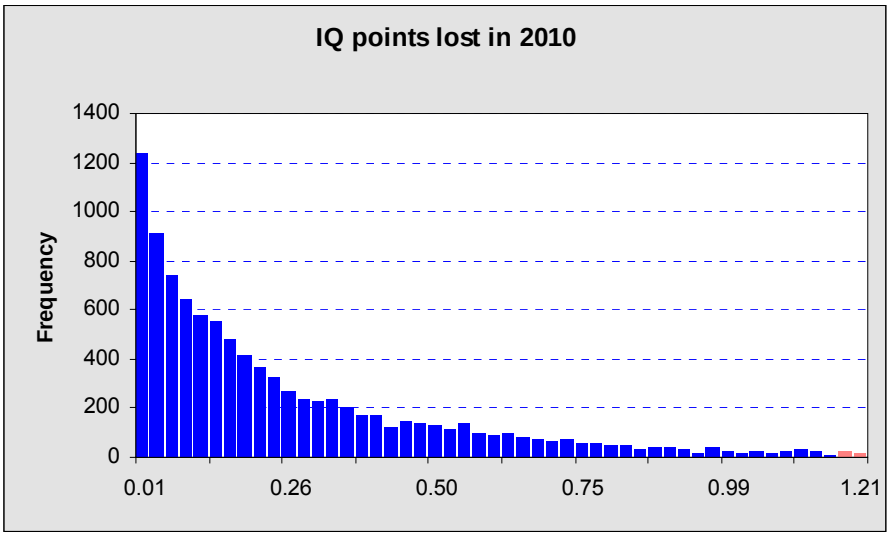
	Forecast values
Trials	10,000
Mean	1.54
Median	0.90
Mode	---
Standard Deviation	1.85
Variance	3.41
Skewness	2.70
Kurtosis	14.74
Coeff. of Variability	1.20
Minimum	0.00
Maximum	22.03
Range Width	22.03
Mean Std. Error	0.02

	Forecast values
0%	0.00
10%	0.10
20%	0.24
30%	0.42
40%	0.65
50%	0.90
60%	1.24
70%	1.75
80%	2.53
90%	3.74
100%	22.03



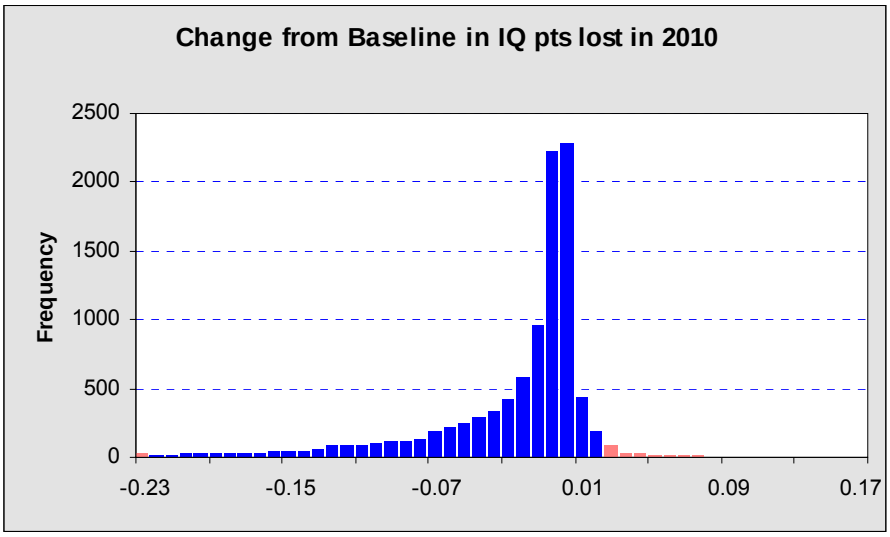
	Forecast values
Trials	10,000
Mean	0.32
Median	0.19
Mode	---
Standard Deviation	0.38
Variance	0.14
Skewness	2.54
Kurtosis	12.52
Coeff. of Variability	1.20
Minimum	0.00
Maximum	3.98
Range Width	3.97
Mean Std. Error	0.00

	Forecast values
0%	0.00
10%	0.02
20%	0.05
30%	0.09
40%	0.13
50%	0.19
60%	0.25
70%	0.35
80%	0.50
90%	0.78
100%	3.98



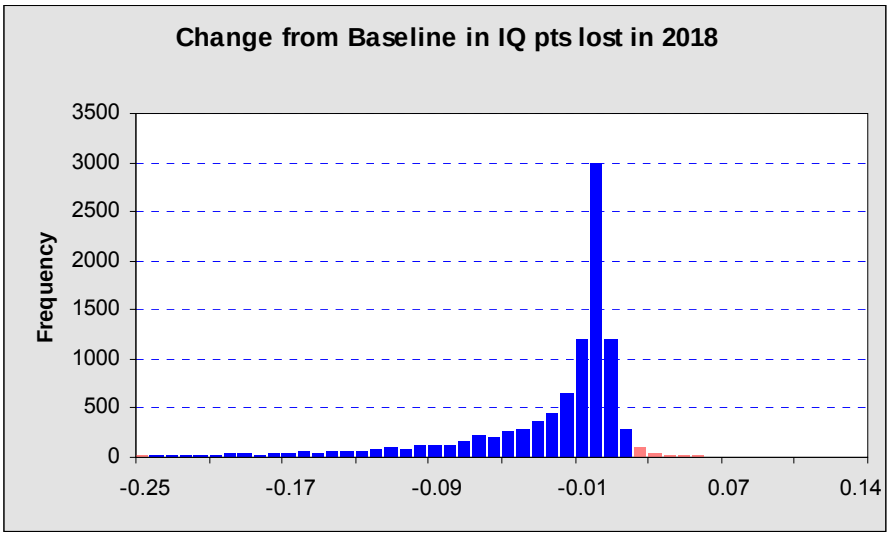
	Forecast values
Trials	10,000
Mean	0.28
Median	0.16
Mode	---
Standard Deviation	0.34
Variance	0.11
Skewness	2.65
Kurtosis	14.05
Coeff. of Variability	1.20
Minimum	0.00
Maximum	3.96
Range Width	3.96
Mean Std. Error	0.00

	Forecast values
0%	0.00
10%	0.02
20%	0.04
30%	0.08
40%	0.12
50%	0.16
60%	0.22
70%	0.32
80%	0.46
90%	0.69
100%	3.96



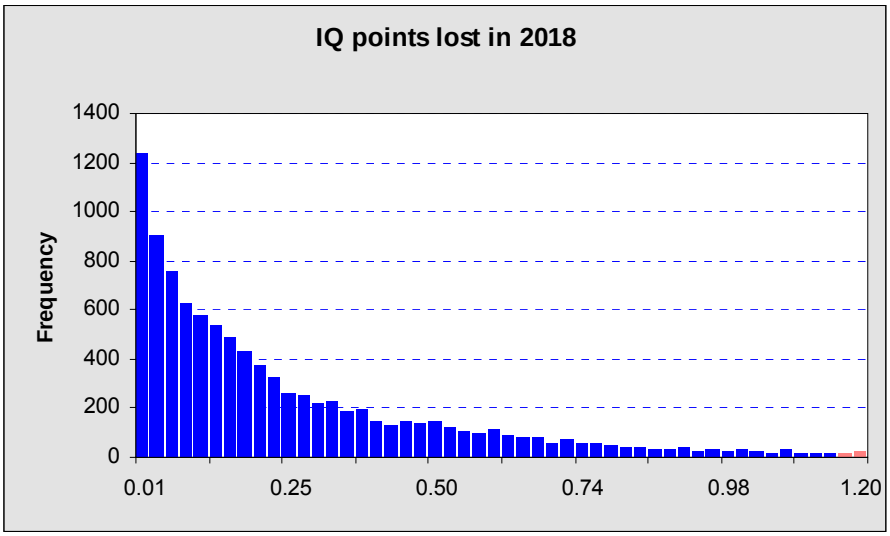
	Forecast values
Trials	10,000
Mean	-0.03
Median	-0.01
Mode	---
Standard Deviation	0.07
Variance	0.01
Skewness	-4.24
Kurtosis	32.08
Coeff. of Variability	-2.15
Minimum	-1.07
Maximum	0.24
Range Width	1.31
Mean Std. Error	0.00

	Forecast values
0%	-1.07
10%	-0.11
20%	-0.05
30%	-0.03
40%	-0.01
50%	-0.01
60%	0.00
70%	0.00
80%	0.00
90%	0.01
100%	0.24



	Forecast values
Trials	10,000
Mean	-0.04
Median	-0.01
Mode	---
Standard Deviation	0.08
Variance	0.01
Skewness	-3.91
Kurtosis	26.39
Coeff. of Variability	-2.07
Minimum	-1.04
Maximum	0.15
Range Width	1.19
Mean Std. Error	0.00

	Forecast values
0%	-1.04
10%	-0.12
20%	-0.06
30%	-0.03
40%	-0.02
50%	-0.01
60%	0.00
70%	0.00
80%	0.00
90%	0.00
100%	0.15



	Forecast values
Trials	10,000
Mean	0.28
Median	0.16
Mode	---
Standard Deviation	0.33
Variance	0.11
Skewness	2.70
Kurtosis	14.74
Coeff. of Variability	1.20
Minimum	0.00
Maximum	3.96
Range Width	3.96
Mean Std. Error	0.00

	Forecast values
0%	0.00
10%	0.02
20%	0.04
30%	0.08
40%	0.12
50%	0.16
60%	0.22
70%	0.32
80%	0.46
90%	0.67
100%	3.96