REPORT OF THE VIRGINIA DEPARTMENT OF ENVIRONMENTAL QUALITY

Evaluation of Environmental Concerns in the Upper Reaches of Buchanan Creek

TO THE GOVERNOR AND
THE GENERAL ASSEMBLY OF VIRGINIA

HOUSE DOCUMENT NO. 11

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Commonwealth of Virginia

VIRGINIA DEPARTMENT OF ENVIRONMENTAL QUALITY

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TO: The Honorable Ralph S. Northam, Governor

Members of the General Assembly

CC: The Honorable Matthew J. Strickler, Secretary of Natural Resources

FROM: David K. Paylor, Director

DATE: October 1, 2019

SUBJECT: Evaluation of Environmental Concerns in the Upper Reaches of Buchanan Creek

Item 366 H in the 2018 – 2020 Biennium Budget provided funding to the Department of Environmental Quality (DEQ) for an evaluation of environmental concerns in the upper reaches of Buchanan Creek, a tributary of the Western Branch of the Lynnhaven River (2018 Special Session 1 Va. Acts Ch. 2). The budget language specifically stated that the study should address: 1) adequacy of the channel, 2) evaluation of shoreline deterioration, and 3) potential contamination from the former Birchwood Gardens private sewage treatment facility.

In September 2018, DEQ contracted with the Virginia Institute of Marine Science (VIMS) to conduct this study. VIMS worked on the project, in consultation with DEQ, through July 2019. To address the items included in the budget language, VIMS reviewed historical water quality data and stream assessments, surveyed the stream channel to evaluate the current channel depth and bank morphology, completed channel coring to characterize surficial sediment types and thicknesses, and conducted water quality monitoring at six locations, including three sites on Buchanan Creek, and one site each on Thalia Creek, Wolfsnare Creek, and the Western Branch of the Lynnhaven River.

The final report is attached, and includes the following major findings:

- The Buchanan Creek channel "has reached a state of geomorphological equilibrium and functions well in providing a conduit for stormwater flow, but is not suitable for much of its length for use by watercraft. Alterations of channel morphology may diminish water quality and contribute to bank instability. From a physical, chemical, and biological perspective the results of this study show that the channel is adequate."

- Historical data reviews show "the shorelines along the whole of Buchanan Creek to be relatively stable." VIMS does provide options for enhancing appropriate sections of Buchanan Creek with living shorelines, but concludes that "[t]he results of this study provide strong evidence that the shoreline deterioration is of little concern."
- The modeling and analyses from the study "provide evidence that any sewage treatment plant residues under Birchwood Malibu Park lands have minimal relative contributions to Buchanan Creek pollutant loads".

DEQ has reviewed the report and concurs with the technical findings presented. Regarding the possible management options presented in the report, please note that the findings or options contained in the report do not constitute approval of any project or eliminate the need to follow local, state and federal regulatory and permitting processes. This includes, for example, any local requirements pertaining to tree removal in the riparian zone to ensure compliance with the Chesapeake Bay Preservation Area Designation and Management Regulations (9VAC25-830).

Evaluation of Environmental Concerns in Buchanan Creek

Submitted by:
Virginia Institute of Marine Science

Submitted to:
Virginia Department of Environmental Quality

June 28, 2019

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Disclaimers:

Findings or options contained herein do not constitute Commonwealth or City of Virginia Beach approval of any project(s) or eliminate the need to follow normal regulatory permitting processes, including addressing restrictions associated with waterfront Resource Protection Areas.

The VIMS research team is aware of the property ownership issues within and adjacent to Buchanan Creek. Any subsequent actions to address the findings of this study surely must respect private property and owners' consent. It is common for VIMS to incorporate proper jurisdiction and private/public property boundaries when developing recommendations. The nature and complexity of the environmental issues and characteristics of the Buchanan Creek headwaters and shorelines precluded us from incorporating those considerations in this report. The recommendations presented later will likely require modifications through cooperation with/of affected property owners prior to any actions. VIMS stands ready to assist with project alterations designed to conform to parcel-specific approaches.

EXECUTIVE SUMMARY

Requested Work

In association with HB5002 Item 366 #2h of the Commonwealth's Natural Resources Budget for fiscal year 2016, the Virginia Department of Environmental Quality (DEQ) was tasked with commissioning a study to evaluate environmental concerns in Buchanan Creek, a tributary of the Western Branch of the Lynnhaven River in the City of Virginia Beach.

In September 2018, DEQ contracted with the Virginia Institute of Marine Science (VIMS) for a study of Buchanan Creek and its watershed, including the following tasks: historical data review, data collection to determine physical characteristics of the creek morphology and shoreline, water quality monitoring assessment of Buchanan Creek and selected similar systems, and analyses utilizing hydrodynamic and water quality models.

In addition, the contract specifically called for VIMS to address the following three objectives: determine the adequacy of the channel for conveying storm runoff, evaluate shoreline deterioration, and address potential contamination of Buchanan Creek from the Birchwood Gardens former private sewage treatment facility.

Approach Employed by VIMS

Observations of creek physical conditions collected by VIMS included topographic surveys of bank slopes and channel depths along Buchanan Creek, coring of channel sediments, and cataloging of bank features, such as fringing marsh, bulkheads, and fallen trees. Historical aerial photos and records of previous dredging were additionally used to evaluate past conditions.

Multiple water quality parameters were recorded at high frequency by sensors deployed at six locations over four separate periods for 10 to 14 days each from September 2018 to April 2019. Three sensor deployment sites were along Buchanan Creek, and one was at a boundary site in the Western Branch of Lynnhaven River. One site each was also placed in the inner sections of Thalia Creek and Wolfsnare Creek, which served as reference creeks with conditions comparable to Buchanan Creek. Additionally, grab sample surveys were conducted over the same period to laboratory analysis of nutrients, algae, suspended solids, and bacteria.

A system of numerical models was applied to simulate the loadings of nutrients from the watershed, determine the resulting response of creek water quality, and calculate creek flushing times. To accurately simulate transport of water and pollutants in the small creeks, a very fine spatial resolution model grid was applied to evaluate complex interactions of geometry and hydrodynamics and to assess possible channel modifications, such as channel deepening.

The results of this project are presented in three major chapters: Shoreline and Channel Assessment (Chapter 1), Water Quality Observations (Chapter 2), Numerical Modeling (3). Below are the main scientific results of this study followed by a summary of options and their possible ramifications.

Major Findings

Shoreline and Channel Assessments **-** The typically low energy environment in the study area results in very low rates of shoreline change. The banks are relatively stable and are only exposed and slowly eroding in the intertidal zone and where trees have fallen.

Buchanan Creek is very shallow at only about -1 ft below mean low water in the lower section of the Area of Concern (the extreme upper portion of Buchanan Creek). Near the stormwater outfall pipes at the upper end of Buchanan Creek, the channel has completely silted in such that it is dry at low water. Bottom sediment coring indicates that at least five feet of alternating fine sand and mud have deposited since the channel in the Area of Concern was dredged. The top foot is relatively coarse sand and gravel indicating that occasional high energy flow is now preventing further accumulation of silt and clay.

For shoreline management specifically, viable options for the Area of Concern include selectively cutting and trimming trees and installing living shorelines consisting of coir logs, sand fill, and marsh plants.

Water Quality Observations **-** Buchanan Creek water quality is similar to conditions typical of shallow-headwater creeks within the Lynnhaven system. Chlorophyll levels in Buchanan Creek are high but within the range documented in the reference creeks. All three creeks exhibit strong day-night cycles in dissolved oxygen (DO) with extended periods of low DO when temperatures are high, patterns to be expected in very shallow, urban tidal systems. Based on national estuarine eutrophication assessment criteria, nitrogen and phosphorus conditions in all three creeks are generally moderate with occasional high levels being observed.

An analysis of rates of ecosystem photosynthesis and respiration indicates that benthic algae (i.e., algae growing on the bed of the creek) is more important to the state of the Buchanan Creek ecosystem than are phytoplankton (i.e., algae in the water column). Thus, the strong daily cycle in DO is not mainly a result of the high chlorophyll levels produced by phytoplankton in the water column, but rather a reflection of the strong benthic contribution to photosynthesis and respiration typical of very shallow tidal creeks.

Samples taken from identified drainages at the Birchwood Malibu Park showed no direct evidence of significant influences on water quality within Buchanan Creek. Low, intermittent flow from these drainages coupled with moderate pollution levels support this conclusion. E*nterococcus* bacteria densities measured in drainages from the park were lower than those observed in Buchanan Creek. In contrast, measured concentrations of dissolve nitrogen and phosphorus from these drainages were greater than the concentrations measured in Buchanan Creek. Nevertheless, the low and intermittent flows from these drainages suggest that they have little impact on Buchanan Creek.

Numerical Modeling **-** The amount of pollutant loadings to Buchanan Creek watershed is within the range typical of urban-dominated areas. The same water quality model parameters were successfully used for Buchanan Creek and the reference creeks, further suggesting the similarity of systems.

Simulation results indicate that during typical low runoff conditions, water residence time in the Area of Concern within Buchanan Creek is long (> 20 days), which is favorable for algal growth and nutrient recycling, but that the system can be flushed out quickly when surface runoff is higher. Model results suggest that Buchanan Creek's present morphology is adequate to convey storm runoff.

Model scenarios with the creek deepened 2 ft by dredging suggests that dredging reduces tidal and stormwater discharge velocities in the channel, slightly increases residence times for pollutants, and has negligible effects on water quality.

Modeling indicates that the dominant contributions of pollutant sources (nutrients and bacteria) to Buchanan Creek and the reference creeks are nonpoint sources delivered by stormwater discharge. The dominant modeled nutrient sources are fertilizer applied to lawns and atmospheric deposition. The dominant bacterial sources in the model are wildlife and pets.

Particle tracking studies show that pollutants can be transported from one creek to another, such as from Buchanan to Thalia, since these creeks are connected. This indicates that the pollutants in Buchanan Creek are not only discharged from the watershed, but also include those transported into the creek from other creeks.

Summary

The findings summarized above and detailed this report provide a basis for addressing the specific charges set forth in HB5002 Item 366 #2h.

Determine the adequacy of the channel **-** The channel has reached a state of geomorphological equilibrium and functions well in providing a conduit for stormwater outflow, but is not suitable for much of its length for use by watercraft. Alterations of channel morphology may diminish water quality and contribute to bank instability. From a physical, chemical, and biological perspective the results of this study show that the channel is adequate.

Conduct an evaluation of shoreline deterioration - Analyses of historical information and data collected as a part of this study show the shorelines along the whole of Buchanan Creek to be relatively stable. We present options to address select candidate areas for living shoreline enhancements, but options such as tree removal and channel modifications carry undesired consequences that could adversely affect bank stability and water quality. The results of this study provide strong evidence that shoreline deterioration is of little concern.

Determine potential contamination of Buchanan Creek from Birchwood Gardens former private sewage treatment facility - We determined that all previous water quality assessments by the City of Virginia Beach, DEQ, and the Virginia Department of Health investigating Birchwood Malibu Park as a legacy pollution source were credible and did not require duplication. The results of this study showed that there are multiple and significant pollutant sources to Buchanan Creek contributing to its condition. The combination of past and present studies clarifies that Buchanan Creek shares water quality and hydrodynamic characteristics similar to other urban tidal headwater creeks, and therefore is not unique with respect to environmental condition. The modeling and analyses from this study provide evidence that any sewage treatment plant residues under Birchwood Malibu Park lands have minimal relative contributions to Buchanan Creek pollutant loads.

Options for Addressing Concerns

Maintenance Dredging - Dredging would provide a temporary increase in water depth for recreational use. However, increased depths might be short-lived, given that coring showed that at least five feet of fine sediments have accumulated in the Area of Concern since it was previously dredged. Performing maintenance dredging of the channel could also destabilize the bank. Therefore, if dredging is to occur, a narrower channel might be an option to reduce bank instability. Modeling suggested that dredging would decrease channel velocities (consistent with rapid accumulation of fine sediment), increase residence time for pollutants, and not meaningfully reduce chlorophyll concentrations or increase dissolved oxygen.

Tree Removal - Selectively cutting and trimming trees and removing fallen trees would increase water access for recreational use and help prevent future tree falls and associated bank instability. Increased sunlight could also aid in establishing beneficial marsh plants along the channel edge, further enhancing bank stability. However, increased sunlight associated with tree removal has the potential of raising water temperature and increasing the growth of algae. Both observations and modeling indicate that high temperatures also reduce the ability of the water to hold oxygen. Increased temperature generally increases rates of photosynthesis and respiration, and sunlight further increases photosynthesis, both potentially leading to increased chlorophyll and more extreme levels of low DO.

Living Shoreline - Living shorelines consisting of coir logs, sand fill, and marsh plants could be constructed as a tertiary buffer for stormwater runoff if the trees are thinned to allow sunlight.

Do Nothing/Mixed Approach - A “do nothing shoreline” option also is valid for the study area. For example, the downstream portion of Buchanan Creek has extensive fringing marsh and little need for tree removal. If any of the above options were considered, they would not be equally appropriate in all areas.

LIST OF ACRONYMS

ACQOP	accumulation rates for nutrients in the LSPC model
Buch	Buchanan
Chl-a	chlorophyll-a
ConMon	continual monitoring instrument (samples every 15 minutes)
Cr	creek
DEM	digital elevation model
DEQ	Department of Environmental Quality
DIN	dissolved inorganic nitrogen
DIP	dissolved inorganic phosphorus
DO	dissolved oxygen
DOC	dissolved organic carbon
DON	dissolved organic nitrogen
DOP	dissolved organic phosphorus
EFDC	Environmental Fluid Dynamics Computer Code
ELCIRC	Eulerian-Lagrangian Circulation model
ELM	Eulerian-Lagrangian Method
FEMA	Federal Emergency Management Agency
FIB	fecal indicator bacteria
GPP	gross primary production
HEM3D	Three-Dimensional Hydrodynamic-Eutrophication Model
HSPF	Hydrologic Simulation Program FORTRAN
LIDAR	Light Detection and Ranging
LSPC	Loading Simulation Program in C^{++}
MHW	mean high water
MLW	mean low water
MS4	Municipal Separate Storm Sewer System
MWD	mean water depth
N	nitrogen
NAVD88	North American Vertical Datum 1988
NEM	net ecosystem metabolism
NERRS	National Estuarine Research Reserve System
NOAA	National Oceanic and Atmospheric Administration
NTU	nephelometric turbidity units
P	phosphorus
POC	particulate organic carbon
PON	particulate organic nitrogen
POP	particulate organic phosphorus
ROMS	Regional Ocean Modeling System
RTK-GPS	Real-Time Kinematic Global Positioning System
SAV	submerged aquatic vegetation
SCHISM	Semi-implicit Cross-scale Hydroscience Integrated System Model
SEAS	Shoreline Erosion Advisory Service
SELFE	Semi-implicit Eulerian-Lagrangian Finite Element model
SOD	sediment oxygen demand

SQOLIM	maximum storage limit for nutrients in the LSPC model
SWCB	State Water Control Board
SWMM	Storm Water Management Model
TDN	total dissolved nitrogen
TDP	total dissolved phosphorus
TMDL	Total Maximum Daily Load
TRO	Tidewater Regional Office
URS	URS Corporation (United Research Services)
US EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VADEQ	Virginia Department of Environmental Quality
VDH	Virginia Department of Health
VGIN	Virginia Geographic Information Network
VIMS	Virginia Institute of Marine Science
VPDES	Virginia Pollutant Discharge Elimination System
WSQOP	land washoff rates for nutrients in the LSPC model

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Introduction

The Virginia Institute of Marine Science (VIMS) was requested by the Virginia Department of Environmental Quality's (DEQ) Tidewater Regional Office (TRO) to assess specific characteristics of Buchanan Creek, a waterbody in the Lynnhaven River watershed, regarding concerns related to water quality. The Virginia General Assembly provided funds to assess the adequacy of Buchanan Creek's channel, shoreline deterioration along the headwaters, and contributions from the site of the former Birchwood Gardens sewage treatment plant adjacent to Buchanan Creek. This study builds on previous studies to address these issues conducted by local and state agencies over the past few years. VIMS investigators included faculty and staff from the Departments of Physical Sciences and Aquatic Animal Health, the National Estuarine Research Reserve System (NERRS) Program, and the Office of Research and Advisory Services.

As context for this work we note that VIMS has a long history of research in tidal hydrodynamic modeling and water quality assessment, and a long history of research on water quality in the Lynnhaven River system. In fact, our involvement with technical water quality issues within the Lynnhaven River began 42 years ago with a similar study of Buchanan Creek (Ho *et al.* 1977a). More details about the breadth and depth of VIMS' hydrodynamic Modeling and water quality assessment capacity, the history of our water quality monitoring and assessments within the Lynnhaven system, and some more historical background related to Buchanan Creek are provided in Appendix A.

Concerns about the general condition of Buchanan Creek have been expressed by watershed residents over a number of years. In response, actions that addressed these concerns were conducted by the City of Virginia Beach, the Tidewater Regional Office (TRO) of the Virginia Department of Environmental Quality (DEQ), the Virginia Department of Health (VDH), and the Shoreline Erosion Advisory Service (SEAS) of the Virginia Department of Conservation and Recreation (DCR). These efforts did not assuage the concerns of watershed residents, which ultimately resulted in action by the Virginia General Assembly to provide funding and instructions to the TRO to oversee a comprehensive analysis of all environmental water quality issues associated with Buchanan Creek.

Subsequently, VIMS was contracted to address three specific issues for Buchanan Creek relating to the condition of the waterway: (i) determine the adequacy of the channel, (ii) evaluation of shoreline deterioration, and (iii) address potential contamination of Buchanan Creek from the Birchwood Gardens former private sewage treatment facility. Existing data were critically reviewed by VIMS faculty and staff and found to be relevant, robust, and credible (see Appendix A for more detail about these data). Nevertheless, additional work was necessary to provide a comprehensive assessment of Buchanan Creek.

To fully address the objectives set forth by the General Assembly, VIMS undertook additional field work and hydrodynamic Modeling. Assessments of the shoreline condition and waterway geomorphology were conducted to address the question of channel adequacy. Channel depths, sediment characteristics, and shoreline/riparian surveys were collectively sampled and analyzed. Details of this work and our findings are presented in Chapter 1.

Water quality sampling and analyses within Buchanan Creek, and parallel efforts in Wolfsnare and Thalia creeks as waterways similar in character to use for comparative analyses were undertaken to establish present conditions and inform subsequent Modeling. Chapter 2 describes this work and presents our findings.

Hydrodynamic and water quality modeling that incorporated historical data and data collected through this study were used to form a comprehensive view of the character, behavior, and condition of Buchanan Creek. In doing, so we utilized the most advanced hydrodynamic modeling system in existence, SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model), to evaluate the effects of channel dredging on hydrodynamics, the LSPC (Loading Simulation Program C) watershed model, developed by the US EPA, to estimate nutrient and organic carbon inputs from upland runoff and stormwater, and the EFDC/HEM3 (Environmental Fluid Dynamics Computer) model, developed by VIMS, to simulate the eutrophication process. Results from this work are detailed in Chapter 3 and more information about these models and their use are provide in Appendix D.

This work serves to describe the condition of Buchanan Creek into the context of similar creeks in the upper Lynnhaven system and to provide some options for environmental managers to consider.

CHAPTER 1
Shoreline and Channel Assessment

Key Findings

- The typical low energy environment results in very low rates of shoreline change.

- Coring indicates that at least five feet of alternating fine sand and mud have deposited since the channel was last dredged. The top foot is relatively coarse sand and gravel indicating that occasional high energy flow is now preventing further accumulation of silt and clay.

- The banks are relatively stable and are only exposed and eroding in the intertidal zone and where trees have fallen.

- Selectively cutting and trimming trees is a viable shoreline management option.

- The Do Nothing shoreline management option also is valid for the study area. However, living shorelines consisting of coir logs, sand fill, and marsh plants can be constructed as a tertiary buffer for stormwater runoff if the trees are thinned to allow sunlight.

- The channel is very shallow at only about -1 ft below mean low water in the lower section of the Area of Concern (the extreme upper portion of Buchanan Creek. Near the stormwater outfall pipes at the upper end of Buchanan Creek the channel has completely silted in such that it is dry at low water.

- Performing maintenance dredging of the channel could destabilize the bank. Therefore, if dredging is to occur, a narrower channel might be an option to reduce bank instability.

Coastal Setting

Geology/Geomorphology

The Lynnhaven River lies within the coastal plain of Virginia Beach. It is connected to the Chesapeake Bay via Lynnhaven Inlet where tidal currents run quickly in both ebb and flood directions (Figure 1.1). Lynnhaven Inlet is the only opening to the Lynnhaven River, Broad Creek and Linkhorn Bay watersheds. It lies about 5 miles west of Cape Henry and about 5 miles east of Little Creek. The shorelines, both east and west along the Chesapeake Bay, are sandy beach and dunes with coastal development along much of the coast.

Just inside the Inlet, the Lynnhaven River diverges both southwest and southeast into the Western and Eastern Branches (Figure 1.1). Lynnhaven Bay also connects to Broad Bay through Long Creek. The Western Branch and Eastern Branch are separated by Little Neck. The drainage area of the Western Branch is about 8.21 square miles and about 6.53 square miles of drainage area for the Eastern Branch (Virginia Beach Comprehensive Plan, 2009). The Eastern Branch narrows southward to about 150 feet at approximately where Route 58 (Virginia Beach Blvd.) crosses the River. The tidal creek continues southward as London Bridge Creek, a narrow channel with minimal branches. The Western Branch of the Lynnhaven River narrows near Route 58 but terminates just beyond as a very narrow, meandering channel bordered by marsh.

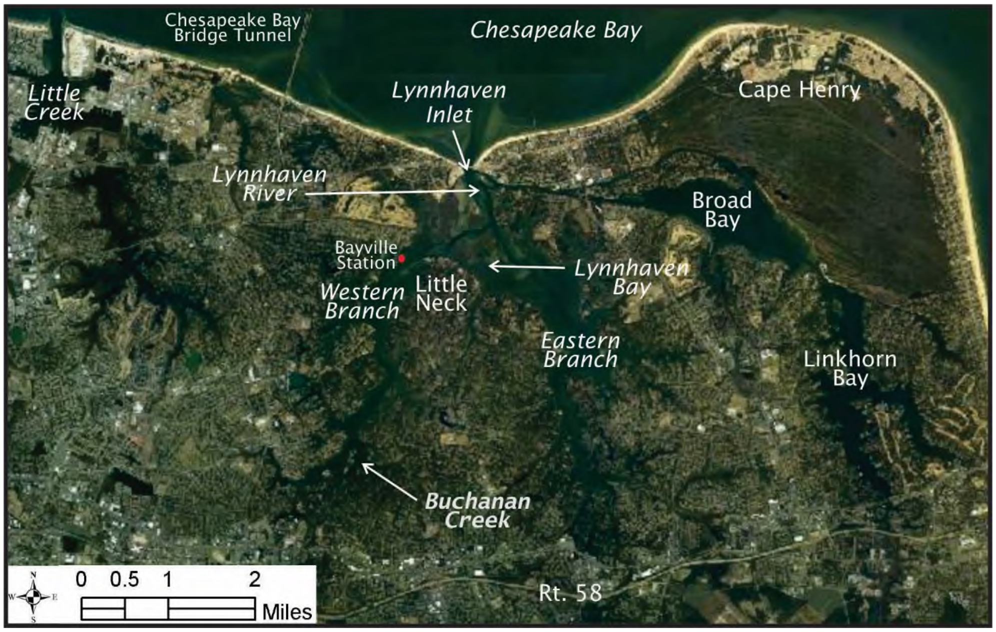
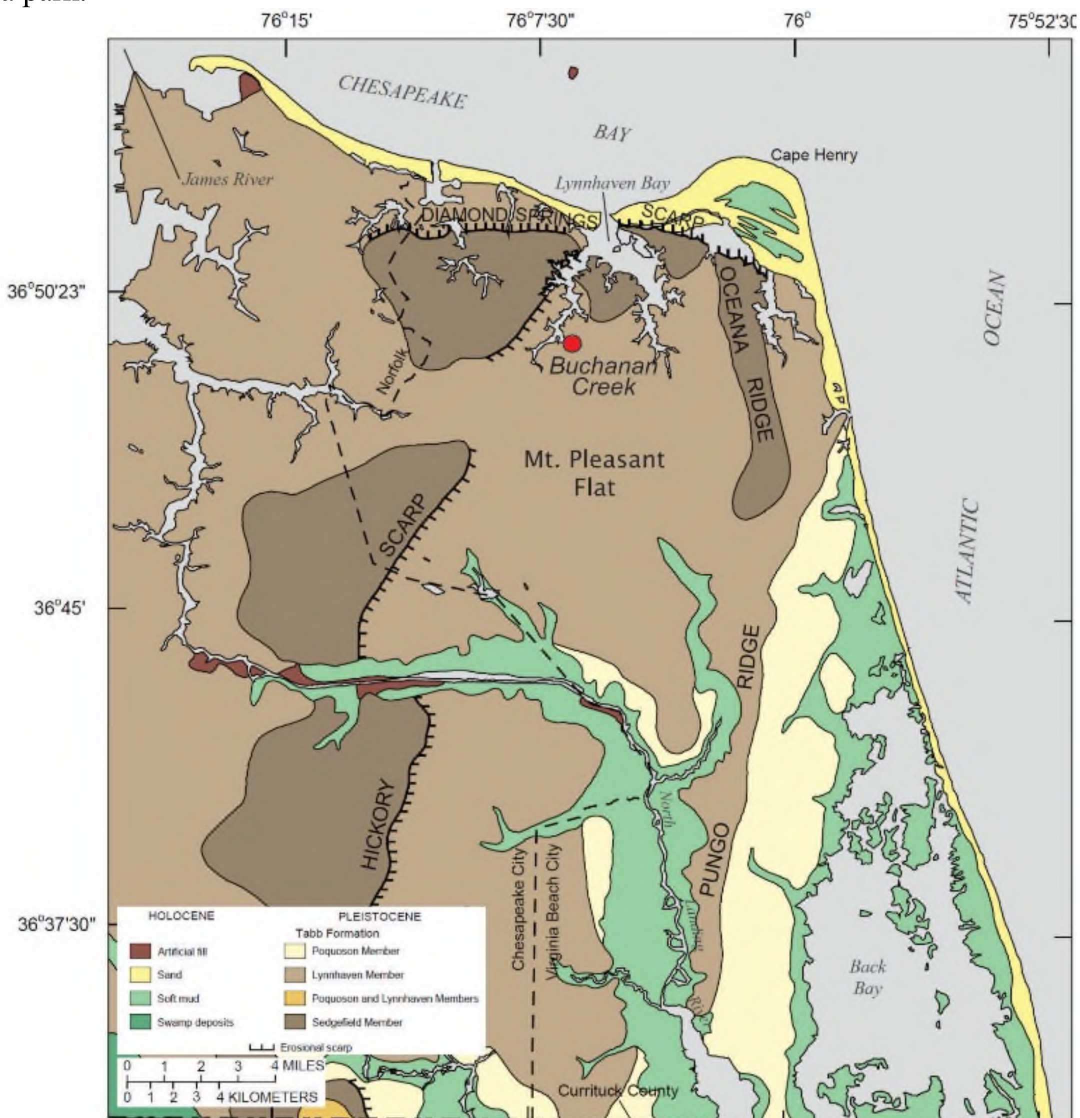


Figure 1.1. Location of Buchanan Creek within the Lynnhaven River watershed.

The Lynnhaven River watershed is formed by the Tabb Formation (Figure 1.2). It was likely deposited during the last major high stand of sea level that extended from approximately 75,000 to 135,000 years ago. The Tabb Formation has been divided from youngest to oldest into the Poquoson, Lynnhaven and Sedgefield Members that are likely the result of small scale variations in sea level with peaks occurring about 80,000, 105,000, and about 125,000 years ago (Toscano, 1992). The Lynnhaven Member underlies most of Virginia Beach and stretches from the west side of the Pungo Ridge to Hickory Scarp and from Lynnhaven Bay to the southern city limits along the North Carolina border (Smith and Harlow, Jr., 2002). A broad swale (low flat lands and wetlands) less than 20 ft above sea level has formed on the Lynnhaven Member (Mt. Pleasant Flat). The Lynnhaven is composed of a gray, pebbly, and cobbly, fine to coarse sand, grading upward into clayey and silty fine sand and sandy silt. These are the sediments that compose the upland banks in the southern portion of both branches of the Lynnhaven River.

In 1937 Buchanan Creek had numerous smaller tidal creeks draining to it (Figure 1.3). The upper reaches of the creek were characterized by narrow tidal channels and wide marshes. The area surrounding the creek was wooded undeveloped properties with a few farms. By approximately the mid-1950s, significant land use changes began with the construction of roads for subdivisions and several more farms (Figure 1.4). The development of residential properties occurred in the areas surrounding Buchanan Creek by 1970 (Figure 1.5). In addition, the upper limits of the creek were dredged to create wider channels likely to provide access for waterfront property owners and to facilitate upland drainage. Many of the shorelines along the Lynnhaven River watershed have changed concomitant with land use changes. This includes channelizing by dredging as well as damming numerous creeks (Figure 1.6). Starting in about 1970, many of the small tidal marsh tributaries to the Lynnhaven River system were dredged to create accessible waterfront. Between 1937 and 2009 approximately 214 acres of tidal marsh were converted to open water (Hardaway et al, 2013). Another trend in man-made impacts to the Lynnhaven River watershed is the damming of tidal creeks to create small lake or ponds. Approximately 202 acres of conversion of this type can be seen in Figure 1.6.   This occurred at Buchanan Creek where a tidal creek was converted into a pond for a sewage treatment plant, which has since closed and become a park.



Base from Mixon and others, 1989, Virginia Geology, 1:250,000

Figure 1.2. Surficial geology and geomorphic features at Virginia Beach, Virginia. (From Smith and Harlow, Jr., 2002)

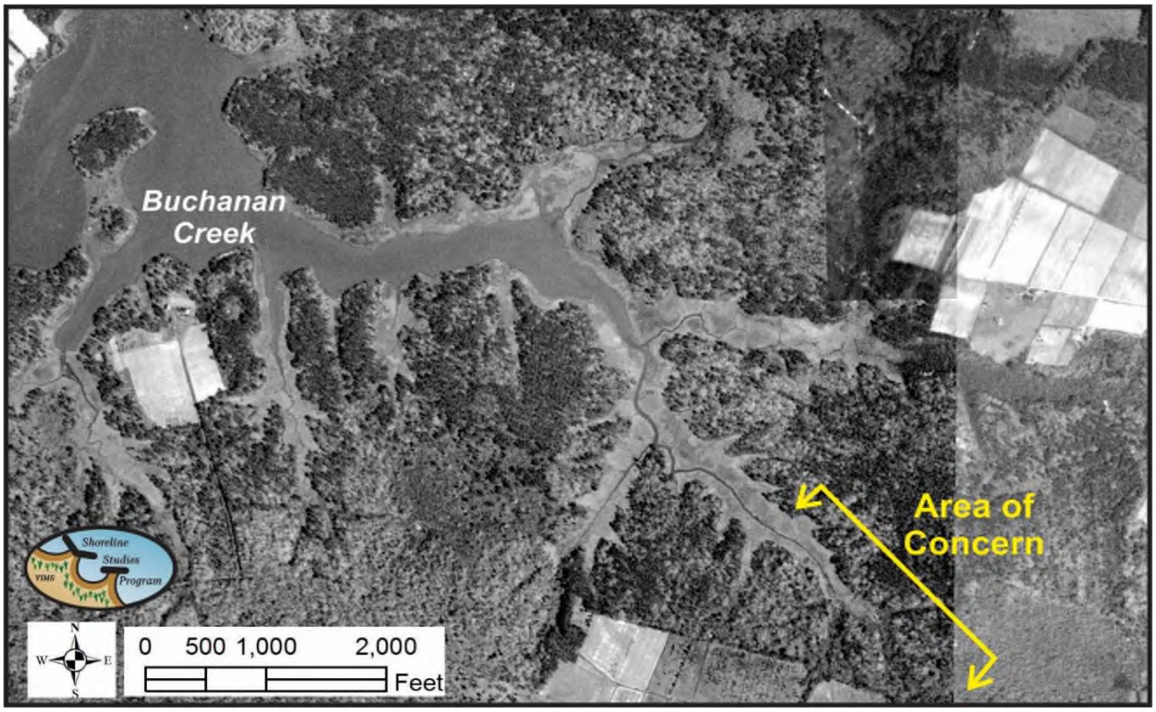


Figure 1.3. Aerial image of Buchanan Creek taken in 1937 (Milligan et al., 2012).

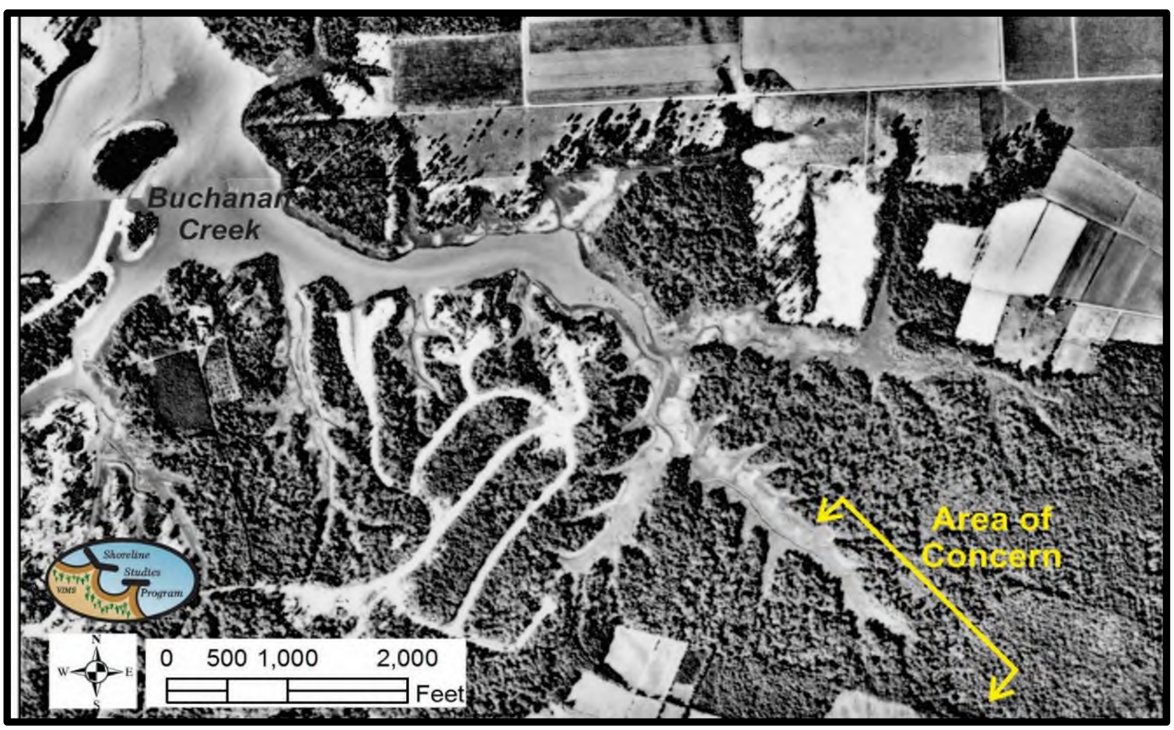


Figure 1.4 Aerial image of Buchanan Creek taken in 1954 (Milligan et al., 2012).

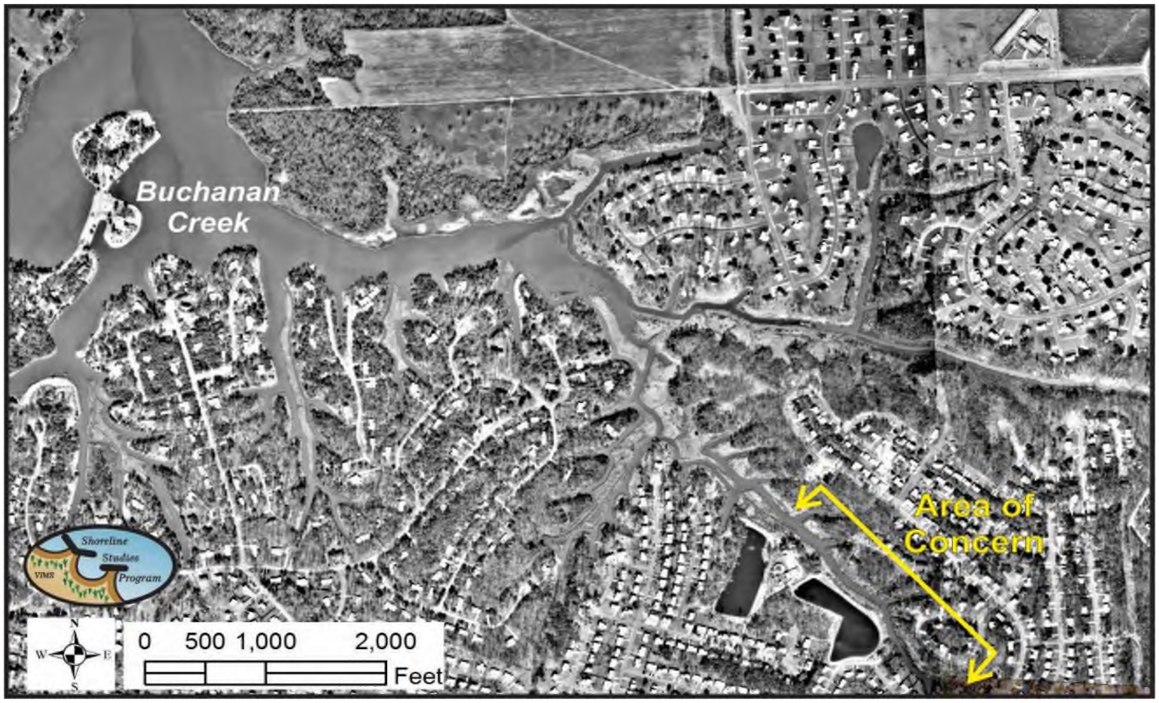


Figure 1.5. Aerial image of Buchanan Creek taken in 1970 (Milligan et al., 2012).

Coastal Hydrodynamics

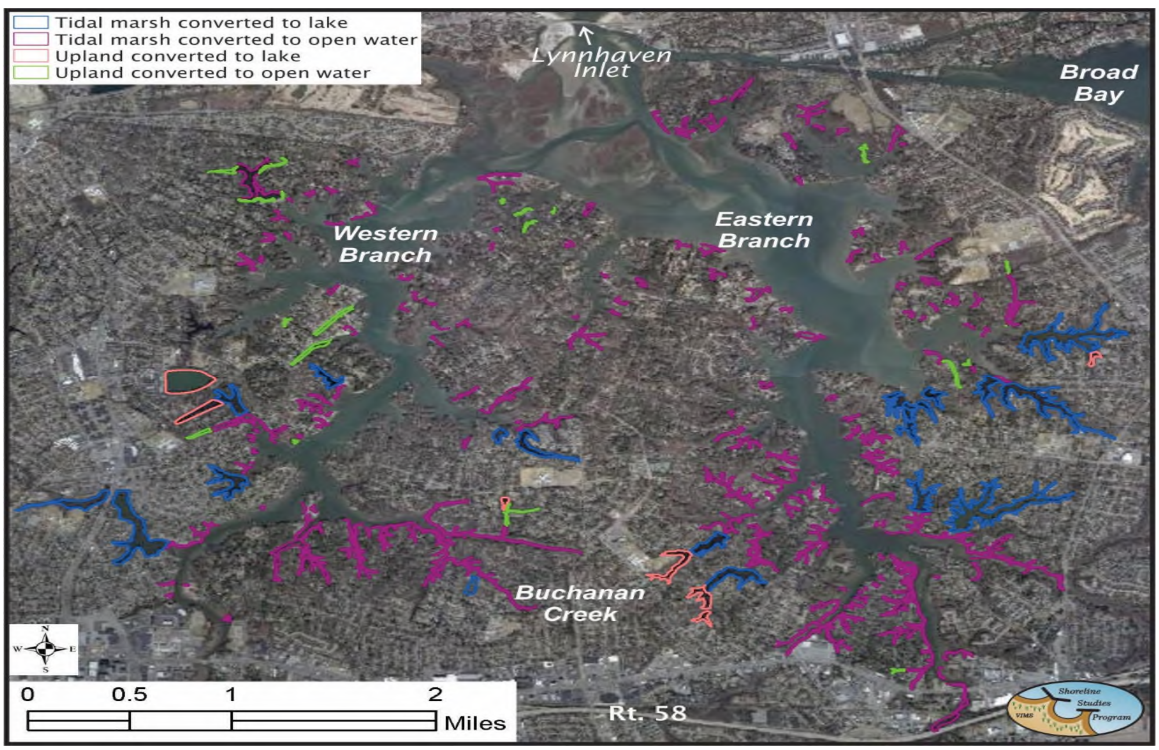


Figure 1.6. Orthorectified image of Lynnhaven River showing the areas where marsh and upland were dredged to create channels and lakes for development (Hardaway et al., 2013).

Wave Climate

Shoreline change (erosion and accretion) is a function of upland geology, shore orientation and the impinging wave climate (Hardaway and Byrne, 1999). Wave climate refers to averaged wave conditions as they change throughout the year. It is a function of seasonal winds as well as extreme storms. Seasonal wind patterns vary. From late fall to spring, the dominant winds are from the north and northwest. During the late spring through the fall, the dominant wind shifts to the southwest. Northeast storms occur from late fall to early spring. Fetch, the distance over which wind blows toward the coast, can be used as a simple measure of relative wave energy acting on shorelines. The shorelines along Buchanan Creek are low energy with minimal or no fetch exposures under normal environmental and meteorological conditions. Therefore, wave climate is not a significant issue in the Area of Concern.

Storm surge frequencies describe the 10%, 2%, 1% and 0.2% chances of water levels attaining these elevations for any given year in the Lynnhaven. These percentages correspond to 10-year, 50-year, 100-year, and 500-year events and are 6.7 ft, 8.0 ft, 8.6 ft, and 10.2 ft MLW, respectively, for the Western Branch of the Lynnhaven River (FEMA, 2015). At Bayville Station on the western side of Lynnhaven Bay, the mean tide is 1.7 ft. Farther into the Western Branch, the mean tide range is 1.9 ft. Water levels during storm surges may affect erosion in the Area of Concern, depending upon duration of exposure.

Sea-Level Rise

On monthly or annual time scales, waves dominate shore processes and, during storm events, leave the most obvious mark. However, on time scales approaching decades or more, sea level rise is the underlying and persistent force responsible for shoreline change. Recent trends based on wave gauge data at the Chesapeake Bay Bridge Tunnel show the annual rate to be 1.94 feet/100 years (5.92 +/-0.72 mm/yr) (NOAA, 2019). Although a primary issue of concern for all of Tidewater, sea level rise is not a significant near-term issue in the Area of Concern and was not a focus of this study.

Shore Erosion

Shoreline erosion results from the combined impacts of waves, sea level rise, tidal currents and, in some cases, shoreline hardening. Since the shorelines are low energy and the amount of shoreline hardening that has occurred, the average end point rate of shoreline change for Lynnhaven River is only -0.1 ft/yr (1937-2009) (Milligan et al., 2012). Therefore, shoreline erosion in the Area of Concern, and adjacent areas, was not expected to be a significant issue.

Area of Concern Setting

Previous dredging

The Area of Concern, the project shoreline, is located near the distal end of the southeast branch of Buchanan Creek (Figure 1.7). The 1937 aerial shows the extent of the natural marsh pre-dredging with the post dredging shoreline of 1970 and recently in 2017. The dredging took place along the central part of the old tidal creek and following up into the lateral small channels. It removed the marsh and significantly widened the channel. At the terminus of the old marsh (Point D of Figure 1.7) the dredging proceeded northeast up a small drainage and southeast following the existing drainage as it curved in an arc. This latter section likely was cut into the uplands adjacent to the drainage in order to maintain the channel width. This area is characterized by steep unvegetated banks, and is the main subject of shoreline management concerns.

In 1970, the dredged channels are clearly shown along with modifications to the adjacent landscape. These include roads and the associated residential housing as well as the sewage treatment plant on the south shore. This includes two associated ponds, the northwest pond was created by damming up a small tidal creek and the southeast pond by excavating the upland. Of note is the riparian buffer, the trees, adjacent to the shoreline. In 1970, few trees existed in the riparian buffer, but by 2017, about 50 years of growth provides significant shade along the waterway. In addition, numerous trees have fallen in the upper reach of the Area of Concern.

Since the initial dredging of Buchanan Creek the channel has had at least one maintenance dredging. This occurred in October/November 2000 at the entrance to Buchanan Creek and extended up the creek about a mile (Figure 1.8). It stopped short of the Area of Concern. Channels were dredged to about -3 ft MLW at that terminus of the project with channel banks on a slope of 1:2 (Figure 1.9).

Shoreline and creek profiles

The bathymetry for the Area of Concern was extracted from a US Geological Survey digital elevation model (DEM) created from Light Detection and Ranging (LIDAR) data taken in 2013. Twenty-one cross-sections were created in the Area of Concern to depict the banks and channels (Figure 1.10). These cross-sections were validated by survey data taken by the Shoreline Studies Program (SSP) across several cross-sections and with elevations taken along the center of the channel. A benchmark was established in the park with Real-Time Kinematic Global Positioning System (RTK-GPS). Surveying under tree cover is not possible for RTK-GPS which uses satellites to establish location and elevation within 6 cm so the elevation of the benchmark was carried to the creek with a Trimble Robotic Total Station to establish temporary benchmarks. The creek channel and cross-sections were surveyed in January 2019 utilizing these temporary benchmarks with the Total Station. Line of site is required to survey with the Total Station so points were limited in this heavily vegetated shoreline area. In addition, some areas of the creek consisted of extremely soft mud and could not be traversed. Though some differences exist between the January 2019 survey and the 2013 LIDAR data and the edges of the banks could not always be surveyed due to no line of site, enough points were obtained to validate the 2013 LIDAR data in the Area of Concern for this project (Figure 1.11). Both the survey data and the LIDAR data were collected relative to North American Vertical Datum 1988 (NAVD88). They were converted to mean low water using The LIDAR DEM and should not be considered accurate for dredging or shore management construction projects.

The cross-sections extracted from the 2013 LIDAR DEM are plotted in Appendix B. They show a steadily decreasing channel depth and increasing bank heights moving from profile 1 to profile 21. From profile 1 to 11, remnant marsh fringe exists on the north and south shoreline. This low fringe is a terrace in front of the upland banks which provides erosion protection to the adjacent low upland banks from tidal action (Figure 1.12). At profile 12, the nature channel and marsh ended; therefore, the dredged channel continued into the underlying upland strata rather than existing natural sub-bottom or natural marsh. Upstream from profile 12, the channel banks get higher, steeper and more exposed proceeding upstream (Figure 1.13).

These upland bank slopes of profiles 12-21 can be characterized by the base of bank that is under the daily influence of the tide and extends from MLW (0') to MHW (+2). The bank face continues landward above MHW (>2'). Table 1-1 shows the slopes measured from the LIDAR DEM profiles (Appendix B) for both the base of bank and bank face. The base of these banks consists primarily of a medium gray stiff clay and have slopes that vary between 2.5:1 (horizontal : vertical) and 5:1 along profiles 12-18. At profiles 19-21, mean low water becomes concurrent with the channel bottom and the intertidal slope decreases. Stiff clay is a difficult substrate for marsh grasses to become established naturally, especially on steeper slopes. The gray clay is interpreted as part of the underlying Pleistocene strata that extends upward and is usually overlain by strata that contain more sand. The bank face is generally steeper and heavily vegetated but stable. No bank face slopes exceed 1:1, which is when the slopes tend to become less stable depending on the geology. With no vertically exposed base of bank and the heavily vegetated bank face, the shorelines along Buchanan Creek are considered stable.

A core was taken at about Profile 12 (Figure 1.14). It shows at least 5 feet of sediments deposited since the channel was dredged. The core likely did not reach the original dredge channel bottom. This depositional sequence shows the bottom few inches to be a peat-like layer overlain be several feet of alternating fine sand and clay indicating episodes of quiescence (characterized by silt and clay deposition) and periods of storm runoff (characterized by sand). The top foot is relatively coarse sand and gravel indicative of high energy storm flow at that location.

Table 1.1. Base of bank and bank face slope measurements from the LIDAR DEM profiles. The larger the horizontal number, the gentler the slope. The smaller the horizontal number, the greater the slope.

Profile Number	Side of Creek	Base of Bank Slope Ratio	Bank Face Slope Ratio
12	North	2.5:1	2.5:1
	South	3.5:1	3.5:1
13	North	5.1:1	2.5:1
	South	-	-
14	North	2.5:1	1.5:1
	South	3.5:1	5.5:1
15	North	5.1:1	2.5:1
	South	2.5:1	2.8:1
16	North	2.5:1	1.5:1
	South	3.5:1	4.1:1
17	North	4.0:1	1.4:1
	South	-	-
18	North	10.0:1	1.6:1
	South	2.0:1	4.6:1
19	North	8.5:1	2.2:1
	South	7.5:1	2.8:1
20	North	11.1:1	1.7:1
	South	8.5:1	3.5:1
21	North	10.0:1	1.3:1
	South	6.0:1	2.0:1

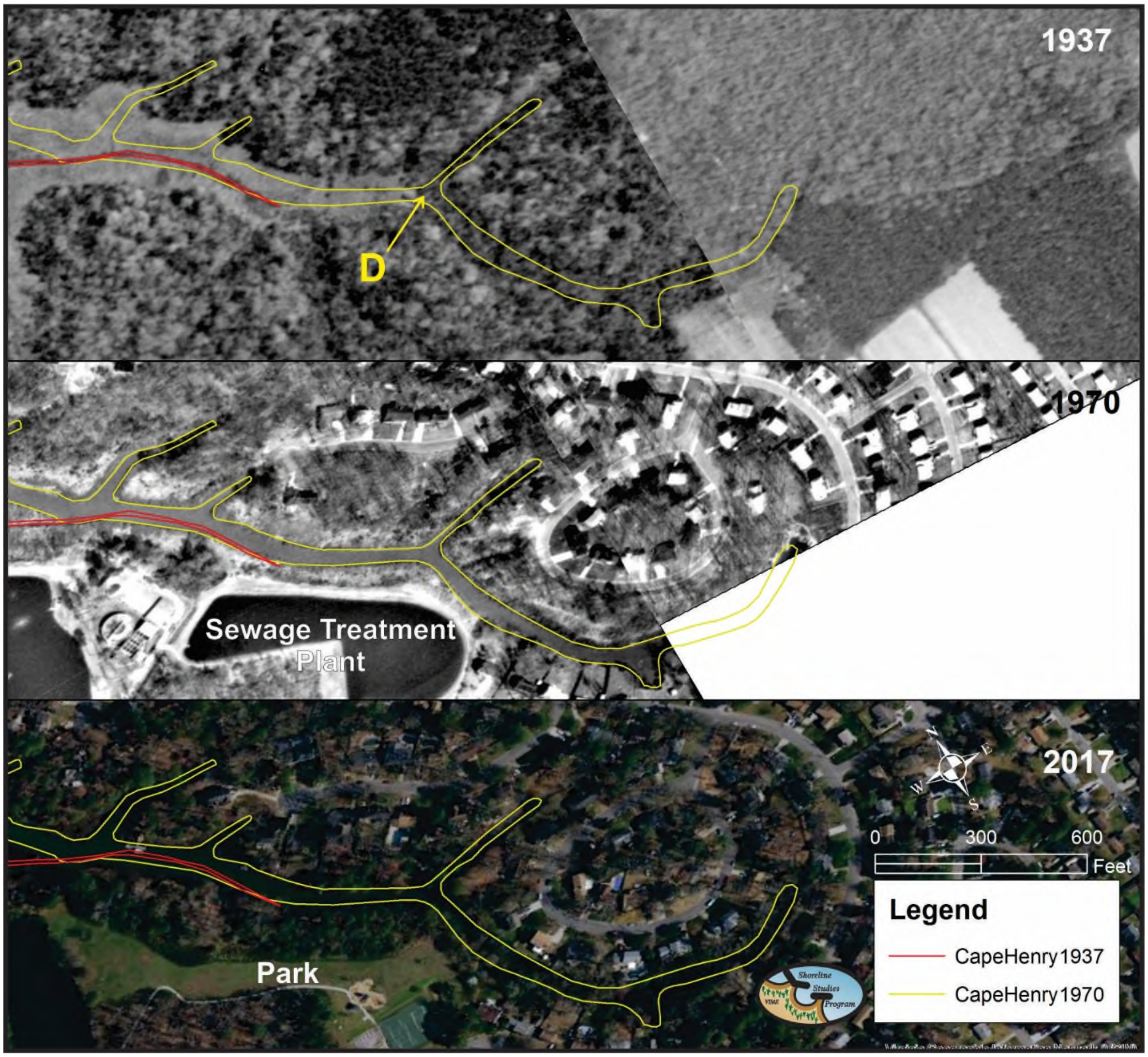


Figure 1.7. Buchanan Creek Area of Concern through time in 1937, 1970, and 2017 showing the digitized shoreline in 1937 and 1970.

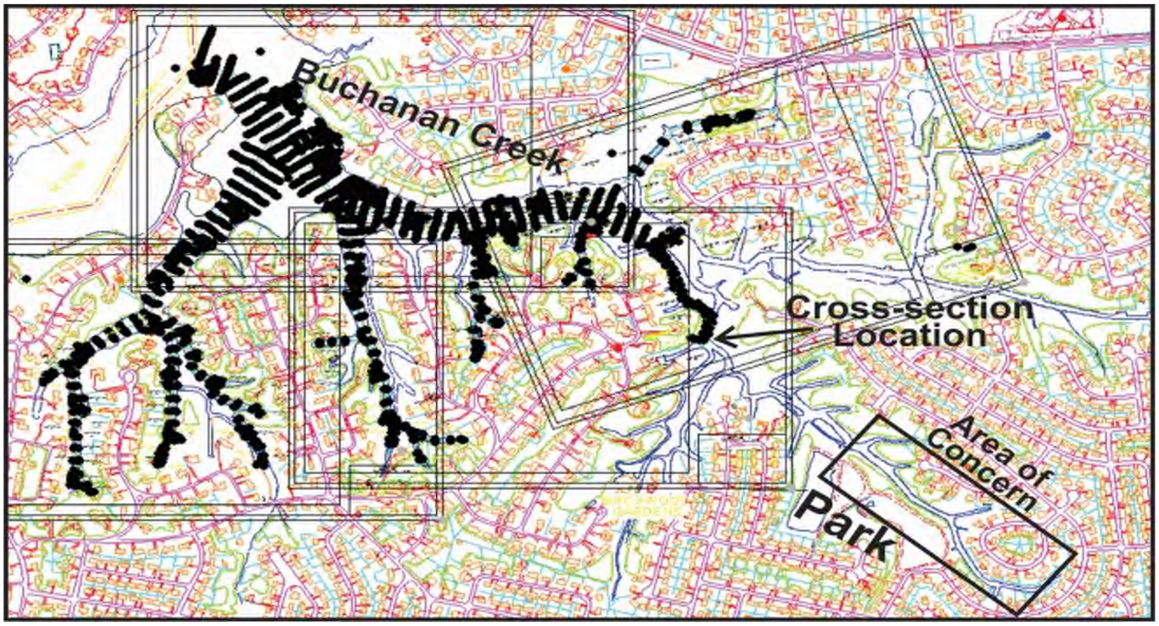


Figure 1.8. The extent of maintenance dredging for Buchanan Creek in October/November 2000. It did not extent to the area of concern. Dredge survey data courtesy of Waterway Surveys & Engineering, Ltd.

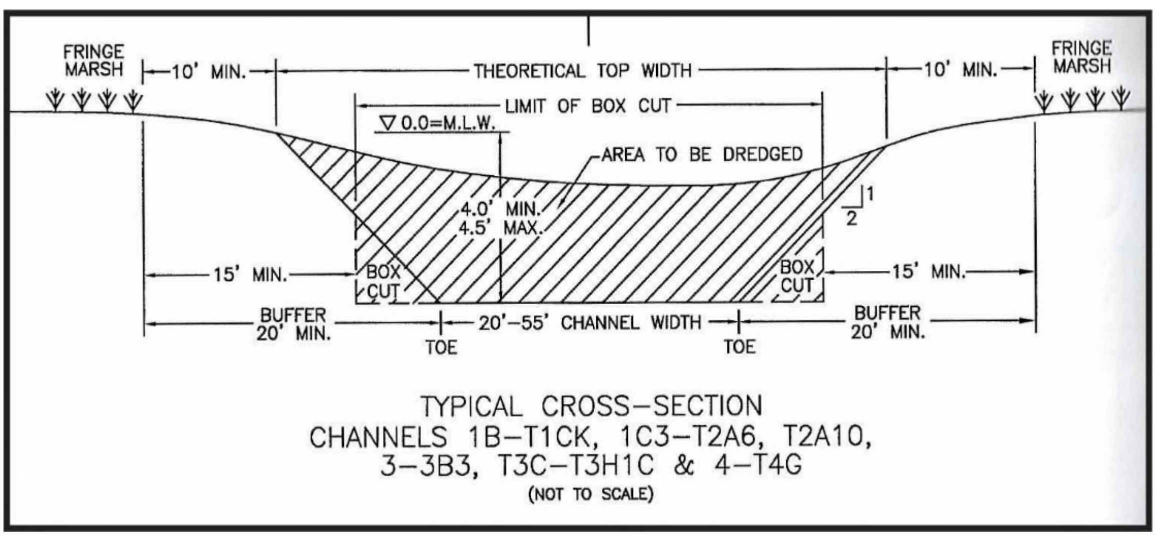


Figure 1.9. The typical cross-section at the terminus of the project for the dredged channel in Buchanan Creek. Dredge survey data courtesy of Waterway Surveys & Engineering, Ltd.

Figure 1.10. Cross-sectional profile locations extracted from the 2013 LIDAR DEM data.

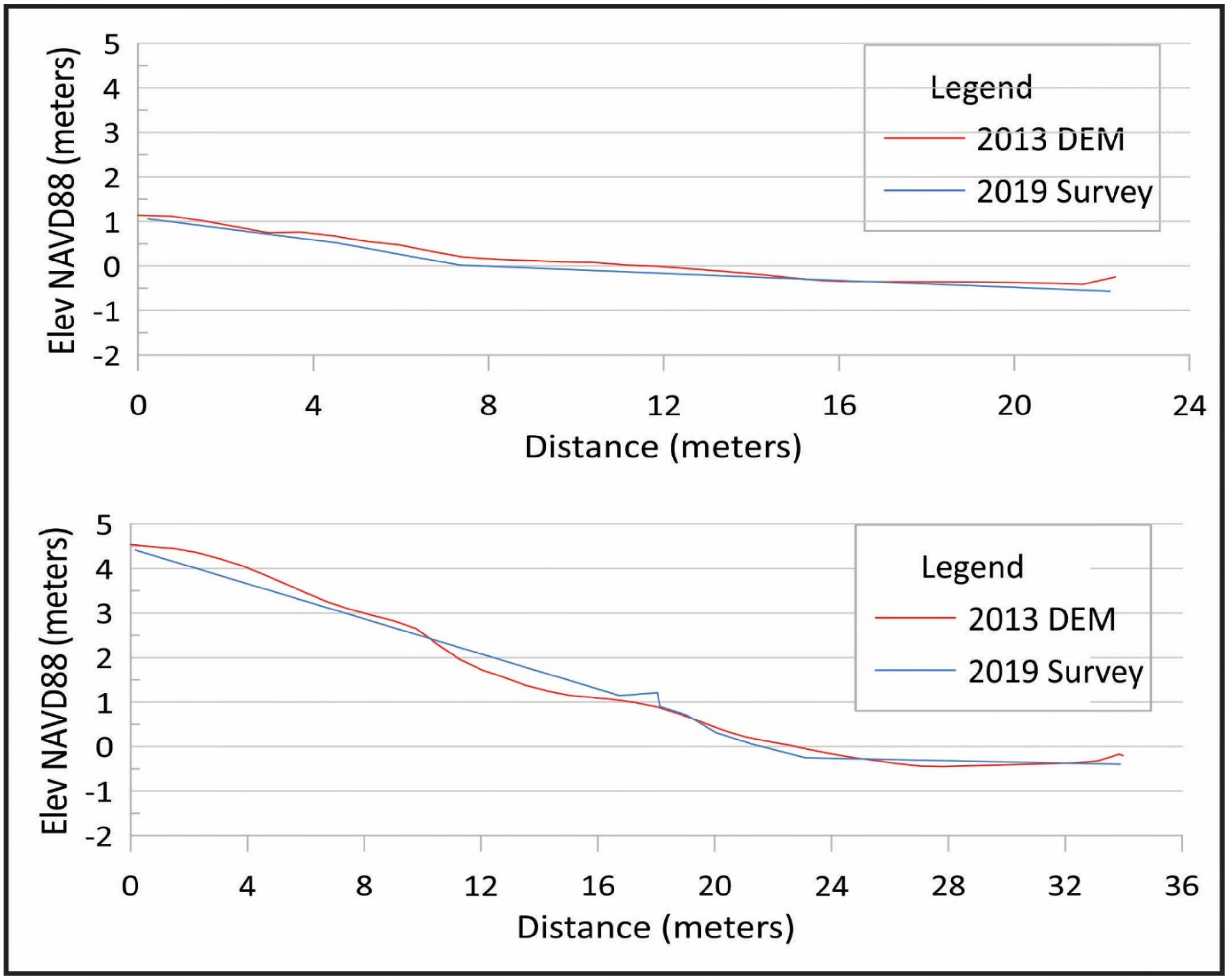


Figure 1.11. Comparison between 2013 LIDAR DEM data and the 2019 Shoreline Studies Program along two cross-sections in the Area of Concern in the upper reaches of Buchanan Creek.

Figure 1.12. Buchanan Creek looking downstream from about profile 11 at wide terrace on south side

Figure 1.13. Buchanan Creek upstream from profile 12 where the channel was incised into the upland so the banks are higher. 2019.

Bank Evolution

The upland banks have evolved since Buchanan Creek was dredged. A box cut channel was most likely dug to provide water access to newly created lots and to facilitate upland drainage. Much of this material may have been side cast onto the adjacent uplands and marsh. As the dredging continued past point D, the upland shoreline banks were most likely left in a state of being exposed and minimally vegetated. The channel was dug at least -6 ft MLW (from the core data) although a deeper channel has been reported by long-term residents of the Creek in a 2018 article by the Southside Daily (Weinstein). Bank evolution from first cut to today involves several factors including 1) tree growth 2) hydrodynamic forces such as tidal and stormwater runoff, and 3) channel infilling that elevates base of bank vertically over time.

With time, tidal action, and rainfall, the bank slopes equilibrated to a state of dynamic equilibrium. The base of the shoreline bank resides in the intertidal zone. Because the channel was deeper when it was first cut, the base of the bank was lower, at least 5 feet lower. With time and sedimentation, the channel filled and the base of bank elevation decreased, which helped stabilize the upper bank face.

Trees have grown along the bank slopes since the original project. Small trees along the bank top became large trees often growing outward and up as the banks sloughed, slowly widening the creek basin. However, over time, as the tree mass becomes too great to be supported by the undercut root system, they fall, often across the creek. When the trees fall, the bank is destabilized. Presently, the intertidal zone lacks and significant wetland vegetation upstream from profile 12. The base of the bank is undercut by tidal action where flow can be exacerbated by significant stormwater events due to the stormwater outfalls located at the upper end of the creek.

Shoreline and channel management

Shoreline management in Chesapeake Bay involves several options including 1) doing nothing, 2) a defensive approach or 3) an offensive approach. A combination of the two may have its place in different sections of Buchanan Creek.

1. The <u>Do Nothing</u> approach is to basically leave the creek and shorelines as they are. This often is not a popular approach with the waterfront property owners because bank undercutting can look like erosion. However, in many low-energy areas, the rate of shoreline change is so low that no management strategy is truly necessary. Any management options applied are for ascetics rather than need.

2. The <u>Defensive</u> approach involves hardening the shoreline with sheet pile bulkhead or rip-rap revetment (Figure 1.15).

3. The <u>Offensive</u> approach involves going into the intertidal zone and channel in order to create a tidal wetland system that will in turn protect the base of the sloughing banks and allow the bank face to evolve toward stability. Bank grading may be possible is some areas. Creating a marsh at the base of bank generally provides overall bank stability.

However, until dense vegetative growth is attained, significant storm events, creating intense stormwater out flow, may impact the newly established vegetation. Also, the success of this approach relies on a minimum of about 6 hours of sunlight during the growing season for low marsh to survive and will require significant tree thinning or removal to attain. Furthermore, this approach may be more practical on the north shore with southern exposure (Figure 1.16). Planting existing intertidal zone with *Spartina alterniflora* can be successful in low wave energy conditions with sufficient sunlight and site maintenance to keep trees and bushes from shading the site (Hardaway et al., 1984).

Shore management options

From Profile 1 to Profile 7, low marsh fringes occur on both sides of the creek with adequate width to buffer the adjacent upland bank (Figure 1.17). The front edges are relatively stable and not undercut so the Do Nothing approach is most appropriate. Moving upstream, at about profile 7 to profile 9, the low intertidal marsh fringe is reduced on the south side but still wide and vibrant on the north side (Figure 1.18). Although some low marsh exists along the very upper reaches of the tide range, the lack of marsh on the south side can be attributed to shading. No upland bank scarping occurs on either side. Thinning trees on the north side may allow enough light to help promote low marsh growth farther into the creek. However, the lower limit to which *Spartina alterniflora* will grow is about mid-tide so not much more fringe can be expected. On the south side, thinning of trees and planting existing substrate may promote marsh growth; however, no erosion problem exists so the Do Nothing option is preferable.

At profile 10 (Figure 1.19) the north and south side marsh fringes are very sparse. An old wood bulkhead can be seen on the north side of profile 11. The recommended option is still a Do Nothing approach. Replacing the old wood bulkhead would be a secondary option.
Profile 12 (Figure 1.20) begins the increase in bank height along the creek because the channel was originally incised into the upland. No significant marsh fringe occurs along the shoreline at profiles 12, 13, and 14 (Figure 1.21). The intertidal zone is exposed clay, and the upland bank portions are heavily vegetated. Trees do grow on the bank and should be thinned before they fall and create local pockets of bank instability. No structural options are necessary along the shoreline; however, if trees are thinned, a marsh can be planted for landscaping purposes or as a tertiary buffer for stormwater runoff and sedimentation. A living shoreline can be constructed with coir logs staked in the nearshore and backfilled with sand (Figure 1.22). Marsh grasses can be planted on the new substrate. Up the creek from profile 12, sections of shoreline that receive enough sunlight will support a narrow fringe marsh in the intertidal zone (Figure 1.23).

Profile 15 also has an exposed intertidal zone and heavily vegetated bank on both sides of the creek. In addition, many trees have grown up along the shoreline. As they fall, the creek is blocked for recreational access (Figure 1.24). This trend continues up the creek through all of the profiles (Figure 1.25). In addition, the channel is narrowing and becoming shallower. Sedimentation from the stormwater outfall pipes have silted in the channel at profile 21 such that is it dry at low water (Figure 1.26). Because the channel has filled in above mean low water the areas between mid-tide and mean high water could be planted with *Spartina alterniflora*.

Several years ago, the Shoreline Erosion Advisory Service in the Department of Conservation and Recreation provided suggestions for the shorelines of Buchanan Creek. The shoreline engineers suggested that the trees and shrubs on the bank and within 15 feet of the top of the bank edge should be selectively cut or trimmed because trees displace large amounts of soil when they fall. Tree removal should decrease the weight on the bank and reduce the chance of bank sloughing (Vanlandingham, 2017). However, tree removal restrictions occur in the riparian buffer under the Chesapeake Bay Preservation Act. If this strategy is applied, the City of Virginia Beach should be contacted for specific guidelines and the Department of Environmental Quality's riparian buffer manual can be found here:

https://www.deq.virginia.gov/Portals/0/DEQ/Water/Publications/RiparianBufferManual.pdf

If trees are removed, the bank should be stabilized with vegetative ground cover. Vanlandingham (2017) recommended a mixture of native grasses and other low growing vegetation that will help protect the bank from erosion, reduce stormwater runoff and sedimentation to the creek. A list of appropriate grasses and ground covers for the upland bank was provided and is shown in Appendix C. Additional information on ground covers can be found online. These plants can only be planted above mean high water:

https://www.pubs.ext.vt.edu/content/dam/pubs_ext_vt_edu/426/426-609/426-609.pdf

Maintenance dredging

Any proposed dredging should be assessed as it relates to shoreline management options. Since the initial dredging of Buchanan Creek in the 1960s, it is likely that the channel within the Area of Concern has not been dredged again. However, the maintenance dredging at the entrance to Buchanan Creek resulted in channel depths to about -4 ft MLW at that terminus (Figures 1.8 and 1.9). Any proposed dredging of the Area of Concern would have to begin at the -4 ft MLW contour and proceed up the creek. This will require the proper dredging equipment and a permitted dredge plan and disposal area. Significant amounts of material would likely have to be taken offsite for disposal. In addition, many trees would have to be removed from the channel and banks to provide equipment access.

The effect of dredging to the original channel width footprint may, in fact, destabilize the banks that have evolved relatively stable bank faces particularly along the upper reaches of the creek (Profiles 12-21). By cutting the channel up to the base of bank, the bank slope may become unstable and the bank face may slump over time. Though it may stabilize in the long-term, its effect would be obvious up the bank face. Therefore, it would be prudent to dredge a narrower channel, if possible, some calculated distance from the creek shoreline that would allow for the box cut to mean low water only.

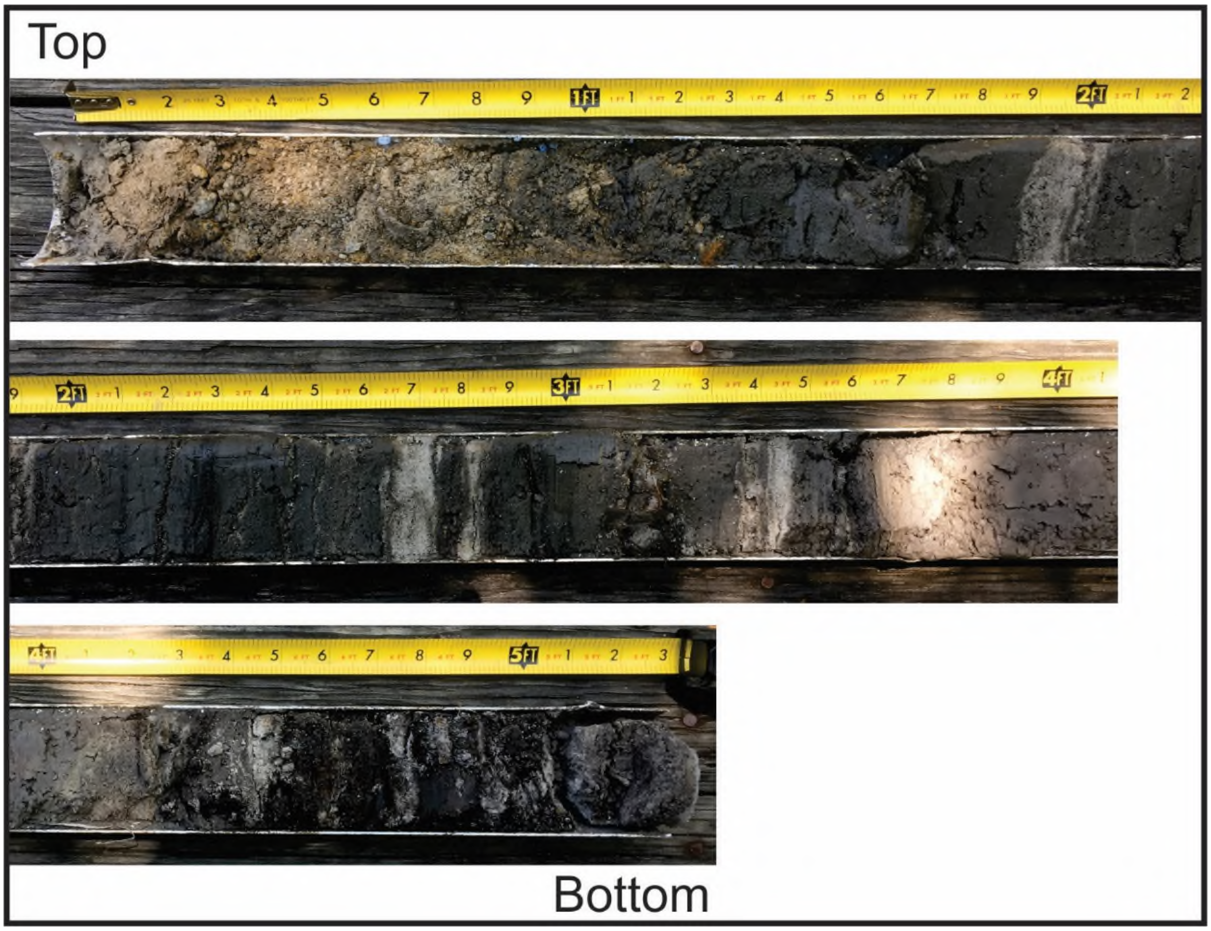


Figure 1.14. Photo of core taken in the Buchanan Creek channel at about profile 12.

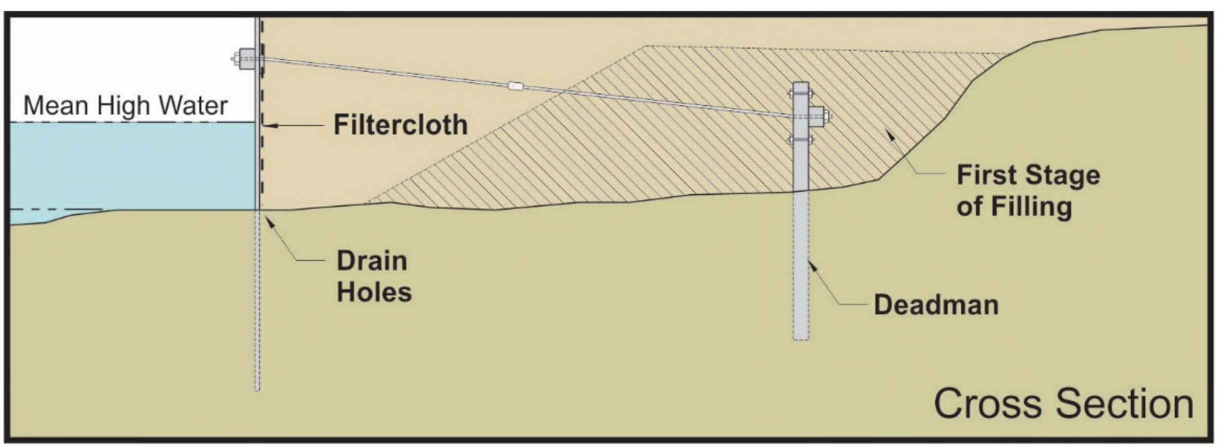


Figure 1.15. Typical cross-section of a sheet pile bulkhead.

Figure 1.16. Marsh restoration site. A) Minor bank grading and temporary toe protection using straw bales was used to protect the planted marsh fringe. B) One year after construction. C) After six years. D) after 24 years.

Figure 1.17. Approximate location of profiles 4, 5, and 6. Both the north and south sides of the creek have wide fringe marshes to protect the upland bank.

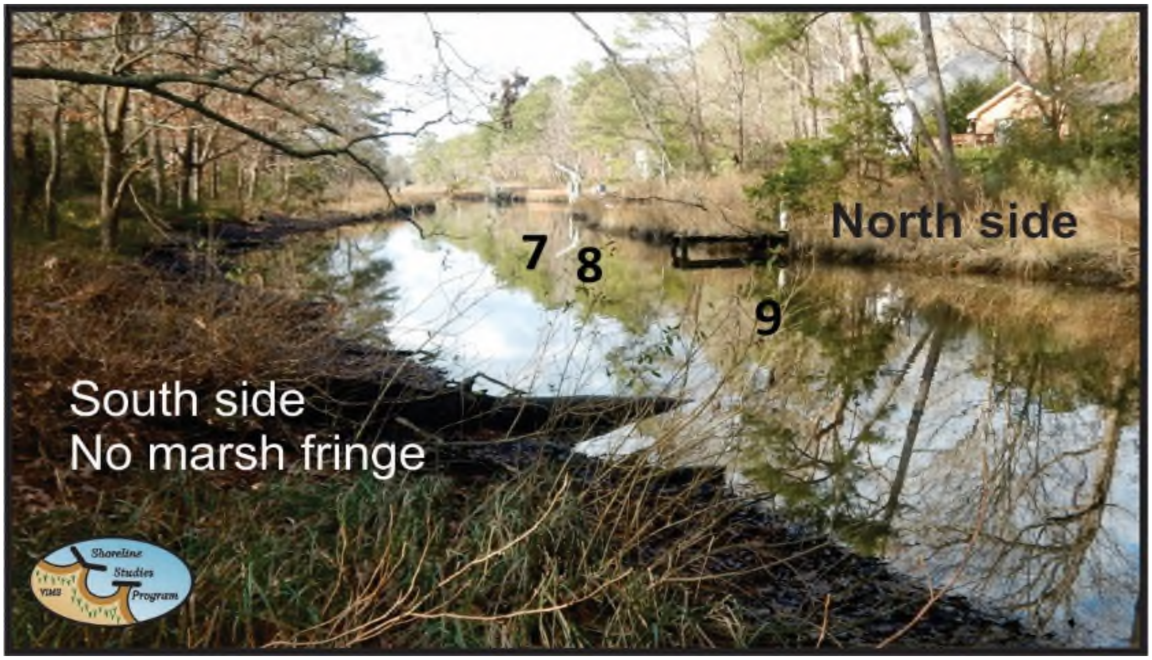


Figure 1.18. Approximate location of profiles 7, 8, and 9. The north side of the creek still has a wide fringe marsh, but no marsh occurs on the south side due to shading.

Figure 1.19. Approximate location of profiles 10 and 11. The north side of the creek still has a wide fringe marsh, but no marsh occurs on the south side due to shading.

Figure 1.20. Approximate location of profile 12. The intertidal zone is exposed clay substrate though the upper bank is heavily vegetated creating an overall stable profile.

Figure 1.21. Approximate location of profiles 13 and 14. The intertidal zone is exposed clay substrate though the upper bank is heavily vegetated creating an overall stable profile.

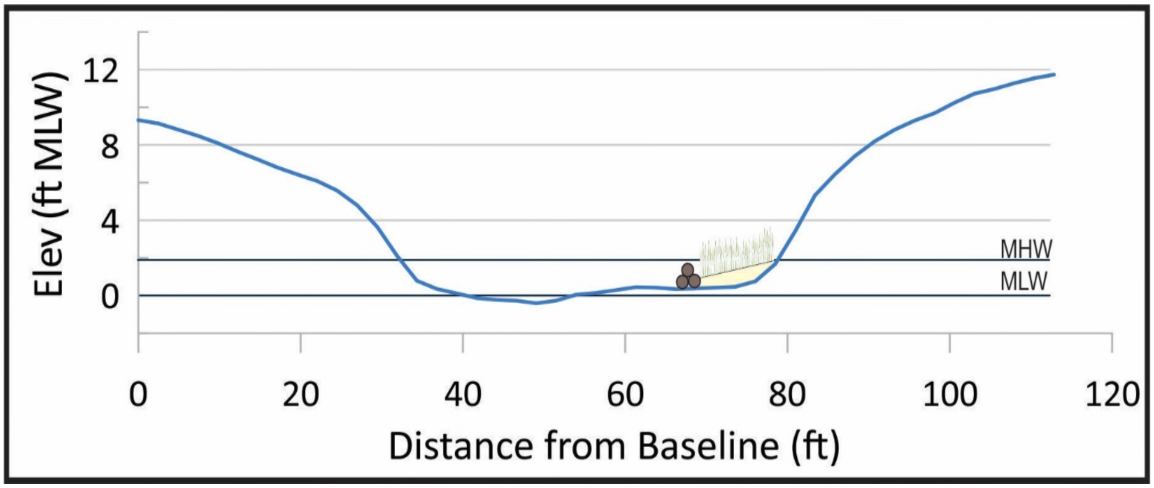


Figure 1.22. Typical cross-section for a living shoreline option to create a marsh in the exposed intertidal zone.

Figure 1.23. In areas of the creek above profile 12 that receive enough sunlight, a narrow fringe marsh can exist in the intertidal zone.

Figure 1.24. Approximate location of profile 15. The intertidal zone is exposed clay substrate though the upper bank is heavily vegetated creating an overall stable profile. However, fallen trees create locally unstable banks and block recreational access.

Figure 1.25. Approximate location of profile 18. The intertidal zone is exposed clay substrate though the upper bank is heavily vegetated creating an overall stable profile, and the channel is narrowing and becoming more shallow up the creek.

Figure 1.26. At the uppermost reach of the creek at profile 21, sediment from the stormwater outfall has accreted and the channel is dry at low water.

Chapter 2
Water Quality Observations

Key Findings

Key findings of water quality high frequency water quality monitoring and field surveys are as follows:

- Buchanan Creek, along with the reference Wolfsnare and Thalia Creek stations, exhibited elevated dissolved oxygen concentration (DO_{conc}) variability and observed minimum and maximum values indicative of shallow creeks with relatively high levels of nutrient input characteristic of urban runoff. Given the regular night-time occurrence of low DO_{conc} events and extended duration of some events, hypoxia can be viewed as a seasonal chronic issue within the upper Buchanan and reference creek systems. It should be noted that periodic low oxygen conditions are a natural characteristic of diel and longer cycles in marsh dominated tidal creek systems that exhibit high metabolism rates and are net heterotrophic (community respiration > gross productivity).

- High (> 20 to ≤ 60 ug/L) to extremely high (> 60 ug/L) concentrations of chlorophyll (Chl) were observed within Buchanan Creek and reference Wolfsnare and Thalia creek stations during the fall and spring sampling periods. Providing a measure as to the degraded nature of algal cells, pheopigments represented 30-40% of total Chl estimates. Ranging from 24-35 mg/L and dominated by inorganic material (i.e, fine sediment), average total suspended solids (TSS) were relatively similar across the studied tidal creeks. With respect to water quality, values > 20 mg/L are considered elevated and negatively impact the health of estuarine ecosystems.

- Average TDN concentration at Buchanan Creek stations varied between 0.43-0.69 mg/L as N and depicted and general increasing trend with distance upstream. Reference Wolfsnare and Thalia creek stations exhibited relatively similar concentrations of 0.78 and 0.56 mg/L as N, respectively. Based on national estuarine eutrophication assessment criteria, TDN concentrations within the studied tidal creeks are generally moderate (≥ 0.1 to < 1.0 mg/L as N) with occasional high (≥ 1.0 mg/L) levels being observed.

- Average TDP concentration at Buchanan Creek stations varied between 0.05-0.08 mg/L as P with reference Wolfsnare and Thalia Creek stations exhibiting similar concentrations. Based on national estuarine eutrophication assessment criteria, TDP concentrations within the studied tidal creeks are generally moderate (≥ 0.01 to < 0.1 mg/L) with occasional high (≥ 0.1 mg/L) levels being observed.

- Enterococci bacteria sample densities varied over 3 orders of magnitude, 20 to >24,000 MPN/100 ml, over the study period. Geometric mean densities of *Enterocci* bacteria showed an increasing trend with distance upstream Buchanan Creek; mean densities were 38 MPN/100 ml at the Western Branch of the Lynnhaven River boundary station and increased to 2,175 MPN/100 ml adjacent to Birchwood Malibu Park. Reference creeks, Wolfsnare (1,664 MPN/100 ml) and Thalia (571 MPN/100 ml), exhibited *Enterococci* bacteria on the same order as Buchanan Creek.

- Birchwood Malibu Park water quality surveys show effluent from identified drainage outfalls to have reduced Enterococci bacteria and total dissolved phosphorus (TDP), and elevated total dissolved nitrogen (TDP) levels relative to receiving Buchanan Creek waters. Origin of the discharge is suspected to be upland groundwater seepage into aging DO-2 pipe infrastructure and a mix of upland seepage and lake drainage into the DO-3 pipe system. Initial assessment would indicate that identified drainages would have limited impact on Buchanan Creek given flow characteristic, ranging from no discharge to intermittent low discharge, coupled to moderate pollutant levels.

Summary

VIMS performed water quality field surveys within Buchanan Creek, local reference tidal creeks, and at the open water boundary with the Western Branch of the Lynnhaven River to offer insight into the eutrophic status of Buchanan Creek and support numerical models to assess hydrodynamic and water quality conditions of the system. Efforts focused on key symptoms which included depressed dissolved oxygen (DO), elevated chlorophyll (Chl) levels, elevated turbidity and total suspended solid (TSS), and elevated total dissolved nitrogen (TDN) and phosphorus (TDP) concentrations. Additionally, information was collected on Enterococci bacteria which was an additional pollutant focus topic of the study. High frequency measurements of water depth, water temperature, salinity, DO, Chl, turbidity and pH were made at six locations over four separate deployment periods for approximately ten days to two weeks from September 2018 to April 2019. Grab sample surveys were also conducted over the same period to provide information on nutrients, algal biomass, suspended solids and pathogen bacteria.

Buchanan Creek, along with studied reference creeks, exhibited elevated dissolved oxygen concentration (DO_{conc}) variability and observed minimum and maximum values indicative of shallow creeks with relatively high levels of nutrient input characteristic of urban runoff. Hypoxic (DO_{conc} <2 mg/L) conditions most notably occurred within the upstream stations of Buchanan Creek and the reference Wolfsnare and Thalia creek stations when mean water temperatures were ≥ 20 $^{\circ}$C. A single hypoxic event was sustained for 15 hours in the headwater region of Buchanan Creek. Given the frequency and duration of low hypoxia, from a water quality management perspective, it should be viewed as a chronic issue. Using an estuarine eutrophic index, Buchanan Creek along with the Wolfsnare and Thalia reference creek systems exhibited seasonally elevated levels of algal biomass (Chl), TDN and TDP, and TSS that could negatively impact the health of estuarine ecosystems. The collected data has been used to support coupled watershed and hydrodynamic model simulations designed to assess the feasibility of management options with respect to water quality restoration and protection. Initial assessments of identified drainages at the Birchwood Malibu Park show no direct evidence of significant influences on water quality within Buchanan Creek. This was based on discharge outlet flow characteristics, ranging from no discharge to intermittent low discharge, coupled to moderate pollutant levels.

Introduction

Water quality field studies were conducted in the tidal Buchanan Creek system to quantify pollutant levels, provide insight as to important controlling processes, and support hydrodynamic and water quality model simulations. Additional water quality information was collected in downstream receiving waters of the Western Branch of the Lynnhaven River, Wolfsnare and Thalia Creeks which will serve as reference sites, and selected points of drainage in Birchwood Malibu Park. Prior to the present study, relatively few field observations were available for Buchanan Creek. A previous study of Buchanan Creek by Ho et al. (1977) was conducted when the Birchwood Gardens Sewage Treatment Plant was still operational. The objective of the study was to calculate pollutant (nitrogen and phosphorus) distributions resulting from treatment plant discharge and assess its contribution to eutrophication issues within Buchanan Creek and upstream portions of the Western Branch of the Lynnhaven River. Water quality surveys found elevated total nitrogen (TN, 1.8 mg/L as N) and phosphorus (TP, 0.54 mg/L as P) concentrations 450 meters down from the treatment plant discharge, undesirable high chlorophyll (Chl) concentrations (> 60 μg/L), reduced dissolved oxygen (DO_{conc}) levels (~ 4 mg/L) and high biochemical oxygen demand (6 mg/L). Model predicted concentrations of TN and TP due to the sewage treatment plant discharge could be as high as 0.9 mg/L as N and 0.34 mg/L as P. A major finding of the study indicated that non-point sources of pollutants were large and would, along with point source loads, need to be controlled to prevent the continuation of water quality degradation in Buchanan Creek. The Birchwood Gardens Sewage Treatment Plant was decommissioned in 1983 and is currently the site of Birchwood Malibu Park.

Due to recent public concern over water quality within Buchanan Creek and the question as to the decommissioned site exacerbating water quality issues, the City of Virginia Beach and Virginia's Department of Environmental Quality conducted site assessment visits and collected and analyzed limited runoff and creek water samples in 2016 and 2017. With respect to pathogen bacteria and nutrients, results showed elevated Enterococci bacteria levels of 187-300 cfu/100 ml, total Kjeldahl nitrogen (TKN) levels ranging from 2.2-2.7 mg/L, and TP levels ranging from 0.39-0.46 mg/L as P (VADEQ 2016; HRSD 2017). In order to aid decision-making, an investigative water quality study was conducted to document current water quality within Buchanan and surrounding creeks and support watershed-water body modeling aspects of this project. Objectives of the field water quality observations component of the project include:

(1) Collect continuous (15-minute interval) water quality data in Buchanan Creek to identify multi-scale temporal (instantaneous, tidal, diurnal and seasonal) variations and assess DO_{conc}, Chl and other parameters of interest against established water quality standards;

(2) Collect continuous (15-minute interval) water quality data in nearby reference creek systems to allow for comparison with Buchanan Creek;

(3) Provide supporting calibration/validation data for water quality / watershed model simulations; and

(4) Conduct a water quality survey at points of discharge in Birchwood Malibu Park.

WATER QUALITY DATA COLLECTION

High Frequency Observations

This study established a total of six continuous monitoring (ConMon) stations to support project efforts. Three stations were located in Buchanan Creek proper from 0.8 km (0.5 mi) upstream from the mouth (Station ID: Buch 1) to approximately 1.8 km (1.1 mi) upstream (Station ID: Buch 3) adjacent to Birchwood Malibu Park. A single ConMon station (Station ID: Boundary) was maintained in the Western Branch of the Lynnhaven River, downstream of Buchanan Creek, to provide information on adjacent open water boundary conditions in support of modeling efforts. The two remaining ConMon stations were established in Wolfsnare Creek and Thalia Creek, to serve as suitable reference sites to Buchanan Creek. ConMon station locations are provided in Figures 2.1 and 2.2 (depicts Buchanan Creek stations in detail) with additional station information provided in Table 2.1. ConMon water quality stations were deployed on four occasions to observe and describe seasonal and storm influences on water quality. Deployment periods along with daily precipitation over the study period (Sept. 2019 through Apr. 2019) are depicted in Figure 2.3 with additional details provided in Table 2.2.

Figure 2.1. Continuous monitoring water quality station locations within Western Branch of the Lynnhaven system.

Figure 2.2. Detailed map depicting continuous monitoring water quality station locations within Buchanan Creek system.

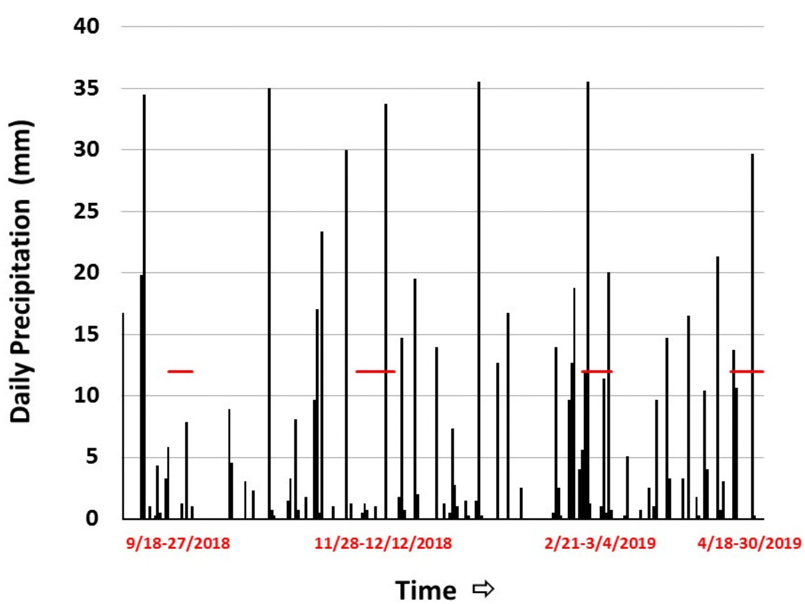


Figure 2.3. Continuous monitoring water quality station deployment intervals and daily precipitation rates during the study period. Notes: (1) Six-minute precipitation data source was the USGS Route 58 Thalia Creek station (USGS ID: 0204291317; 36 50.598, -76 07.468) and considered provisional at the time of the report submission. Rainfall amounts were 16.3 mm over 9.3 days, 37.3 mm over

Table 2.1. Descriptive summary of established continuous monitoring water quality stations. Notes: (1) Station Buch 3* was used for the first deployment only, with subsequent deployments occurring at Buch 3, approximately 130 m upstream; (2) MWD denotes mean water depth.

Station ID	Water Body	Latitude	Longitude	Notes
Buch 1	Lower Buchanan Creek	36° 51.472	-76° 06.364	MWD: ~1.1 m
Buch 2	Mid Buchanan Creek	36° 51.169	-76° 06.020	MWD: ~0.9 m
Buch 3	Upper Buchanan Creek	36° 51.022	-76° 05.856	MWD: ~0.7 m; bank shading
Buch 3*		36° 51.084	-76° 05.924	
Boundary	W. Branch Lynnhaven	36° 52.901	-76° 06.604	MWD: ~2.3 m
Wolfsnare	Wolfsnare Creek	36° 51.088	-76° 02.888	MWD: ~1.7 m
Thalia	Thalia Creek	36° 50.650	-76° 07.450	MWD: ~1.2 m

Table 2.2. Continuous monitoring water quality station deployment time periods (Sept. 2018-April 2019). Time is presented as eastern standard time (EST).

Station ID	Deployment No.	Start date (time)	End date (time)	No. of Obs.
Buch 1	1	9/18/18 (11:00)	9/27/18 (12:00)	869
Buch 2	1	9/18/18 (11:15)	9/27/18 (11:45)	867
Buch 3	1	9/18/18 (11:30)	9/27/18 (11:15)	864
Boundary	1	9/18/18 (13:30)	9/27/18 (14:00)	866
Wolfsnare Cr.	1	9/18/18 (14:45)	9/27/18 (15:15)	867
Thalia Cr.	1	9/18/18 (12:45)	9/27/18 (13:00)	866
Buch 1	2	11/28/18 (13:45)	12/12/18 (13:45)	1345
Buch 2	2	11/28/18 (14:15)	12/12/18 (13:15)	1341
Buch 3	2	11/28/18 (14:45)	12/12/18 (12:45)	1075
Boundary	2	11/28/18 (12:30)	12/12/18 (14:15)	1352
Wolfsnare Cr.	2	11/28/18 (11:00)	12/12/18 (15:30)	1360
Thalia Cr.	2	11/28/18 (13:15)	12/12/18 (15:45)	1102
Buch 1	3	2/21/19 (13:45)	3/4/19 (12:00)	1050
Buch 2	3	2/21/19 (14:30)	3/4/19 (11:45)	975
Buch 3	3	2/21/19 (14:15)	3/4/19 (11:30)	909
Boundary	3	2/21/19 (15:00)	3/4/19 (12:30)	1047
Wolfsnare Cr.	3	2/21/19 (10:15)	3/4/19 (13:45)	1071
Thalia Cr.	3	2/21/19 (11:00)	3/4/19 (14:15)	1070
Buch 1	4	4/18/19 (12:30)	4/30/19 (10:15)	1144
Buch 2	4	4/18/19 (12:00)	4/30/19 (10:00)	1145
Buch 3	4	4/18/19 (11:30)	4/30/19 (11:00)	1151
Boundary	4	4/18/19 (13:00)	4/30/19 (10:30)	1143
Wolfsnare Cr.	4	4/18/19 (14:45)	4/30/19 (11:45)	1141
Thalia Cr.	4	4/18/19 (15:45)	4/30/19 (12:15)	1139

Given the desire to measure mid-channel conditions over intermittent periods and study site characteristics (e.g., shallowness and security concerns), ConMon water quality instrumentation (YSI 6600 EDS V2, see details below) were deployed using two basic platform designs. In the upper reaches of Buchanan Creek (Stations: Buch 1 and Buch 2) where low water conditions make vessel access problematic and leave instrumentation exposed (see Figure 2.4 for upper creek view), instruments were attached to heavy gauge galvanized U-channel sign posts with a VIMS identifying float attached for surface identification. The remaining stations used a mooring anchor and surface float design with an additional float attached immediately above instruments so as to maintain vertical or near vertical position over various tide conditions. Platform design maintained instruments between 0.25-0.5 m (0.8-1.6 ft) above the bottom substrate. Of note, due to the shallowness of the upstream portions of Buchanan Creek and Thalia Creek, there were times during low-tide conditions when water quality sensors were aerially exposed. Impacted stations included Buch 2 (exposed 5.6% of the deployment 3), Buch 3 (exposed 13.3% of deployment 2, 12.6% of deployment 3, and 14.2% of deployment 4) and Thalia Creek (exposed 14.2% of deployment 2).

Figure 2.4. Image of upper tidal Buchanan Creek looking downstream of Buch 3 station.

Fixed ConMon stations utilized YSI 6600EDS V2 sondes equipped with the Clean Sweep Extended Deployment System (EDS) to reduce biofouling impacts which can significantly impact sensor performance. Additionally, sonde sensor protective cages and individual sensors were treated with antifouling paint and copper tape to provide additional biofouling protection. Sondes sampled at 15-minute intervals to allow sufficient temporal resolution to capture dynamic changes in water level and quality while maintaining adequate battery voltage throughout the 9-14 day deployment periods. Measured parameters included: (1) temperature (unit: °C; resolution: 0.01 °C; accuracy: ± 0.15 °C; range: -5 to 50), (2) specific conductance (unit: mS/cm; accuracy: ± 0.5% of reading; range: 0 to 100), (3) % DO saturation (% DO_{sat}; unit: %; accuracy: ± 1% of reading; range: 0 to 500), (4) turbidity (unit: NTU; accuracy: ± 2% of reading; range: 0 to 1,000), (5) Chlorophyll fluorescence (Chl; unit: ug/L; accuracy: 0.1 ug/L; range: 0 to 400), and (6) pH (unit: SU standard units; ± 0.2%; range: 0 to 14). Calculated parameters included: (1) salinity (units: psu; accuracy; ±1% of reading; range: 0 to 70) and (2) DO concentration (DO_{conc}; unit: mg/L; accuracy: ± 1% of reading; range: 0 to 50). Water depth (unit: meter; accuracy: ± 0.02; range: 0 to 9.1) was measured with internal non-vented pressure sensors that required correcting for atmospheric pressure changes during deployment periods.

Following retrieval of ConMon instrumentation and return to VIMS, data were transferred electronically from the YSI 6600EDS V2 to the laboratory computer hard drive and stored as an Excel file. Data quality control was conducted to identify 'bad' and 'suspect' data. Much of the quality control protocols follow guidance based on the U.S. Integrated Observing System Quality Assurance/Quality Control of Real-Time Oceanographic Data (QARTOD) Program (IOOS 2012 and 2014). Data quality control tests included: (1) instrument operational but not deployed (prior and post deployment), (2) time gaps (skips or changes in regular 15 minute data collection interval), (3) sensor out of water due to low water condition, (4) missing data, (5) measurement outside sensor range specifications, (6) negative values (temperature is an exception), (7) significant single point spikes (utilized a dynamically established threshold), and (8) general sensor failure (includes flat line, attenuated and drift signals). Data were flagged as passing, suspect, or failing quality control tests. Details are provided in the study's Quality Assurance Project Plan. In addition to water quality sondes, high frequency (6-minute interval) data from an onsite Thalia Creek (58; 36° 50.598′, -76 7.468′; USGS Site ID: 0204291317) rainfall tipping bucket was utilized in this report. Precipitation data was provisional at the time of report submittal.

Manually Collected Observations

Manually collected water samples were taken to provide supporting information as related to total suspended solids (TSS), plant pigments (Chlorophyll-a and pheopigment), nutrients (nitrogen and phosphorus species) and Enterococci bacteria. Sample stations included the ConMon stations (see Figure 2.1) and selected locations within and adjacent to Birchwood Malibu Park (see Figure 2.5). Water column samples were collected approximately 0.25 m (~10 in) below the surface with a horizontal Niskin bottle. Water temperature, salinity, dissolved oxygen and pH were collected concurrently with a YSI 600 XL instrument. Suspended solids, plant pigment and nutrient samples were stored in acid-washed darkened bottles that were rinsed three times with ambient water before sample collection. Bacteria samples were collected, without sample bottle rinsing, in sterilized and sealed clear plastic sample bottles. Immediately following collection, water samples were stored on ice in a darkened cooler. Upon return to VIMS, samples were delivered to the VIMS Analytical Service Center for processing. The VIMS Analytical Service Center is certified by Virginia's Department of General Services, Division of Consolidated Laboratory Services (VELAP Certificate No. 9577). VIMS Analytical Service Center follows standard methods for total suspended solids (TSS; SM 2540 D-1997; minimum detection limit (MDL): 1.4 mg/L), volatile suspended solids (VSS; SM 2540 E-1997; MDL: 2.5 mg/L), chlorophyll and pheopigments (Chl-a and Pheo; EPA 445 Rev. 1.2; MDL: 0.50 ug/L), ammonium (NH_4; SM 4500-NH_3 H-1997; MDL: 0.0062 mg/L as N), nitrate plus nitrite (NO_{23}; SM 4500- NO_3^{-1} F-2000; MDL: 0.0055 mg/L as N), nitrite (NO_2; SM 4500- NO_2^{-1} F-2000; MDL: 0.0050 mg/L as N), total dissolved nitrogen (TDN; SM 4500-N C-1997; MDL: 0.0285 mg/L as N), orthophosphate (PO_4; SM 4500-P F-2011; MDL: 0.0016 mg/L as P), total dissolved phosphorus (TDP; SM 4500 P F-2011; MDL: 0.0095 mg/L as P) and Enterococci bacteria (Enterolert; MDL: 10 MPN/100ml). Fixed suspended solids were determined as the difference between total suspended solids and volatile suspended solids. Functional Chl-a was determined as the difference between Chl-a and pheopigment fractions. Dissolved organic nitrogen (DON) and phosphorus (DOP) were determined as the difference between total and inorganic fractions. Values below MDL were reported as ½ MDL for analysis purposes.

Figure 2.5. Selected water quality grab sample station locations within Buchanan Creek and Birchwood-Malibu Park.

Results and Discussion

ConMon Water Temperature

Water temperature time series plots for each ConMon water quality station are shown in Figures 2.6, 2.7, 2.8 and 2.9 for deployment periods 1 through 4, respectively. Summary statistics for individual stations and deployment period are provided in Table 2.3. During deployment periods, surface water temperatures ranged between 4.3-30.6 ˚C (39.7-87.1 °F) within Buchanan Creek, 5.8-27.8 ˚C (42.4-82.0 °F) at the Western Branch of the Lynnhaven River station, 3.7-30.6 ˚C (38.7-87.1 °F) in Wolfsnare Creek and 5.2-29 ˚C (41.4-84.2 °F) in Thalia Creek. Average water temperature was within 0.5 °C (0.9 °F) among the Buchanan Creek stations (Buch 1, Buch 2 and Buch 3) for all deployment periods. Maximum average temperature differences between Buchanan Creek and the reference creeks, Wolfsnare and Thalia, over individual deployment periods was typically ≤ 0.8 °C (1.4 °F) and ≤ 0.5 °C (0.9 °F), respectively.

Water temperature within estuarine systems is influenced by a number of interacting factors including streamflow, atmospheric heat exchange, water and heat exchange with subaqueous and intertidal substrate, and tidal exchange with coastal waters. Due to their shallowness and position in the landscape, shallow tidal creek systems are particularly sensitive to many of these factors as compared to more open water locations. Tidal influenced semi-diurnal and atmospheric heat exchange patterns (both diel and seasonal) were observed in temperature time series at all stations. Fluctuations in water temperature due to frontal systems with associated rainfall/runoff were also observed over the study. Most notably, severe weather on April 26, 2019 resulted in 29 mm (1.14 in) of precipitation; see Figure 2.9 deploy hour ~200). As expected, upstream stations were influenced to a greater degree than the more open water boundary region.

For tidal waters of Virginia, water temperature standards are only established to control heated wastewater discharge and therefore would not apply to the Buchanan Creek. However, water temperature is an important element of water quality through its influence on biological activity and water chemistry. Specific to concerns within Buchanan Creek, increased water temperature would support relatively high rates of water column and benthic algal productivity and microbial respiration, lower dissolved oxygen saturation levels, and enhanced survival of microbial pathogens. During the first deployment period (September 18-27, 2018), average water temperatures exceeded 25 ºC (77 °F) at all stations with maximum temperatures approaching or exceeding 30 ºC (86 °F). It should be noted that the time constraints of the study did not allow for field data collection during the summer period when temperatures would be elevated. Based on long-term air temperature records at nearby weather stations (Diamond Springs ID: 442368; Norfolk WSO Airport ID: 446139; Cape Henry ID: 441362; Langley Air Force Base ID: 444720), average monthly July air temperatures are elevated on the order of 7 °C (12.6 °F) greater than September and 11 °C (19.8 °F) greater than April. It would be anticipated that summer air temperatures would result in mean creek water temperature on the order of 30 °C (86 °F) with peak values ≥ 32 °C (90 °F). These elevated temperature values would be expected to compound water quality issues during the summer period. Of note, watershed development and certain shoreline activities have the potential to impact water temperature in smaller-scale, and partially shaded water bodies such as the upper reaches of Buchanan Creek. Influences on water temperature should be considered when considering and/or planning for removal of shade providing riparian canopy vegetation and installing upland hardening surfaces that would warm storm runoff.

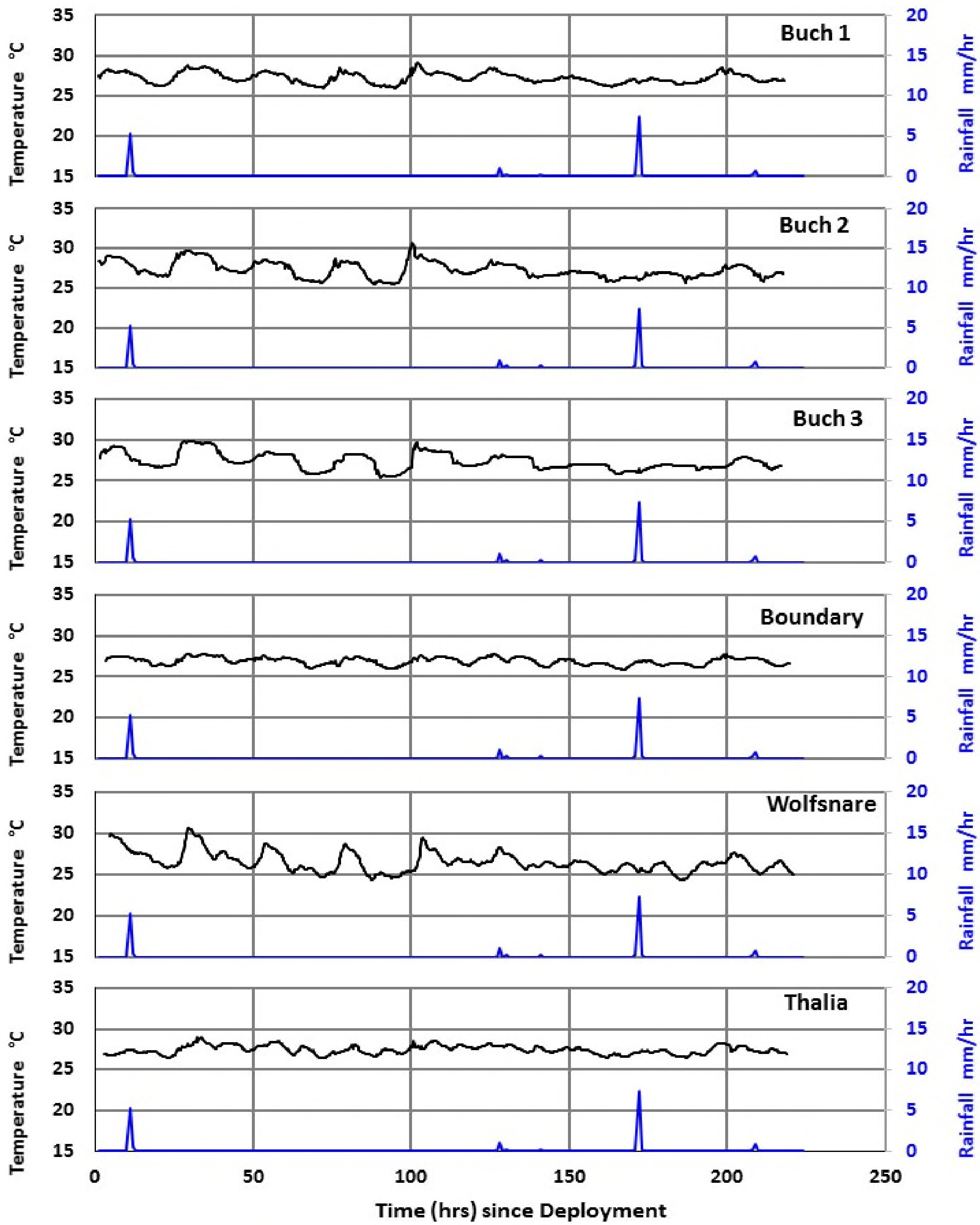


Figure 2.6. Continuous monitoring temperature (°C) and hourly precipitation (mm) time series during first (9/18/2018 - 9/27/2018) deployment period.

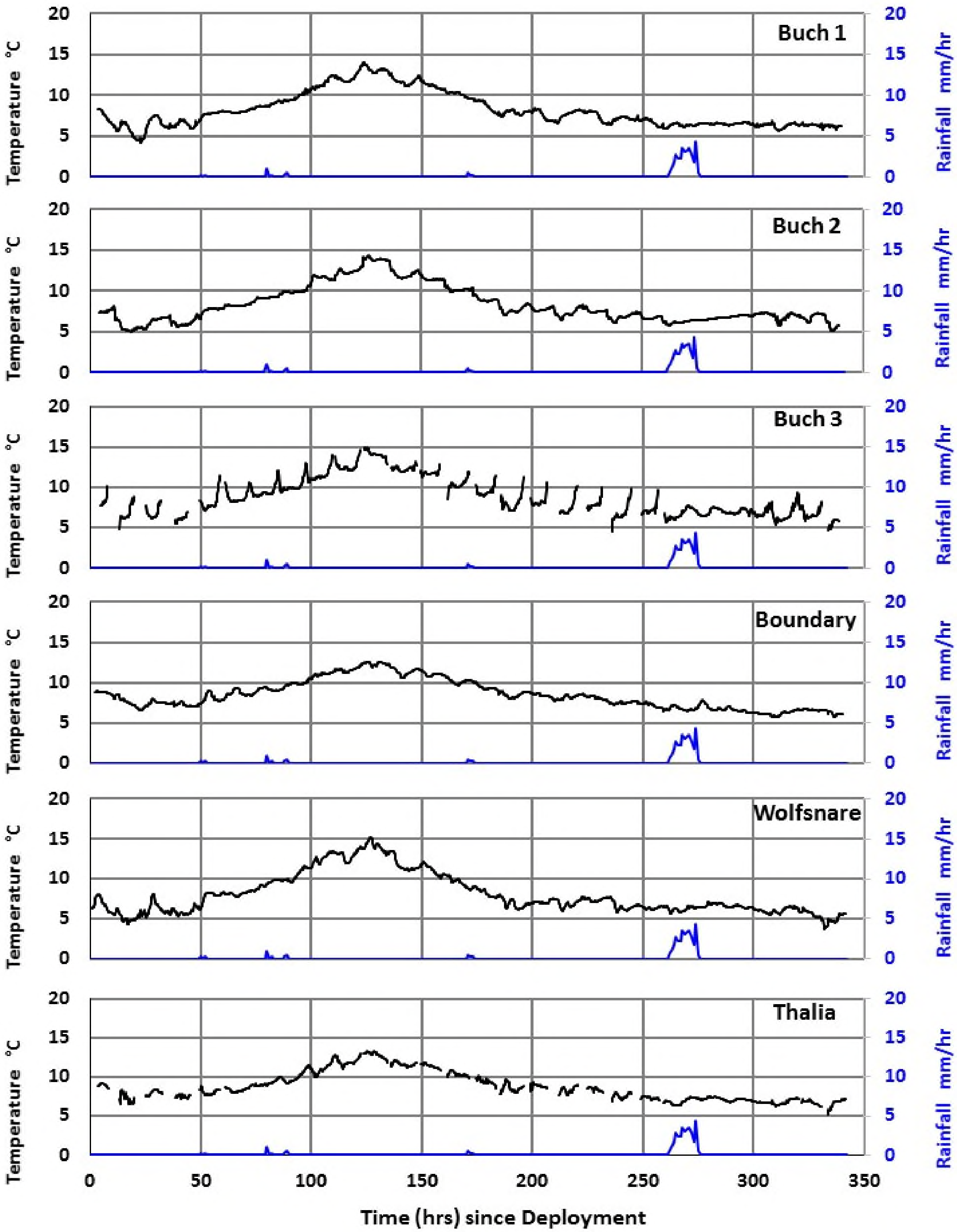


Figure 2.7. Continuous monitoring temperature (°C) and hourly precipitation (mm) time series during second (11/28/2018 - 12/12/2018) deployment period.

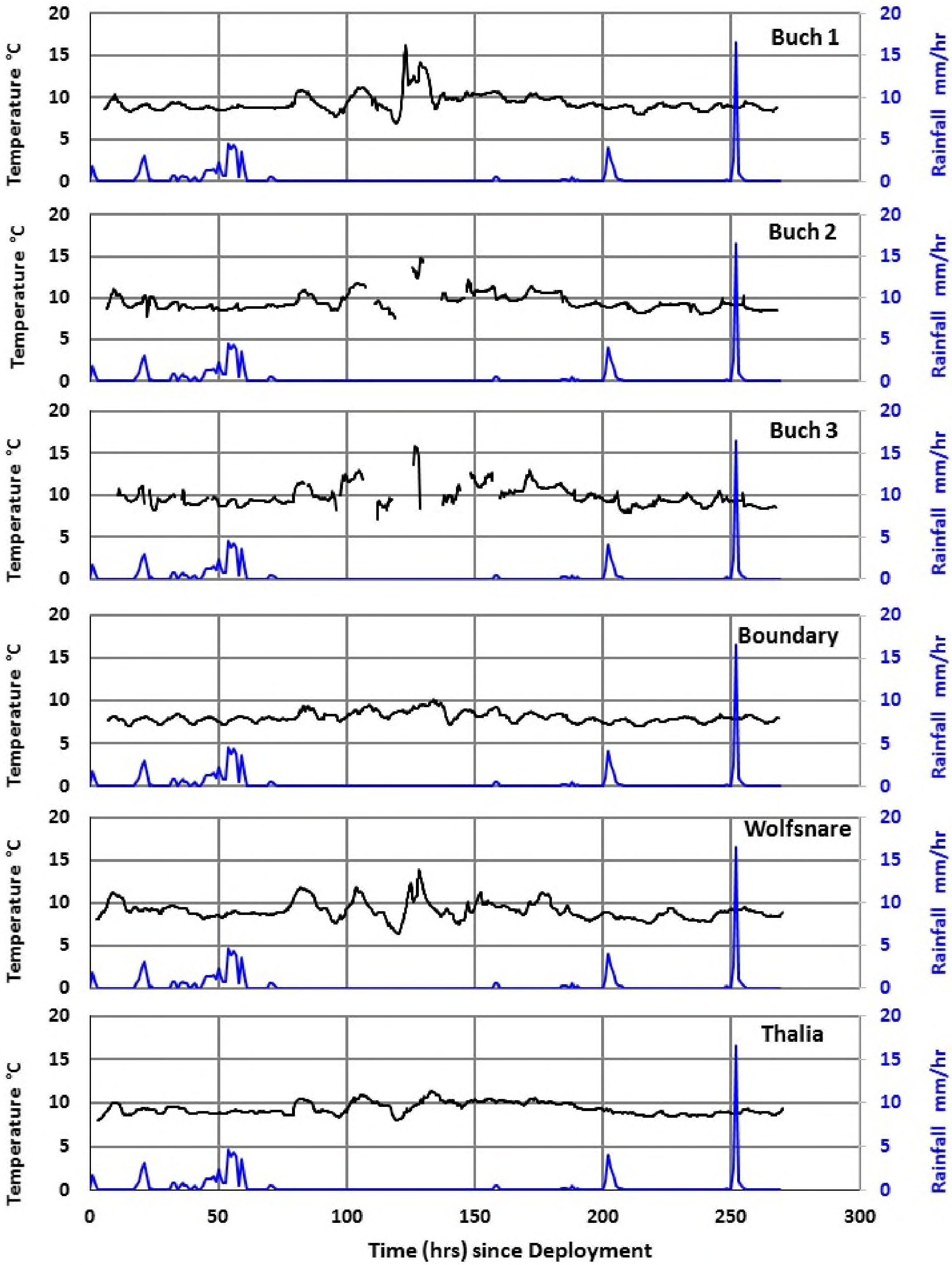


Figure 2.8. Continuous monitoring temperature (°C) and hourly precipitation (mm) time series during third (2/21/2019 - 3/4/2019) deployment period.

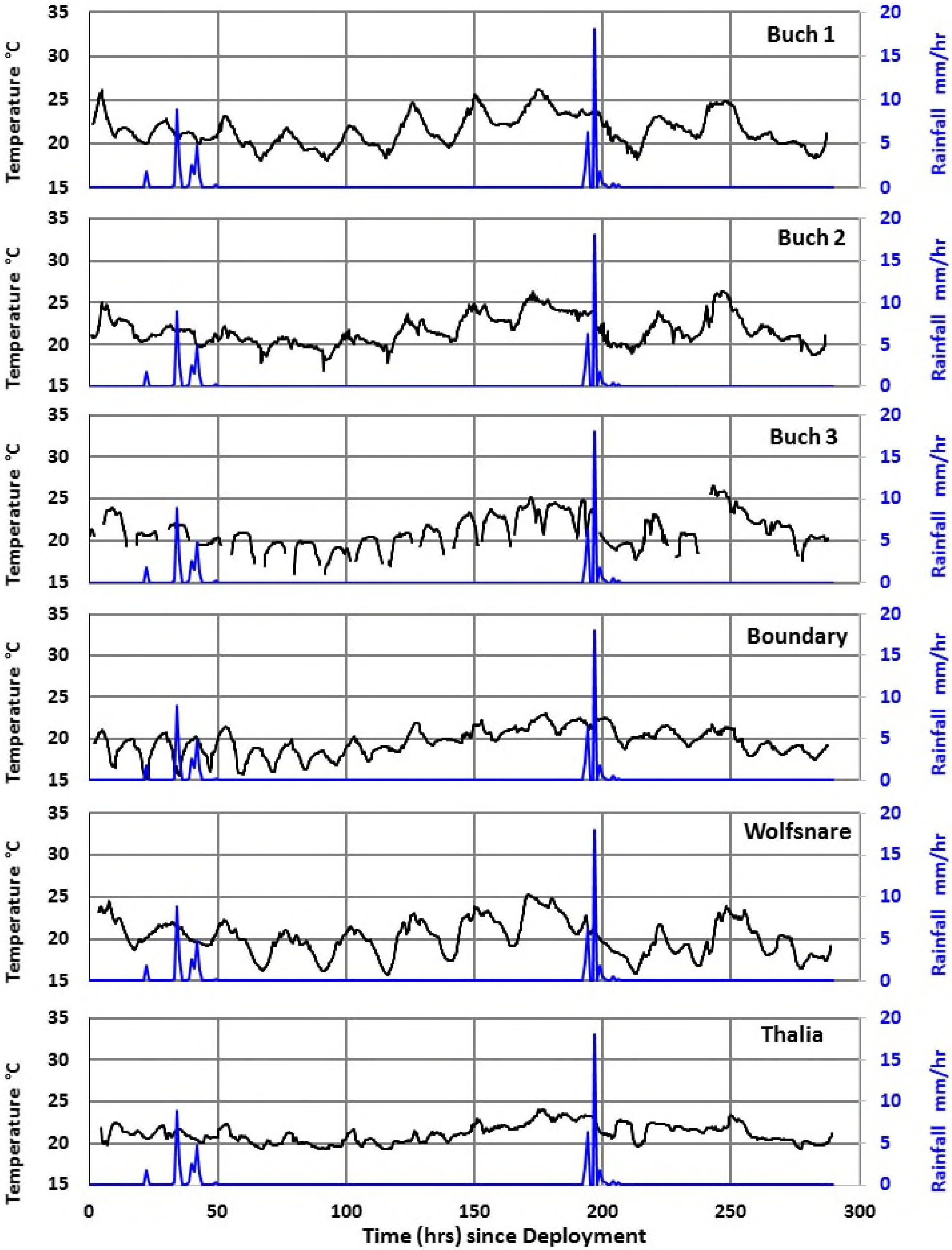


Figure 2.9. Continuous monitoring temperature (°C) and hourly precipitation (mm) time series during fourth (4/18/2019 - 4/30/2019) deployment period.

Table 2.3. Summary statistics for water temperature (°C) by continuous monitoring (ConMon) water quality station and deployment period.

ConMon Station ID	Deployment 1 (9/18/18 - 9/27/18)	Deployment 2 (11/28/18 - 12/12/18)	Deployment 3 (2/21/19 - 3/4/19)	Deployment 4 (4/18/19 - 4/30/19)
Buch 1	Avg: 27.2 Min: 26.0 Max: 29.1 Std Dev: 0.7 N: 869	Avg: 8.2 Min: 4.3 Max: 14.1 Std Dev: 2.1 N: 1345	Avg: 9.3 Min: 6.9 Max: 16.2 Std Dev: 1.1 N: 1050	Avg: 21.5 Min: 18.0 Max: 26.2 Std Dev: 1.8 N: 1144
Buch 2	Avg: 27.3 Min: 25.5 Max: 30.6 Std Dev: 1.0 N: 867	Avg: 8.3 Min: 4.9 Max: 14.3 Std Dev: 2.2 N: 1341	Avg: 9.5 Min: 7.6 Max: 14.7 Std Dev: 1.0 N: 975	Avg: 21.7 Min: 17.0 Max: 26.4 Std Dev: 1.8 N: 1145
Buch 3	Avg: 27.3 Min: 25.4 Max: 29.8 Std Dev: 1.0 N: 864	Avg: 8.7 Min: 4.6 Max: 14.9 Std Dev: 2.3 N: 1075	Avg: 9.8 Min: 7.2 Max: 15.8 Std Dev: 1.2 N: 883	Avg: 21.2 Min: 16.0 Max: 26.6 Std Dev: 2.0 N: 946
Boundary	Avg: 26.9 Min: 25.9 Max: 27.8 Std Dev: 0.4 N: 867	Avg: 8.5 Min: 5.8 Max: 12.5 Std Dev: 1.8 N: 1352	Avg: 8.1 Min: 7.1 Max: 10.2 Std Dev: 0.6 N: 1047	Avg: 19.6 Min: 15.2 Max: 23.1 Std Dev: 1.6 N: 1143
Wolfsnare	Avg: 26.5 Min: 24.4 Max: 30.6 Std Dev: 1.2 N: 867	Avg: 8.0 Min: 3.7 Max: 15.2 Std Dev: 2.5 N: 1363	Avg: 9.0 Min: 6.3 Max: 13.8 Std Dev: 1.0 N: 1071	Avg: 20.2 Min: 15.7 Max: 25.3 Std Dev: 2.1 N: 1141
Thalia	Avg: 27.4 Min: 26.4 Max: 29.0 Std Dev: 0.5 N: 866	Avg: 8.7 Min: 5.2 Max: 13.3 Std Dev: 1.9 N: 1121	Avg: 9.3 Min: 8.0 Max: 11.3 Std Dev: 0.7 N: 1070	Avg: 21.2 Min: 19.2 Max: 24.1 Std Dev: 1.1 N: 1139

ConMon Salinity

Salinity time series plots for each ConMon water quality station are shown in Figures 2.10, 2.11, 2.12 and 2.13 for deployment periods 1 through 4, respectively. Summary statistics for individual stations and deployment period are provided in Table 2.4. During deployment periods, salinities ranged between 0.0 -17.3 psu within Buchanan Creek (Stations Buch 1-3), 10.0-22.9 psu at the Western Branch of the Lynnhaven River boundary station, 0.0-14.8 psu at the Wolfsnare Creek station and 0.2-15.4 psu at the Thalia Creeks station. Semi-diurnal patterns of salinity were observed at all stations over the four deployments, with salinity ranges typically increasing at upstream stations as compared to the more open water boundary station. Depending on station and deployment period, semi-diurnal salinity ranges could vary as much as 7.5-12.5 psu. Large tidal induced salinity changes are indicative of high flushing rates as a result of elevated tide range: mean water depth ratio (0.3-0.7:1 at creek stations) and significant streamflow.

Based on averaged deployment values, the Buchanan Creek study area was predominantly mesohaline, with exception occurring in the upper region (stations Buch 2 and 3) during the third deployment where mean salinities were characteristic of oligohaline conditions; see Figure 2.14. The Western Branch of the Lynnhaven River station exhibited elevated mesohaline to low polyhaline conditions. Mean salinities at the Wolfsnare reference creek exhibited low mesohaline conditions during deployments 1 and 2 and low oligohaline conditions during deployment 3 and 4. The Thalia Creek station followed a similar pattern as the upstream portion of Buchanan and Wolfsnare Creeks with exception during the fourth deployment where mean salinity was characteristic of mesohaline conditions. Relatively depressed salinity within the upper creek regions during deployments 3 and 4 would be anticipated given expected elevated seasonal baseflow and elevated observed precipitation amounts. Significant salinity depressions associated with rainfall events were observed within the upper tidal creeks during all deployment periods. Most notably were the storms that occurred on December 9, 2019 and February 22, 2019 where sustained precipitation resulted in a daily total on the order of 35 mm (1.4 in), and on April 26, 2019 where severe weather resulted in 18 mm (0.7 in) of precipitation over a 30 minute period. Stations exhibiting near freshwater conditions ($\leq$ 0.5 psu) following storm events included Buch 2 and 3 and the Wolfsnare and Thalia reference creek stations.

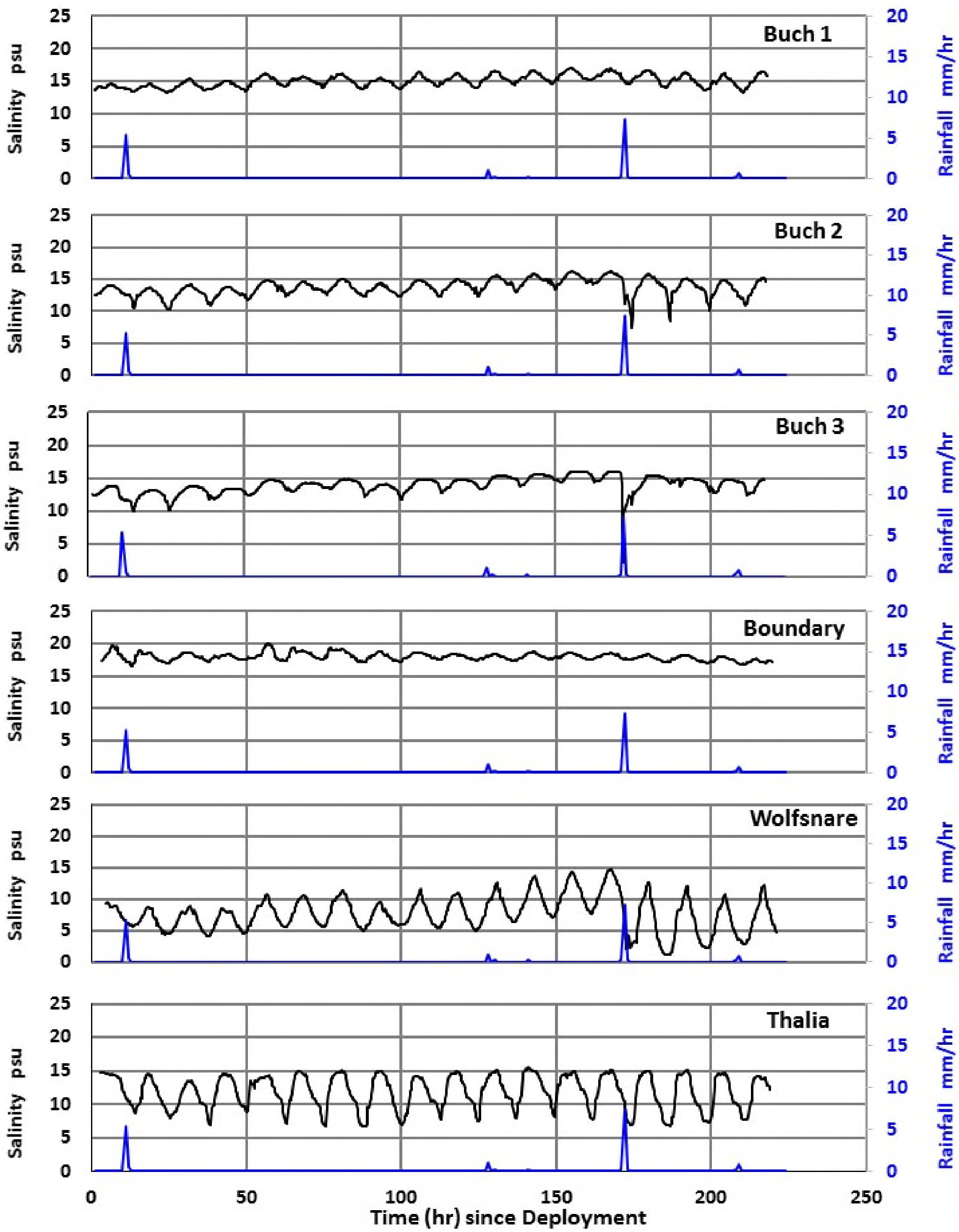


Figure 2.10. Continuous monitoring salinity (psu) and hourly precipitation (mm) time series during first (9/18/2018 - 9/27/2018) deployment period.

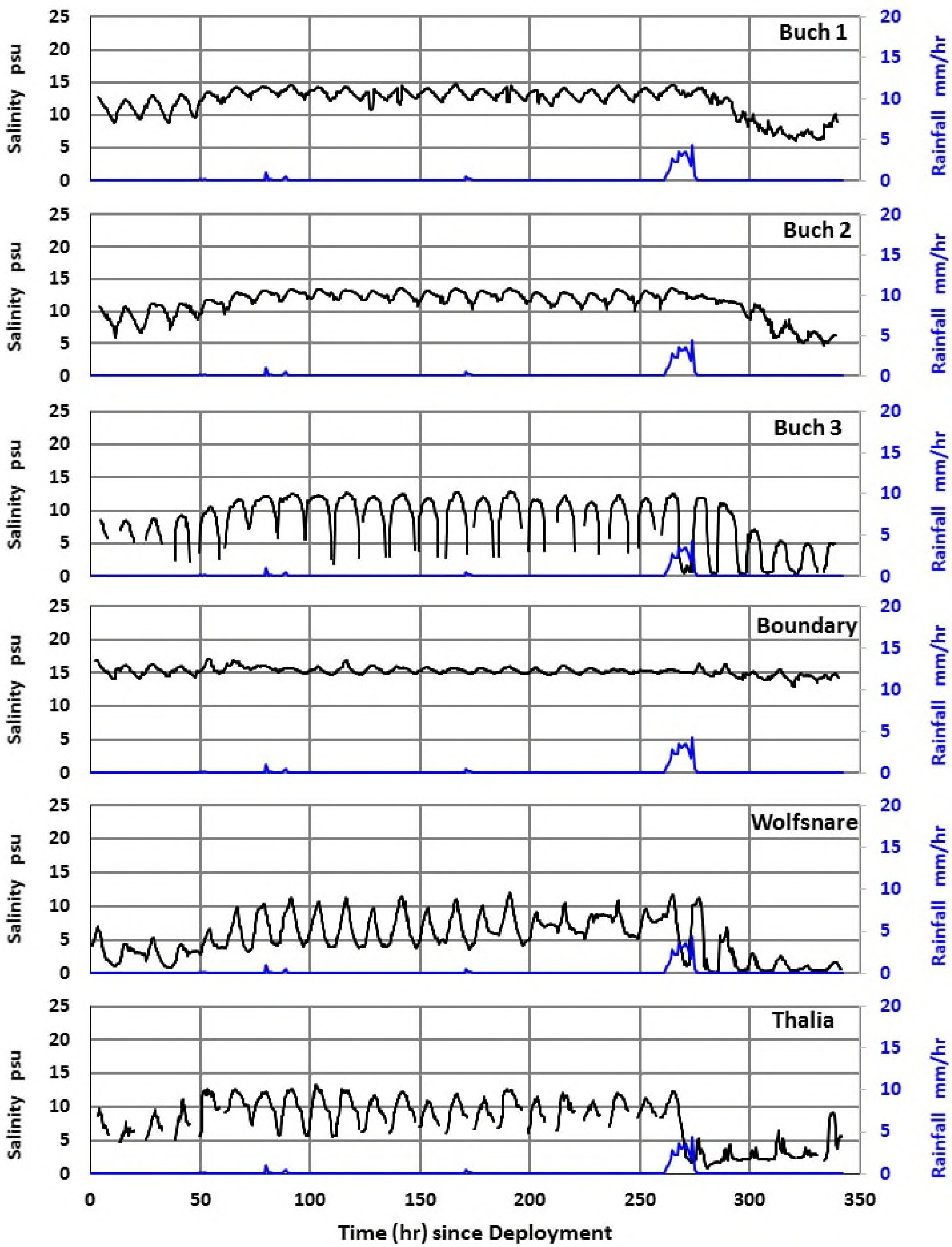


Figure 2.11. Continuous monitoring salinity (psu) and hourly precipitation (mm) time series during second (11/28/2018 - 12/12/2018) deployment period.

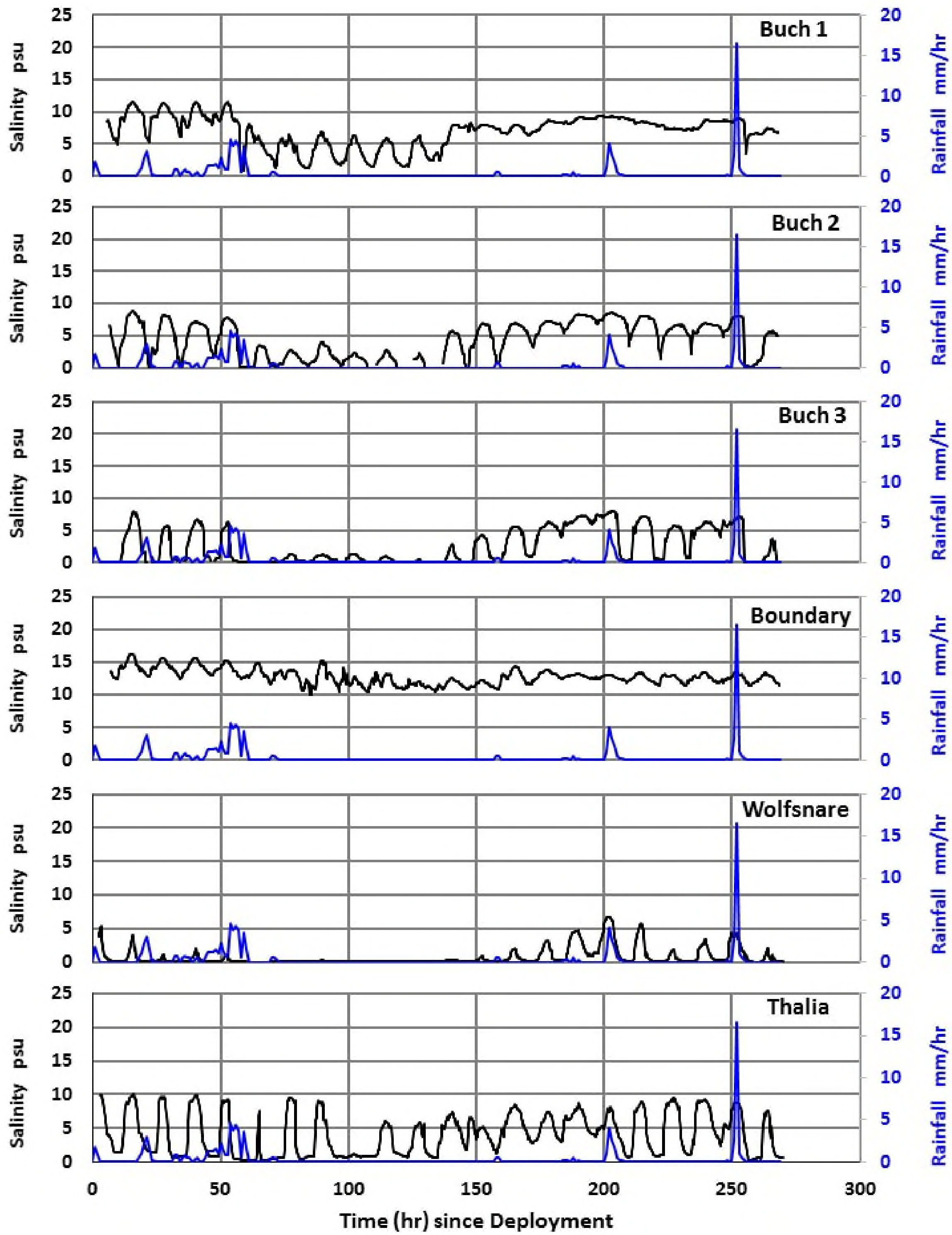


Figure 2.12. Continuous monitoring salinity (psu) and hourly precipitation (mm) time series during third (2/21/2019 - 3/4/2019) deployment period.

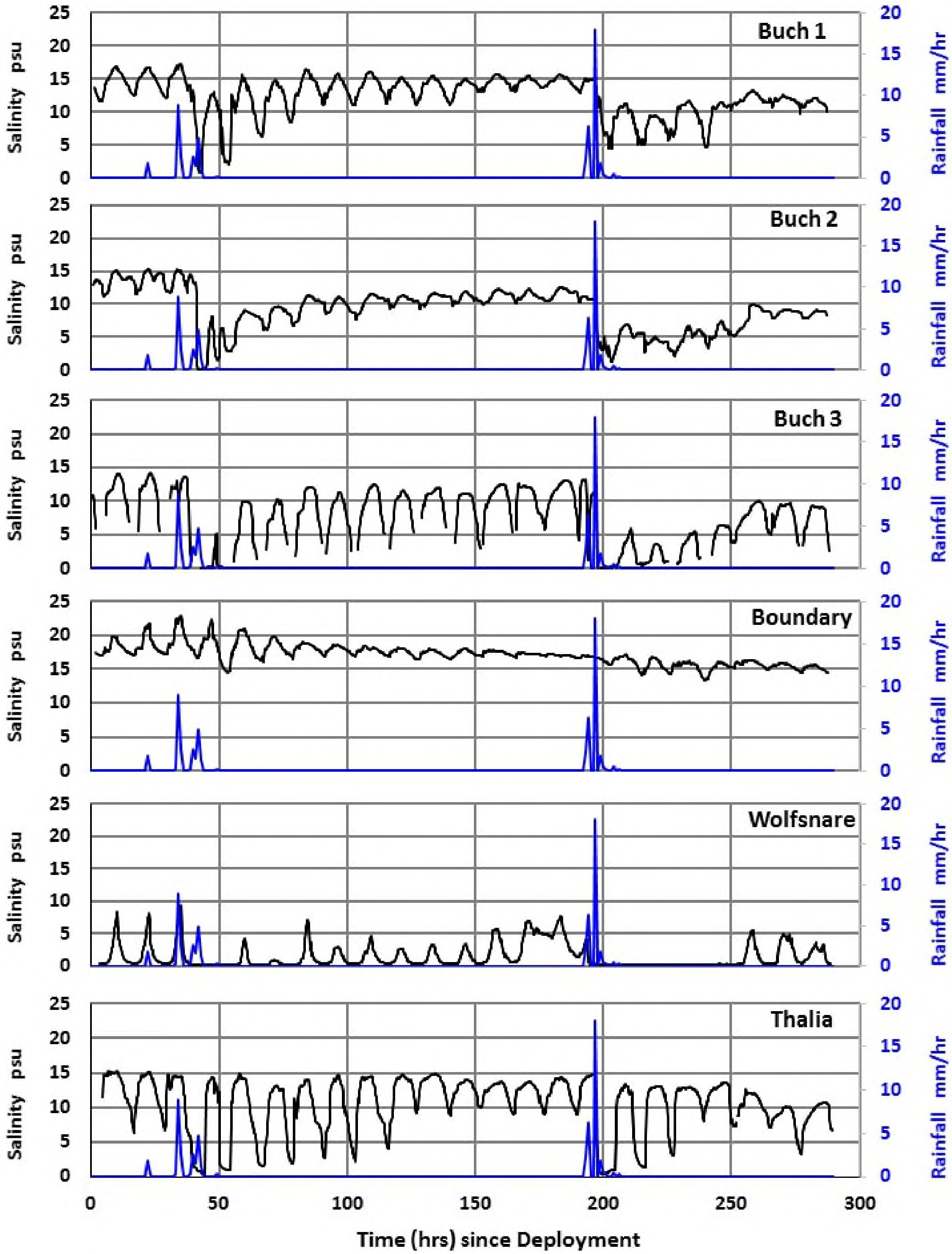


Figure 2.13. Continuous monitoring salinity (psu) and hourly precipitation (mm) time series during fourth (4/18/2019 - 4/30/2019) deployment period.

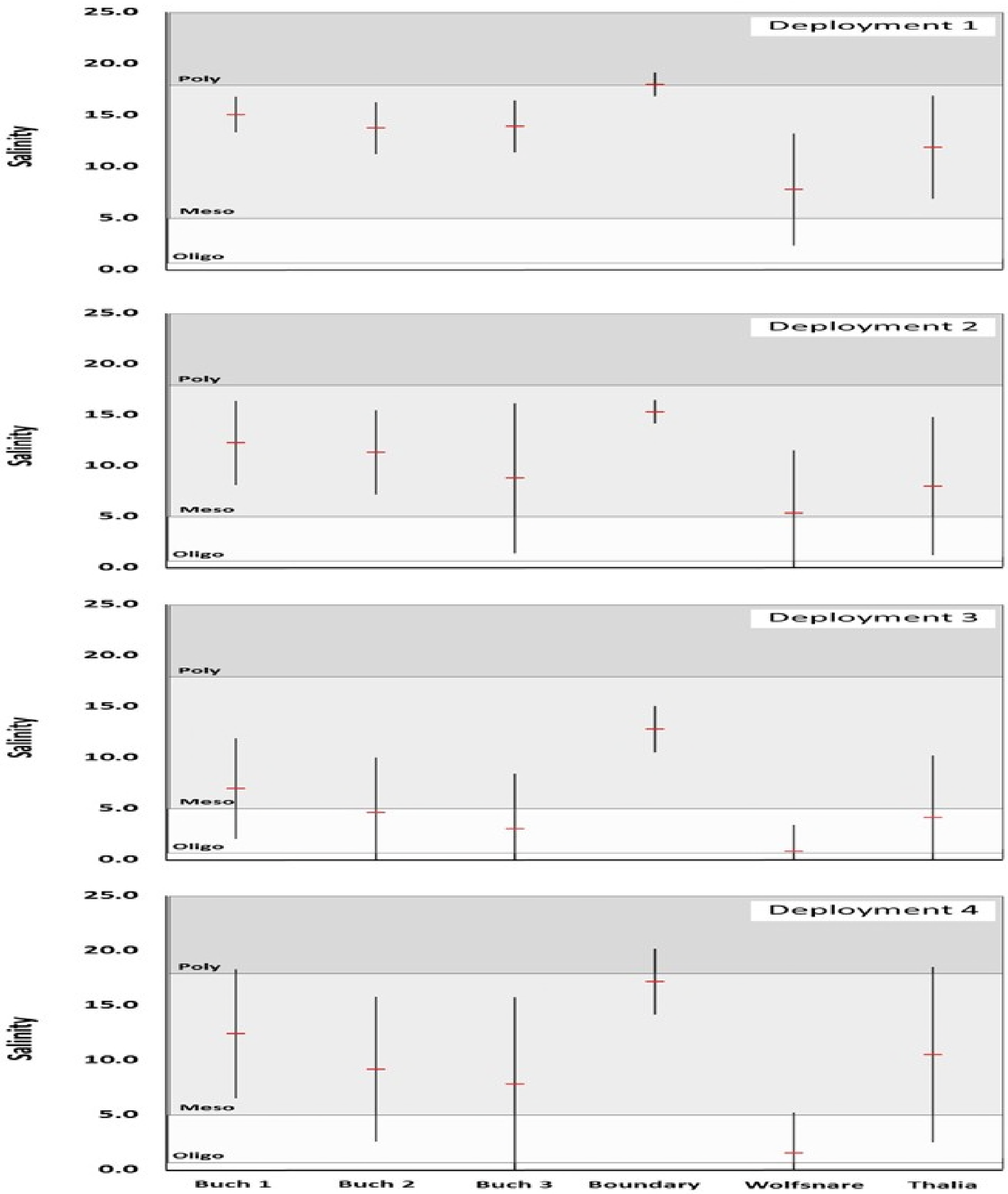


Figure 2.14. Average continuous monitoring salinity with ± 2 Std. Dev. confidence bars by station and deployment interval. Values are presented with shaded ranges for tidal fresh (0.0-0.5 psu), oligohaline (> 0.5-5.0 psu), meso (> 5.0-18 psu) and polyhaline (> 18-30 psu) salinity regimes.

Table 2.4. Summary statistics for salinity (psu) by continuous monitoring (ConMon) water quality station and deployment period.

ConMon Station ID	Deployment 1 (9/18/18 - 9/27/18)	Deployment 2 (11/28/18 - 12/12/18)	Deployment 3 (2/21/19 - 3/4/19)	Deployment 4 (4/18/19 - 4/30/19)
Buch 1	Avg: 15.0 Min: 13.2 Max: 17.0 Std Dev: 0.9 N: 869	Avg: 12.2 Min: 6.0 Max: 14.7 Std Dev: 2.1 N: 1345	Avg: 6.9 Min: 0.8 Max: 11.6 Std Dev: 2.5 N: 1050	Avg: 12.4 Min: 0.9 Max: 17.3 Std Dev: 3.0 N: 1144
Buch 2	Avg: 13.7 Min: 7.4 Max: 16.2 Std Dev: 1.3 N: 867	Avg: 11.3 Min: 4.7 Max: 13.6 Std Dev: 2.1 N: 1341	Avg: 4.6 Min: 0.0 Max: 8.8 Std Dev: 2.7 N: 974	Avg: 9.2 Min: 0.2 Max: 15.3 Std Dev: 3.3 N: 1145
Buch 3	Avg: 13.9 Min: 2.1 Max: 16.0 Std Dev: 1.3 N: 864	Avg: 8.8 Min: 0.3 Max: 12.8 Std Dev: 3.7 N: 1076	Avg: 3.0 Min: 0.0 Max: 8.1 Std Dev: 2.7 N: 882	Avg: 7.8 Min: 0.0 Max: 14.2 Std Dev: 3.9 N: 948
Boundary	Avg: 18.0 Min: 16.5 Max: 20.0 Std Dev: 0.6 N: 867	Avg: 15.3 Min: 13.0 Max: 17.1 Std Dev: 0.6 N: 1352	Avg: 12.7 Min: 10.0 Max: 16.2 Std Dev: 1.1 N: 1047	Avg: 17.1 Min: 13.4 Max: 22.9 Std Dev: 1.5 N: 1143
Wolfsnare	Avg: 7.7 Min: 1.1 Max: 14.8 Std Dev: 2.7 N: 867	Avg: 5.3 Min: 0.2 Max: 12.0 Std Dev: 3.1 N: 1363	Avg: 0.8 Min: 0.0 Max: 6.7 Std Dev: 1.3 N: 1071	Avg: 1.5 Min: 0.1 Max: 9.4 Std Dev: 1.9 N: 1141
Thalia	Avg: 11.9 Min: 6.6 Max: 15.4 Std Dev: 2.5 N: 866	Avg: 8.0 Min: 0.8 Max: 13.3 Std Dev: 3.5 N: 1121	Avg: 4.1 Min: 0.2 Max: 10.1 Std Dev: 3.1 N: 1070	Avg: 10.5 Min: 0.3 Max: 15.4 Std Dev: 4.0 N: 1138

ConMon Dissolved Oxygen

DO_{conc} (mg/L) time series plots for each ConMon water quality station are shown in Figures 2.15, 2.16, 2.17 and 2.18 for deployment periods 1 through 4, respectively. Summary statistics for individual stations and deployment period are provided in Table 2.5. Figures 2.19, 2.20, 2.21 and 2.22 show times series of % DO_{sat} accounting for *in situ* salinity and temperature with summary statistics provided in Table 2.6. DO_{conc} levels were highly dynamic with concentrations ranging from near anoxic to supersaturated conditions; minimum and maximum concentrations observed during the study were 0.2 and 21.4 mg/L with corresponding % DO_{sat} of 2.4 and 268.2%. As compared to the open water boundary station, the Buchanan, Wolfsnare and Thalia tidal creek stations exhibited elevated DO_{conc} variability and observed minimum and maximum values indicative of shallow creeks with relatively high levels of nutrient input characteristic of urban runoff (see Figure 2.23 for station mean values with ± 3.5 standard error of the mean). DO_{conc} followed a typical diel pattern (indicative of daytime net photosynthetic activity and night time respiration losses) with more secondary diurnal influences (indicative of tidal mixing) superimposed at all stations during deployments 1, 3 and 4. A semi-diurnal pattern was more prominent during the second deployment, suggesting reduced biological activity as a result of reduced temperatures, time of solar radiation, and algal biomass standing stock. When not under the influence of storm activity, low DO_{conc} usually occurred in the early morning with peak concentrations occurring in the late afternoon. Low DO_{conc} were also observed as early as midnight to 02:00 when low water preceded early morning hours. Given the relatively low water volume at these times, the influence of tidal creek sediment oxygen demand along with draining waters from intertidal mud flats and marshes that also exhibit high sediment respiration rates would be enhanced. Storm impacts were somewhat muted with reduced DO_{conc} levels occurring prior to and after significant events which is due to complex interactions including: reduced solar insolation driven by cloud cover, increased water column light attenuation as a result of increase sediment resuspension and/or watershed loading, increased watershed loadings of high oxygen demanding labile material, and die-off and/or flushing of algal biomass.

With exception of the open water boundary, severe hypoxia (defined as $DO_{conc} < 2$ mg/L) was observed, to varying degrees, within the tidal creek systems during the study period. Detailed information, by station and deployment period, regarding overall percent of time severe hypoxic conditions were observed, as well as number of events and duration are provided in Tables 2.7, 2.8, 2.9 and 2.10. Hypoxic conditions most notably occurred within the upstream stations of Buchanan Creek (Stations Buch 2 and 3) and the reference Wolfsnare and Thalia creek stations when mean water temperatures were ≥ 20 °C (≥ 68°F) as observed during deployments 1 and 4. The duration of single event hypoxia ranged from 15 minutes to over six hours at Buch 2, 15 hours at Buch 3, eight hours at Wolfsnare and 16 hours at Thalia Creek. Given the number of events and extended duration of some events, hypoxia can be viewed as a chronic issue within the upper Buchanan and reference creek systems. It should be noted that periodic low oxygen conditions are a natural characteristic of diel and longer cycles in a marsh dominated tidal creek where rates of metabolism are high and overall net heterotrophic (community respiration > gross productivity) (Wang et al. 2018).

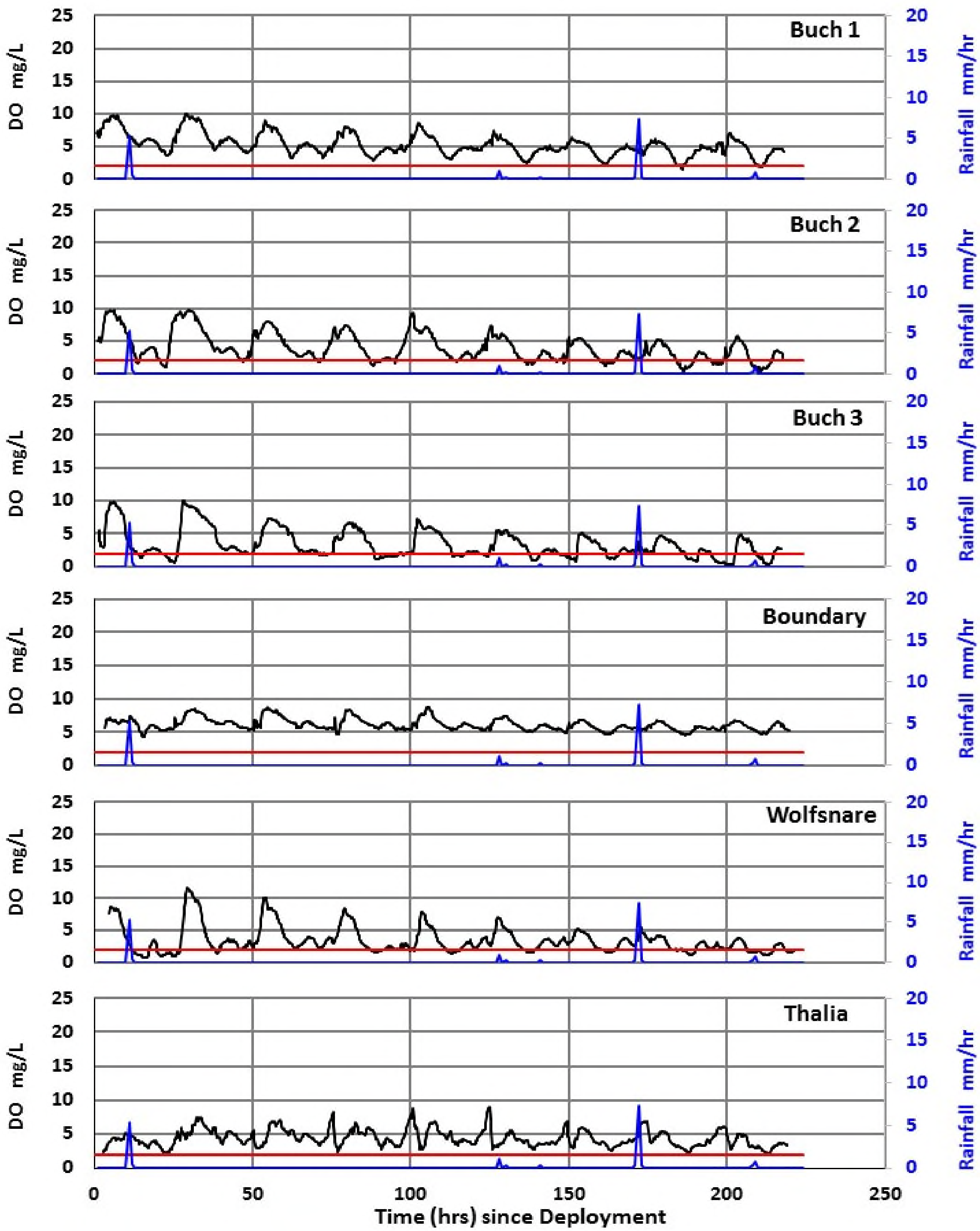


Figure 2.15. Continuous monitoring DO_{conc} (mg/L) and hourly precipitation (mm) time series during first (9/18/2018 - 9/27/2018) deployment period. Note: red dashed line represents hypoxia (< 2 mg/L) concentration limit.

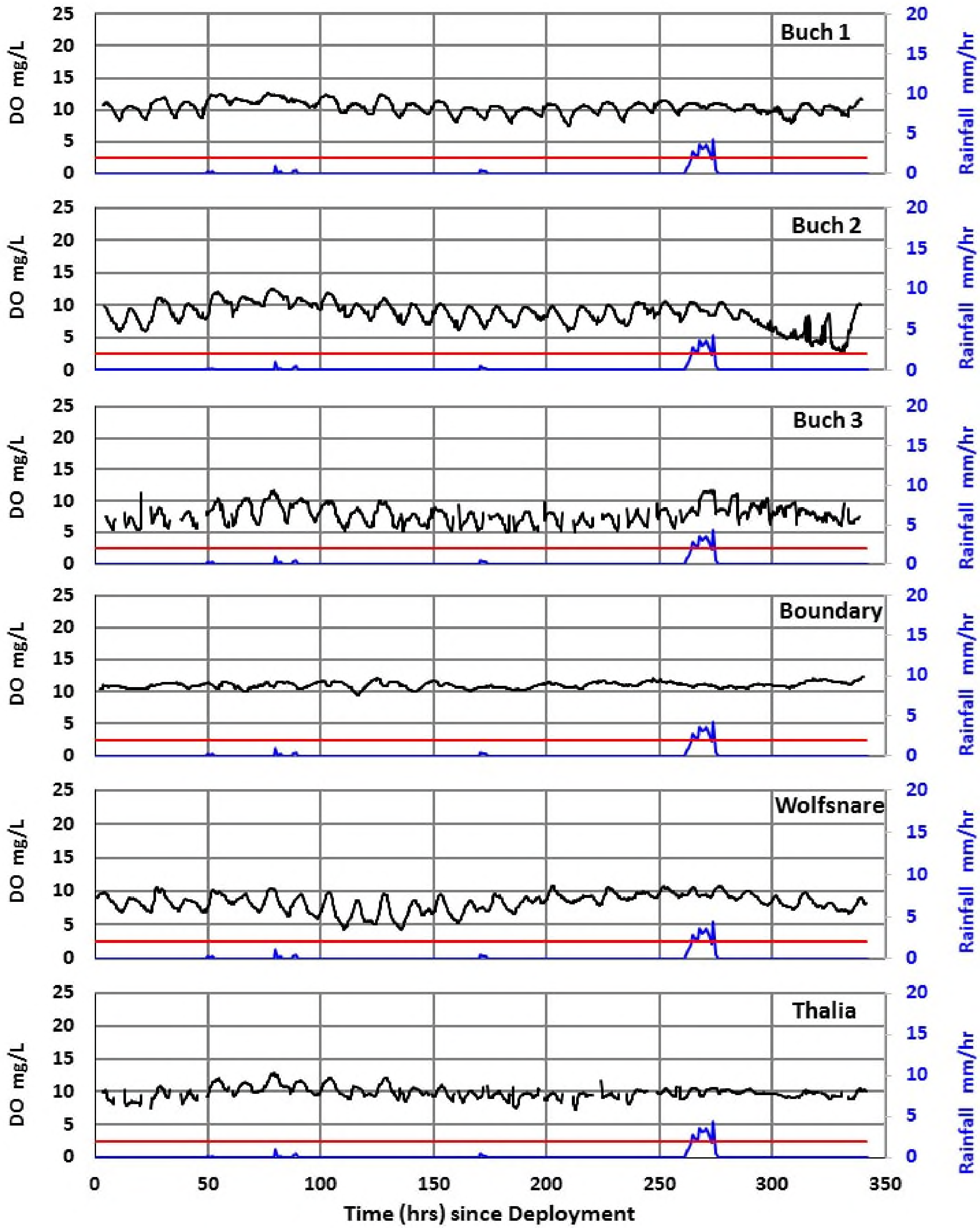


Figure 2.16. Continuous monitoring DO_{conc} (mg/L) and hourly precipitation (mm) time series during second (11/28/2018 - 12/12/2018) deployment period. Note: red dashed line represents hypoxia (< 2 mg/L) concentration limit.

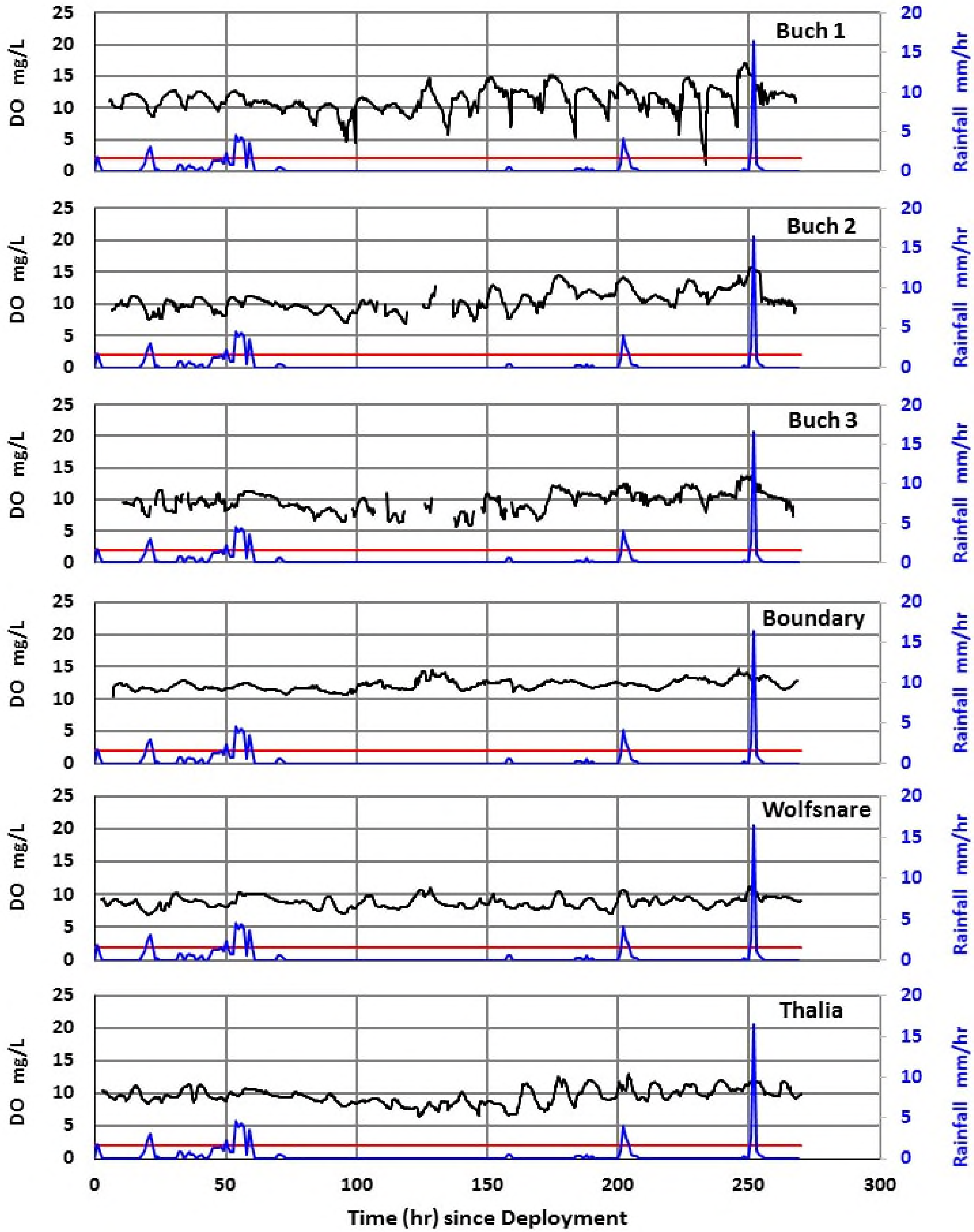


Figure 2.17. Continuous monitoring DO_{conc} (mg/L) and hourly precipitation (mm) time series during third (2/21/2019 - 3/4/2019) deployment period. Note: red dashed line represents hypoxia (< 2 mg/L) concentration limit.

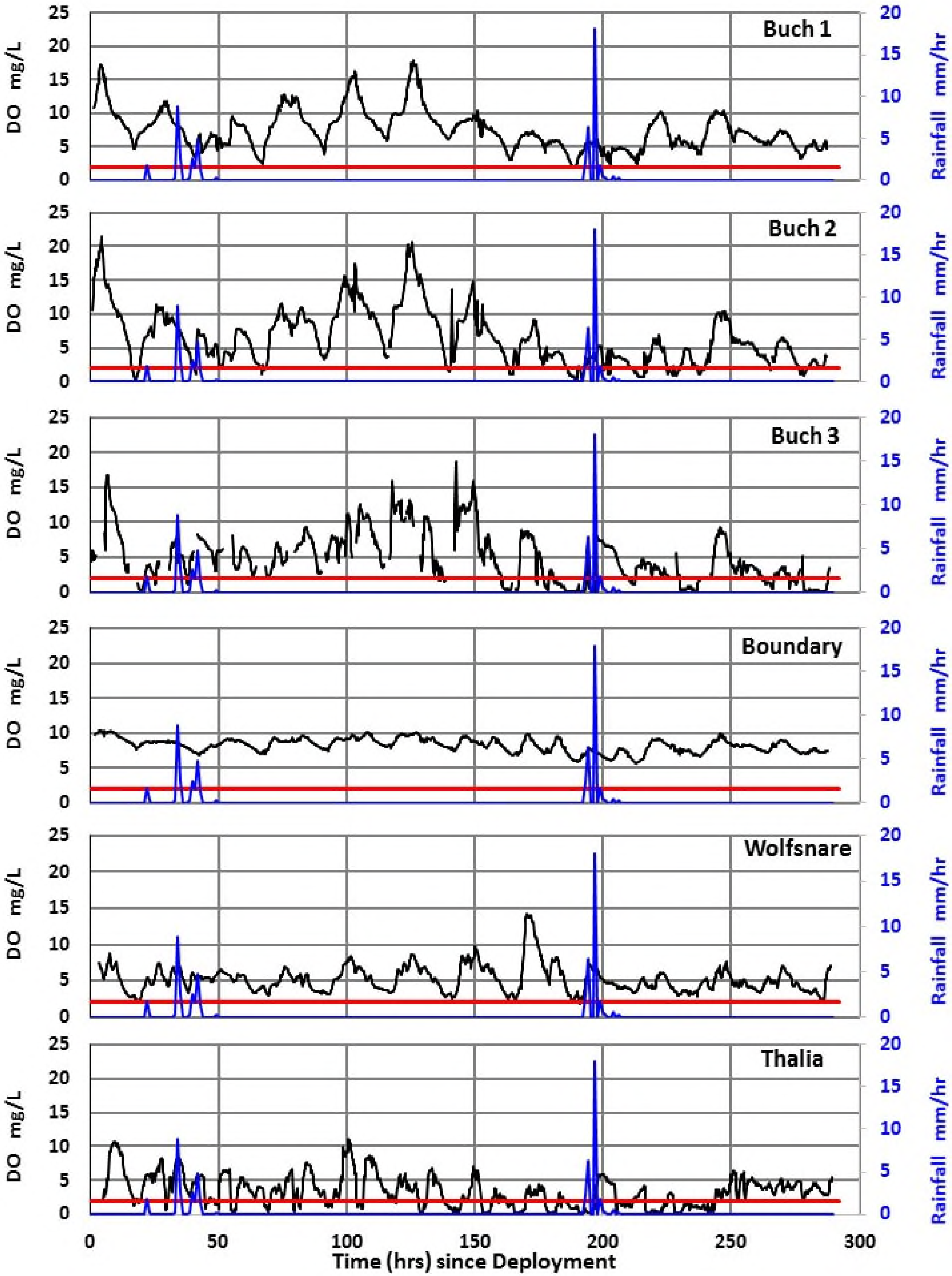


Figure 2.18. Continuous monitoring DO_{conc} (mg/L) and hourly precipitation (mm) time series during fourth (4/18/2019 - 4/30/2019) deployment period. Note: red dashed line represents hypoxia (< 2 mg/L) concentration limit.

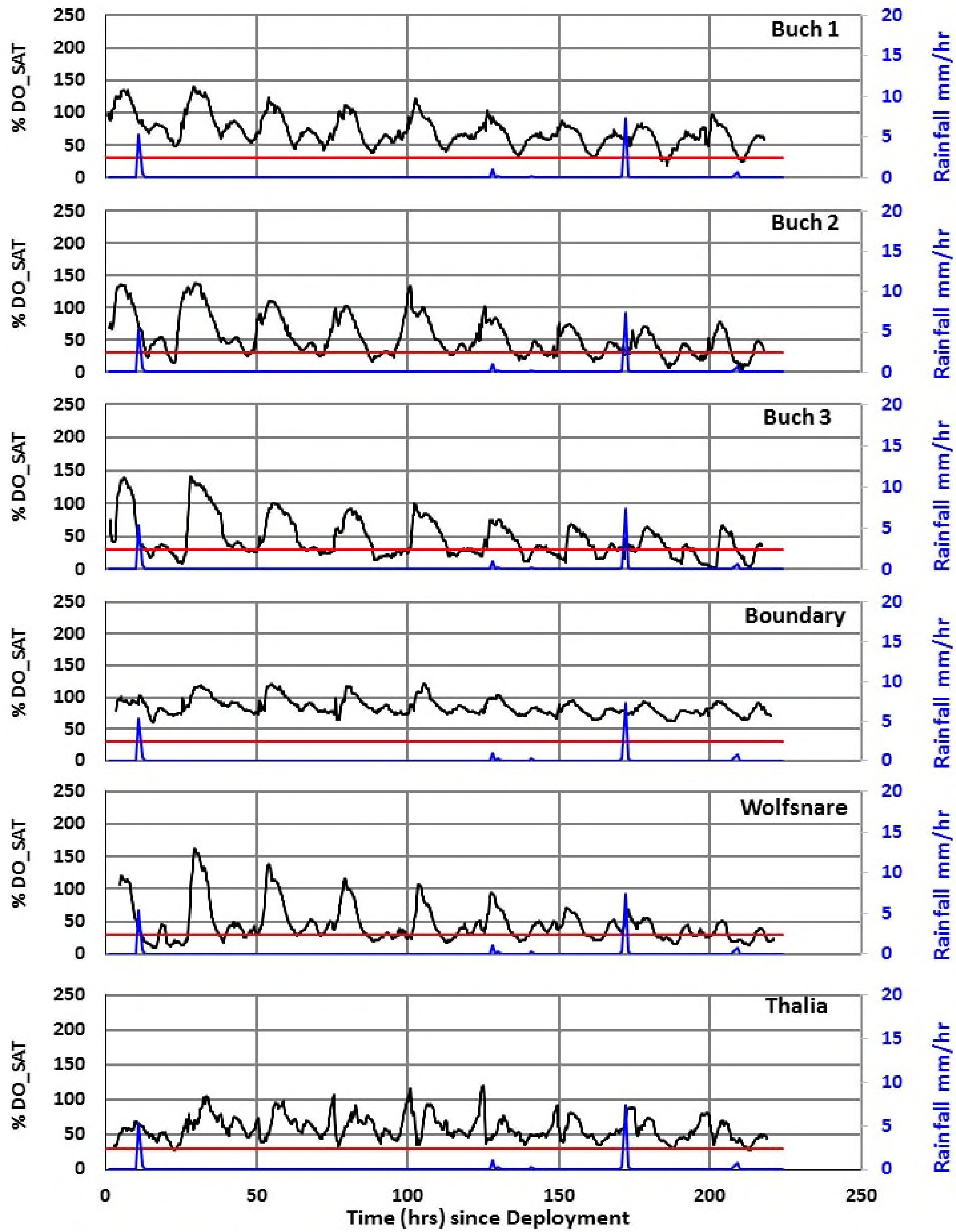


Figure 2.19. Continuous monitoring % DO_{sat} and hourly precipitation (mm) time series during first (9/18/2018 - 9/27/2018) deployment period. Note: red dashed line represents hypoxia (< 30%) saturation limit.

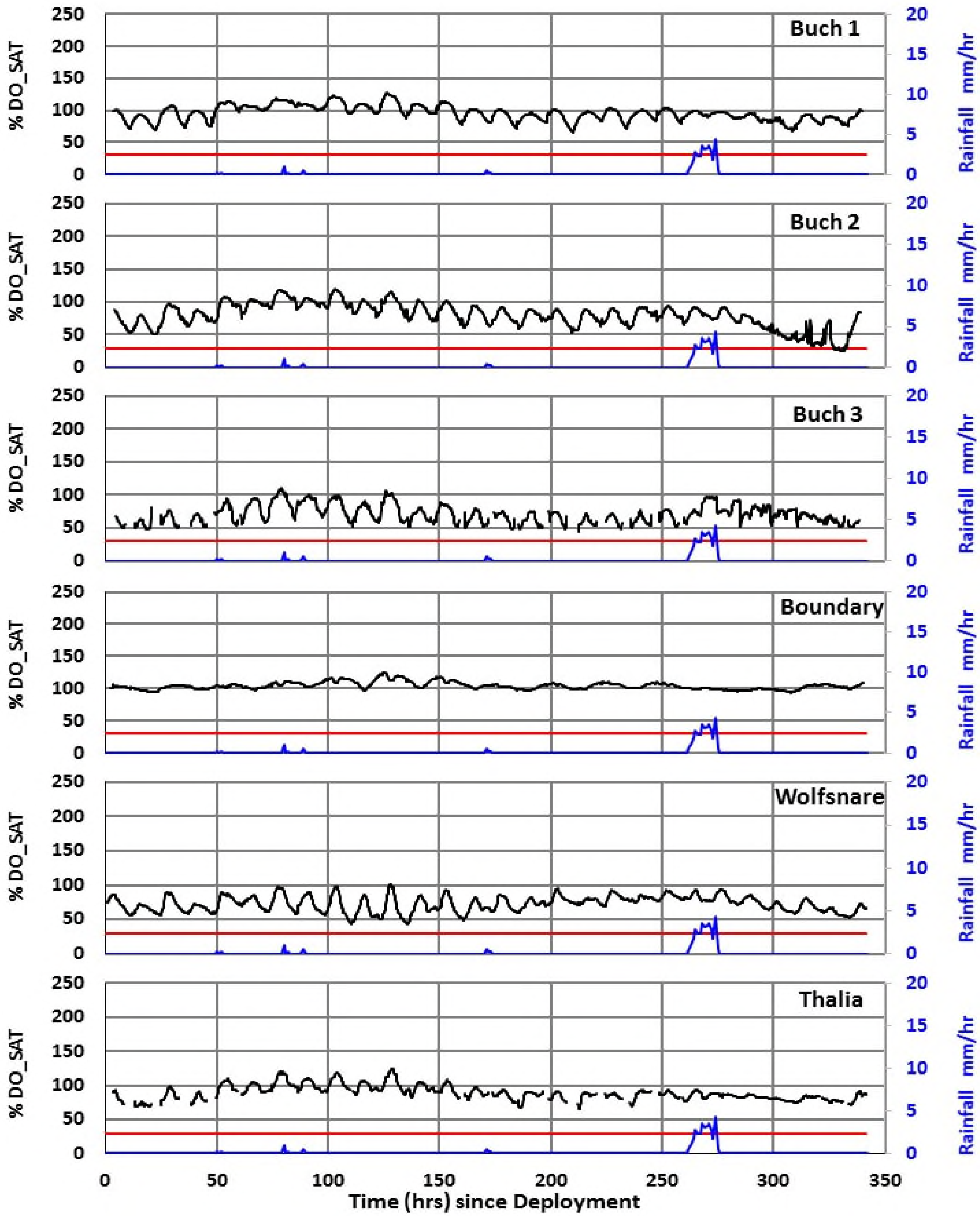


Figure 2.20. Continuous monitoring % DO_{sat} and hourly precipitation (mm) time series during second (11/28/2018 - 12/12/2018) deployment period. Note: red dashed line represents hypoxia (< 30%) saturation limit.

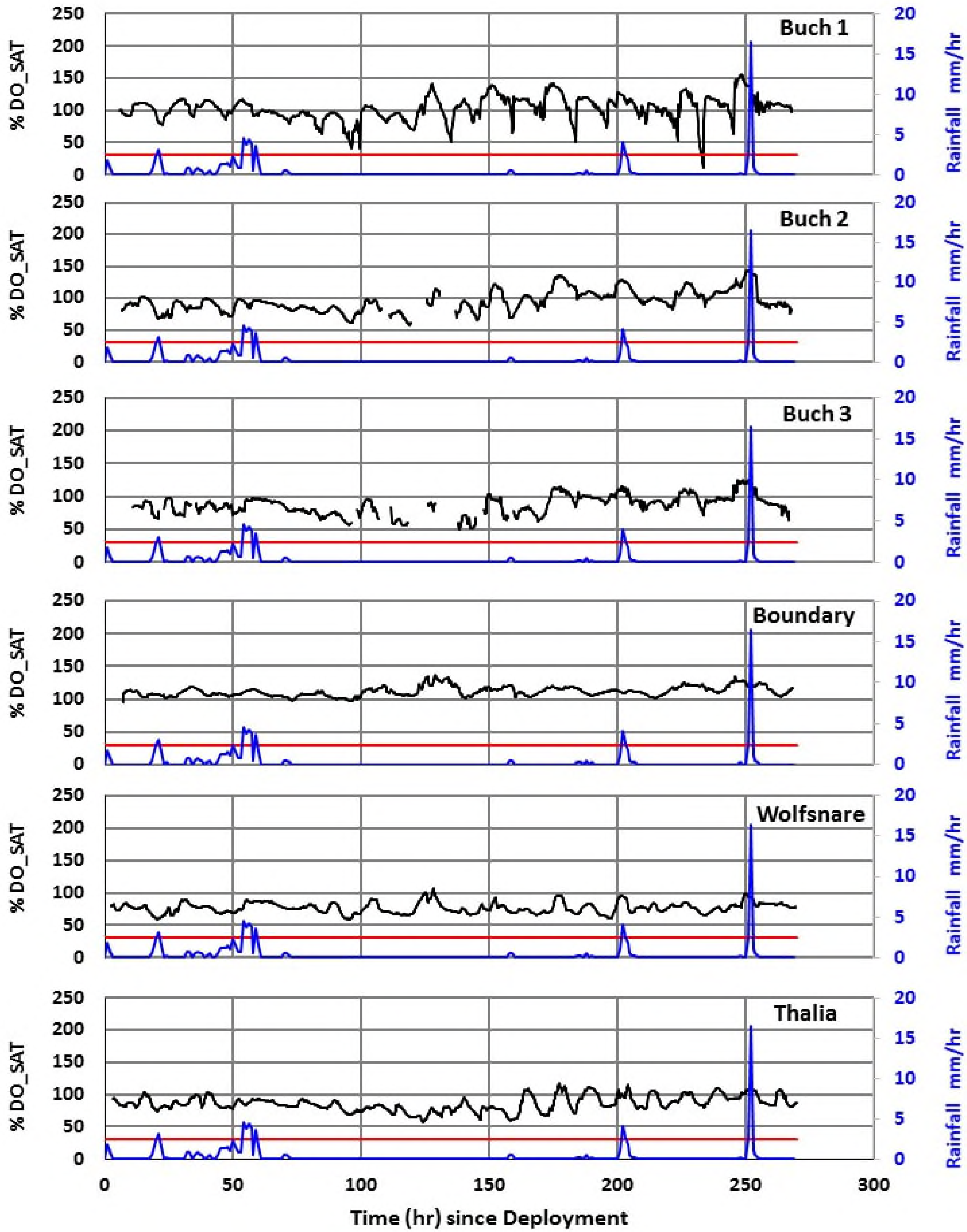


Figure 2.21. Continuous monitoring % DO_{sat} and hourly precipitation (mm) time series during third (2/21/2019 - 3/4/2019) deployment period. Note: red dashed line represents hypoxia (< 30%) saturation limit.

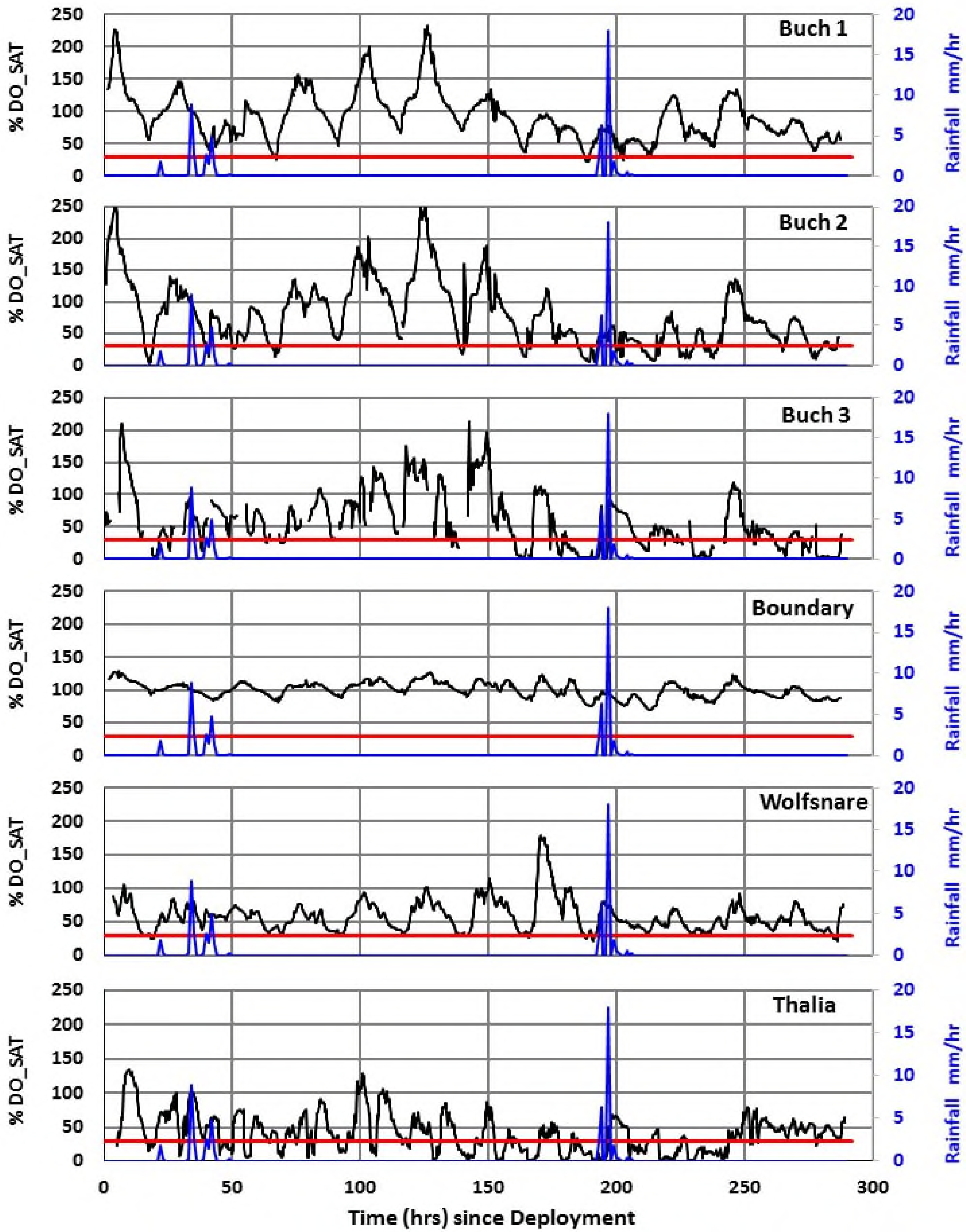


Figure 2.22. Continuous monitoring % DO_{sat} and hourly precipitation (mm) time series during fourth (4/18/2019 - 4/30/2019) deployment period. Note: red dashed line represents hypoxia (< 30%) concentration limit.

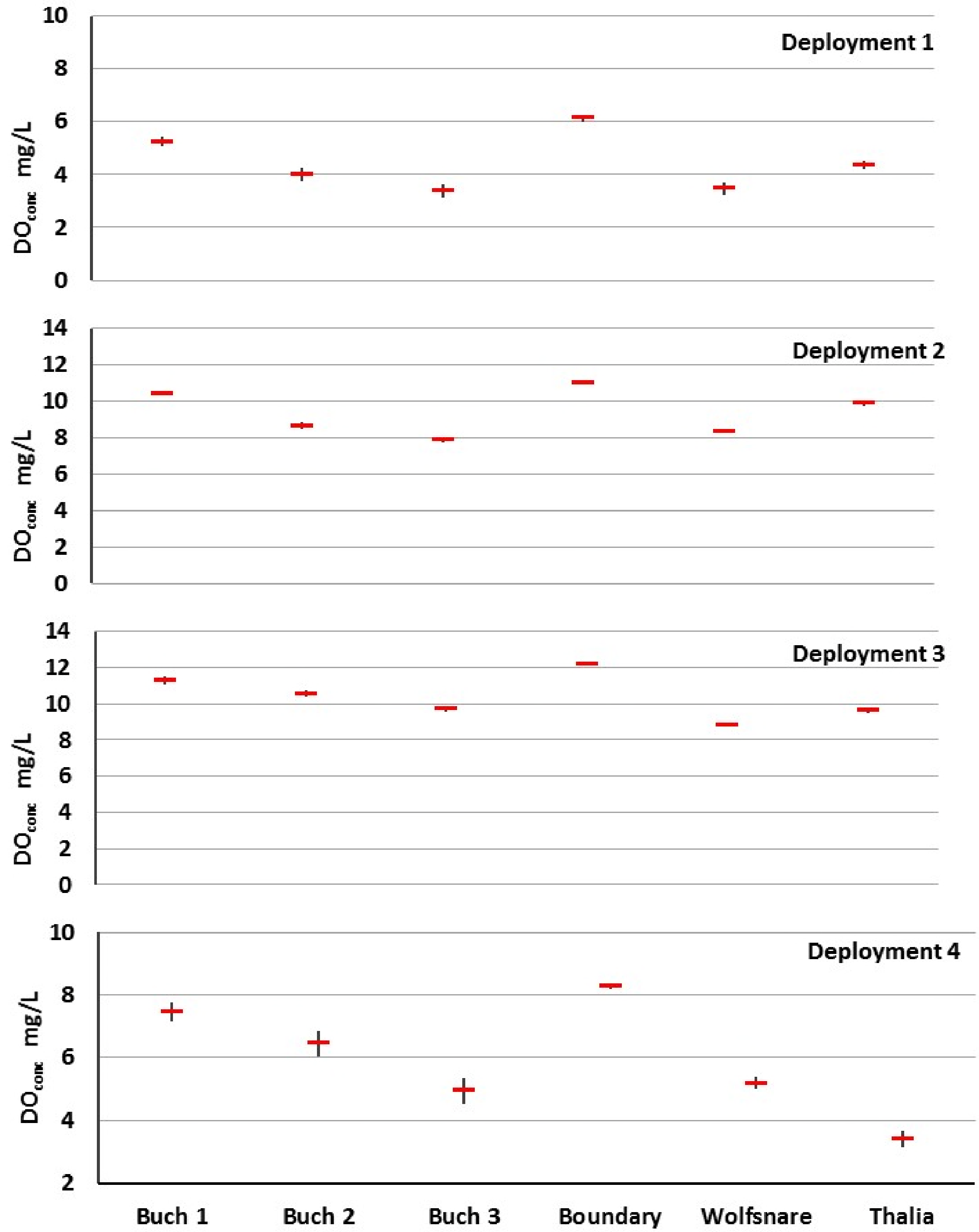


Figure 2.23. Average continuous monitoring DO_{conc} (mg/L) with ± 3.5 SEM confidence bars by station and deployment interval.

Table 2.5. Summary statistics for dissolved oxygen concentration (DO_{conc} (mg/L) by continuous monitoring water quality station and deployment period.

ConMon Station ID	**Deployment 1** (9/18/18 - 9/27/18)	**Deployment 2** (11/28/18 -12/12/18)	**Deployment 3** (2/21/19 - 3/4/19)	**Deployment 4** (4/18/19 - 4/30/19)
Buch 1	Avg: 5.2 Min: 1.4 Max: 10.0 Std Dev: 1.7 N: 869	Avg: 10.4 Min: 7.4 Max: 12.6 Std Dev: 1.0 N: 1345	Avg: 11.3 Min: 1.0 Max: 17.1 Std Dev: 2.0 N: 1049	Avg: 7.5 Min: 1.8 Max: 18.1 Std Dev: 2.9 N: 1143
Buch 2	Avg: 4.0 Min: 0.3 Max: 9.8 Std Dev: 2.2 N: 867	Avg: 8.7 Min: 2.8 Max: 12.5 Std Dev: 1.8 N: 1341	Avg: 10.6 Min: 6.8 Max: 15.6 Std Dev: 1.7 N: 986	Avg: 6.5 Min: 0.3 Max: 21.4 Std Dev: 4.1 N: 1142
Buch 3	Avg: 3.4 Min: 0.3 Max: 10.0 Std Dev: 2.1 N: 864	Avg: 7.9 Min: 5.0 Max: 11.8 Std Dev: 1.5 N: 1159	Avg: 9.7 Min: 5.7 Max: 13.7 Std Dev: 1.6 N: 909	Avg: 5.0 Min: 0.2 Max: 18.7 Std Dev: 3.7 N: 981
Boundary	Avg: 6.1 Min: 4.3 Max: 8.8 Std Dev: 0.9 N: 866	Avg: 11.0 Min: 9.5 Max: 12.3 Std Dev: 0.4 N: 1352	Avg: 12.2 Min: 10.4 Max: 14.6 Std Dev: 0.8 N: 1047	Avg: 8.3 Min: 5.7 Max: 10.3 Std Dev: 1.0 N: 1143
Wolfsnare	Avg: 3.5 Min: 0.7 Max: 11.6 Std Dev: 2.1 N: 867	Avg: 8.3 Min: 4.4 Max: 10.8 Std Dev: 1.3 N: 1363	Avg: 8.8 Min: 6.9 Max: 11.2 Std Dev: 0.8 N: 1071	Avg: 5.2 Min: 1.9 Max: 14.2 Std Dev: 1.8 N: 1141
Thalia	Avg: 4.4 Min: 2.1 Max: 9.0 Std Dev: 1.2 N: 863	Avg: 9.9 Min: 7.3 Max: 12.8 Std Dev: 0.9 N: 1162	Avg: 9.6 Min: 6.4 Max: 13.0 Std Dev: 1.2 N: 1070	Avg: 3.4 Min: 0.2 Max: 11.1 Std Dev: 2.3 N: 1138

Table 2.6. Summary statistics for % DO_{sat} by continuous monitoring (ConMon) water quality station and deployment period.

ConMon Station ID	Deployment 1 (9/18/18 - 9/27/18)	Deployment 2 (11/28/18 - 12/12/18)	Deployment 3 (2/21/19 - 3/4/19)	Deployment 4 (4/18/19 - 4/30/19)
Buch 1	Avg: 72.2 Min: 18.3 Max: 139.5 Std Dev: 23.5 N: 869	Avg: 95.7 Min: 65.5 Max: 127.5 Std Dev: 11.7 N: 1345	Avg: 103.1 Min: 9.5 Max: 156.0 Std Dev: 18.8 N: 1049	Avg: 91.6 Min: 23.2 Max: 233.6 Std Dev: 37.3 N: 1143
Buch 2	Avg: 55.1 Min: 3.8 Max: 138.7 Std Dev: 31.1 N: 867	Avg: 79.6 Min: 24.4 Max: 118.8 Std Dev: 18.4 N: 1341	Avg: 95.2 Min: 57.4 Max: 142.7 Std Dev: 16.5 N: 986	Avg: 77.9 Min: 3.6 Max: 268.2 Std Dev: 50.6 N: 1142
Buch 3	Avg: 46.5 Min: 3.6 Max: 140.9 Std Dev: 30.3 N: 864	Avg: 71.1 Min: 43.4 Max: 109.6 Std Dev: 13.7 N: 1159	Avg: 87.2 Min: 50.3 Max: 124.6 Std Dev: 14.4 N: 909	Avg: 58.4 Min: 2.4 Max: 212.2 Std Dev: 43.9 N: 981
Boundary	Avg: 84.8 Min: 60.0 Max: 121.6 Std Dev: 12.7 N: 866	Avg: 103.9 Min: 93.3 Max: 125.0 Std Dev: 5.7 N: 1352	Avg: 111.9 Min: 95.4 Max: 137.1 Std Dev: 7.4 N: 1047	Avg: 99.9 Min: 69.5 Max: 128.0 Std Dev: 11.7 N: 1143
Wolfsnare	Avg: 45.6 Min: 9.1 Max: 162.4 Std Dev: 28.8 N: 867	Avg: 72.8 Min: 42.9 Max: 100.8 Std Dev: 11.4 N: 1363	Avg: 76.8 Min: 59.5 Max: 106.2 Std Dev: 8.1 N: 1071	Avg: 58.3 Min: 20.9 Max: 179.1 Std Dev: 23.4 N: 1141
Thalia	Avg: 58.9 Min: 119.7 Max: 119.7 Std Dev: 16.7 N: 863	Avg: 89.2 Min: 64.6 Max: 124.6 Std Dev: 11.0 N: 1163	Avg: 86.0 Min: 56.4 Max: 117.8 Std Dev: 11.6 N: 1070	Avg: 40.6 Min: 2.5 Max: 133.6 Std Dev: 27.7 N: 1137

Table 2.7. Percent of time that continuous monitoring water quality stations exhibited hypoxic conditions (hypoxia criteria: DO_{conc} < 2.0 mg/L) and non-attainment of Virginia open water DO_{conc} criteria for Chesapeake Bay and its tidal tributaries (Virginia instantaneous DO_{conc} standard: ≥ 4.3 mg/L at ≥ 29 °C and ≥ 3.2 mg/L at < 29 °C; VaSWCB 2009) during deployment period 1. Information on individual hypoxic events is also provided. Time is presented in eastern standard time (EST).

ConMon Station ID	% time hypoxic conditions	% time DO non-attainment of instantaneous standard	Individual Hypoxia Events			
			Event	Start Date	Start Time EST	Duration hr:min
Buch 1	0.8	9.4	1	9/26/2018	2:15	00:15
			2	9/26/2018	3:45	00:30
			3	9/27/2018	4:15	01:00
Buch 2	17.0	28.3	1	9/18/2019	23:30	01:00
			2	9/19/2018	07:00	02:00
			3	9/20/2018	08:45	00:30
			4	9/21/2018	08:45	00:30
			5	9/22:2018	01:15	03:30
			6	9/22/2018	08:15	01:00
			7	9/23/2018	04:00	01:00
			8	9/24/2018	02:15	03:15
			9	9/24/2018	11:15	00:15
			10	9/24/2018	12:00	00:30
			11	9/24/2018	13:00	00:15
			12	9/24/2018	14:30	00:30
			13	9/25/2018	02:00	04:30
			14	9/26/2018	02:15	05:15
			15	9/26/2018	12:15	00:15
			16	9/26/2018	13:00	03:45
			17	9/27/2018	01:15	06:45
Buch 3	28.5	60.9	1	9/18/2018	23:45	02:00
			2	9/19/2018	07:15	05:00
			3	9/20/2018	09:15	00:15
			4	9/20/2018	11:15	00:45
			5	9/21/2018	08:45	03:45
			6	9/22/2018	02:30	07:30
			7	9/22/2018	11:30	00:45
			8	9/22/2018	14:00	00:15
			9	9/23/2018	03:15	03:45
			10	9/23/2018	11:15	00:15
			11	9:23/2018	12:00	02:45
			12	9/24/2018	12:15	00:15
			13	9/24/2018	12:45	05:45
			14	9/25/2018	04:00	03:45
			15	9/25/2018	13:30	00:15
			16	9/25/2018	17:15	00:15
			17	9/26/2018	04:45	04:15
			18	9/26/2018	13:00	07:45
			19	9/27/2018	03:30	05:30
Boundary	0.0	0.0	-	-	-	-

Table 2.7. (cont.)

ConMon Station ID	% time hypoxic conditions	% time DO non-attainment of instantaneous standard	Individual Hypoxia Events			
			Event	Start Date	Start Time EST	Duration hr:min
Wolfsnare	22.0	59.3	1	9/22/2018	02:00	03:00
			2	9/22/2018	08:45	00:30
			3	9/22/2018	13:30	00:30
			4	9/23/2018	01:45	04:00
			5	9/24/2018	02:15	03:00
			6	9/25/2018	03:15	03:15
			7	9/26/2018	02:15	00:45
			8	9/26/2018	04:15	03:30
			9	9/26/2018	16:45	00:15
			10	9/27/2018	00:30	08:00
			11	9/27/2018	12:45	00:15
			12	9/27/2018	13:00	02:15
Thalia	0.0	16.3	-	-	-	-

Table 2.8. Percent of time that continuous monitoring water quality stations exhibited hypoxic conditions (hypoxia criteria: DO_{conc} < 2.0 mg/L) and non-attainment of Virginia open water DO_{conc} criteria for Chesapeake Bay and its tidal tributaries (Virginia instantaneous DO_{conc} standard as in Fig. 2.7) during deployment period 2. Information on individual hypoxic events is also provided.

ConMon Station ID	% time hypoxic conditions	% time DO non-attainment of instantaneous standard	Individual Hypoxia Events			
			Event	Start Date	Start Time EST	Duration hr:min
Buch 1	0.0	0.0	-	-	-	-
Buch 2	0.0	0.7	-	-	-	-
Buch 3	0.0	0.0	-	-	-	-
Boundary	0.0	0.0	-	-	-	-
Wolfsnare	0.0	0.0	-	-	-	-
Thalia	0.0	0.0	-	-	-	-

Table 2.9. Percent of time that continuous monitoring water quality stations exhibited hypoxic conditions (hypoxia criteria: DO_{conc} < 2.0 $mg \cdot L^{-1}$) and non-attainment of Virginia open water DO_{conc} criteria for Chesapeake Bay and its tidal tributaries (Virginia instantaneous DO_{conc} standard as in Fig. 2.7) during deployment period 3. Information on individual hypoxic events is also provided.

ConMon Station ID	% time hypoxic conditions	% time DO non-attainment of instantaneous standard	Individual Hypoxia Events			
			Event	Start Date	Start Time EST	Duration hr:min
Buch 1	0.2	0.3	1	3/3/2019	01:15	00:30
Buch 2	0.0	0.0	-	-	-	-
Buch 3	0.0	0.0	-	-	-	-
Boundary	0.0	0.0	-	-	-	-
Wolfsnare	0.0	0.0	-	-	-	-
Thalia	0.0	0.0	-	-	-	-

Table 2.10. Percent of time that continuous monitoring (ConMon) water quality stations exhibited hypoxic conditions (hypoxia criteria: $DO_{conc} < 2.0\ mg \cdot L^{-1}$) and non-attainment of Virginia open water DO_{conc} criteria for Chesapeake Bay and its tidal tributaries (Virginia instantaneous DO_{conc} standard as in Fig. 2.7) during deployment period 4. Information on individual hypoxic events is also provided.

ConMon Station ID	% time hypoxic conditions	% time DO non-attainment of instantaneous standard	Individual Hypoxia Events			
			Event	Start Date	Start Time EST	Duration hr:min
Buch 1	0.4	1.4	1	4/26/2019	07:00	01:15
Buch 2	11.6	23.6	1	4/19/2019	03:30	02:45
			2	4/20/2019	03:45	00:45
			3	4/20/2019	05:45	00:30
			4	4/20/2019	06:45	00:45
			5	4/24/2019	06:45	00:45
			6	4/25/2019	06:30	01:30
			7	4/25/2019	08:00	00:15
			8	4/26/2019	05:15	06:15
			9	4/26/2019	19:15	00:30
			10	4/26/2019	21:00	01:00
			11	4/27/2019	05:30	00:15
			12	4/27/2019	06:00	04:15
			13	4/27/2019	11:30	00:45
			14	4/27/2019	20:00	04:45
			15	4/28/2019	06:00	00:15
			16	4/28/2019	07:00	03:45
			17	4/29/2019	12:15	00:15
			18	4/29/2019	23:15	03:15
Buch 3	23.6	47.5	1	4/19/2019	05:45	02:30
			2	4/19/2019	12:15	00:45
			3	4/20/2019	01:00	00:45
			4	4/24/2019	03:00	00:30
			5	4/24/2019	04:45	01:00
			6	4/25/2019	03:30	04:00
			7	4/25/2019	09:00	01:15
			8	4/25/2019	17:00	00:30
			9	4/25/2019	20:00	15:30
			10	4/26/2019	13:45	02:15
			11	4/27/2019	05:00	02:30
			12	4/28/2019	01:00	07:45
			13	4/28/2019	13:15	00:15
			14	4/29/2019	01:00	00:30
			15	4/29/2019	09:15	03:45
			16	4/29/2019	19:45	00:45
			17	4/29/2019	21:00	02:00
			18	4/30/2019	01:15	09:15
Boundary	0.0	0.0	-	-	-	-
Wolfsnare	0.2	10.3	1	4/26/2019	10:00	00:15
			2	4/30/2019	09:15	00:15

Table 2.10. (cont.)

ConMon Station ID	% time hypoxic conditions	% time DO non-attainment of instantaneous standard	Individual Hypoxia Events			
			Event	Start Date	Start Time EST	Duration hr:min
Thalia	32.7	49.3	1	4/18/2019	15:45	00:15
			2	4/19/2019	04:15	00:30
			3	4/19/2019	05:45	00:45
			4	4/19/2019	16:30	01:15
			5	4/20/2019	08:00	01:30
			6	4/20/2019	10:30	00:30
			7	4/20/2019	11:30	02:00
			8	4/20/2019	17:45	02:30
			9	4/21/2019	07:00	02:15
			10	4/21/2019	18:30	00:45
			11	4/21/2019	20:15	01:00
			12	4/22/2018	06:54	03:00
			13	4/22/2018	19:15	02:15
			14	4/23/2018	09:30	01:00
			15	4/23/2018	19:15	03:15
			16	4/24/2019	05:00	05:30
			17	4/24/2019	14:15	00:15
			18	4/24/2019	19:45	03:45
			19	4/25/2019	02:15	00:15
			20	4/25/2019	05:15	07:15
			21	4/25/2019	20:45	04:30
			22	4/26/2019	02:30	00:45
			23	4/26/2019	03:45	00:30
			24	4/26/2019	04:30	11:15
			25	4/27/2019	06:45	00:15
			26	4/27/2019	11:45	08:30
			27	4/27/2019	22:45	16:00
			28	4/30/2019	01:15	00:15

ConMon Chlorophyll

Chl (µg/L) time series plots for each ConMon water quality station are shown in Figures 2.24, 2.25, 2.26 and 2.27 for deployment periods 1 through 4, respectively. Summary statistics for individual stations and deployment period are provided in Table 2.11 with station mean values and ± 3.5 standard error of the mean confidence bars presented in Figure 2.28. It should be noted that unadjusted instrument Chl concentrations are used in reporting time series data; this decision was based on preliminary comparisons made between YSI Chl sensor and lab extracted functional Chl-a from the Buchanan Creek and Western Branch of the Lynnhaven River stations. While limited in number of samples, a significant linear relationship with slope near unity (0.91) was found (see Figure 2.29).

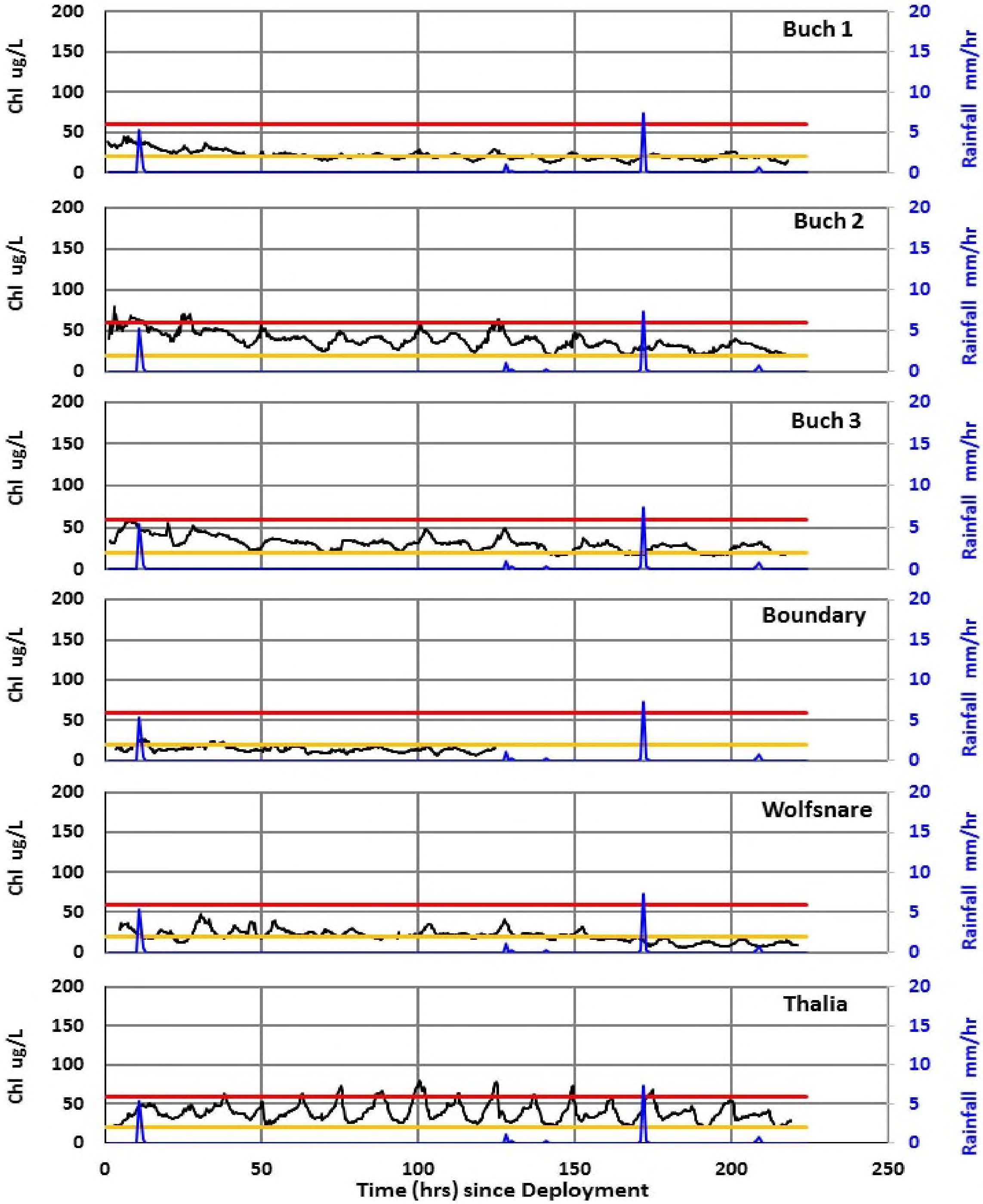


Figure 2.24. Continuous monitoring unadjusted chlorophyll concentration (µg/L) and hourly precipitation (mm) time series during first (9/18/2018 - 9/27/2018) deployment period. Note: orange and red lines represent lower limit of high (20-60 ug/L) and hyper (> 60 ug/L) chlorophyll eutrophic index, respectively.

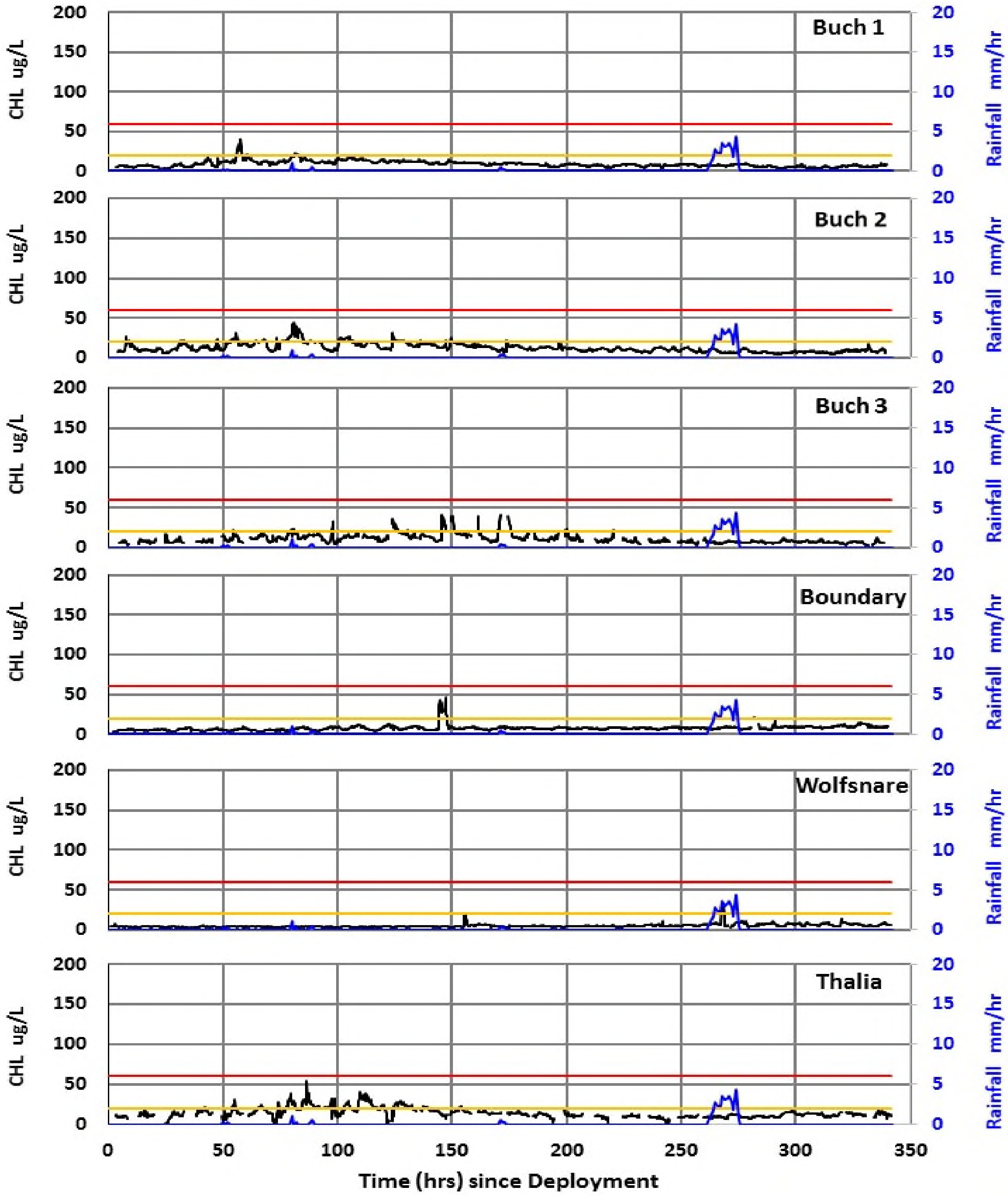


Figure 2.25. Continuous monitoring unadjusted chlorophyll concentration (µg/L) and hourly precipitation (mm) time series during second (11/28-12/12/2018) deployment period. Note: orange and red lines represent lower limit of high (20-60 ug/L) and hyper (> 60 ug/L) chlorophyll eutrophic index, respectively.

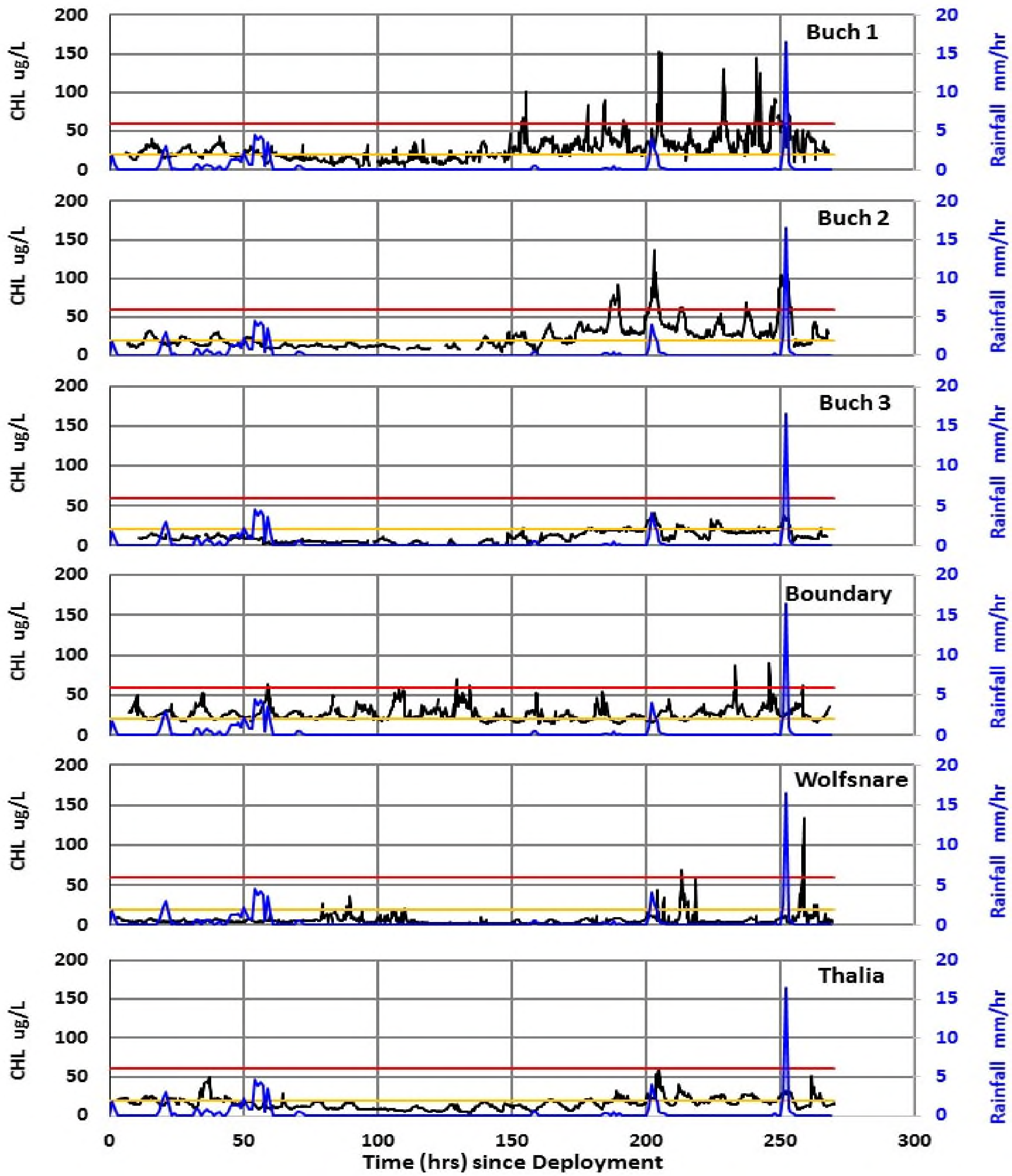


Figure 2.26. Continuous monitoring unadjusted chlorophyll concentration (μg/L) and hourly precipitation (mm) time series during third (2/21/2019-3/4/2019) deployment period. Note: orange and red lines represent lower limit of high (20-60 ug/L) and hyper (> 60 ug/L) chlorophyll eutrophic index, respectively.

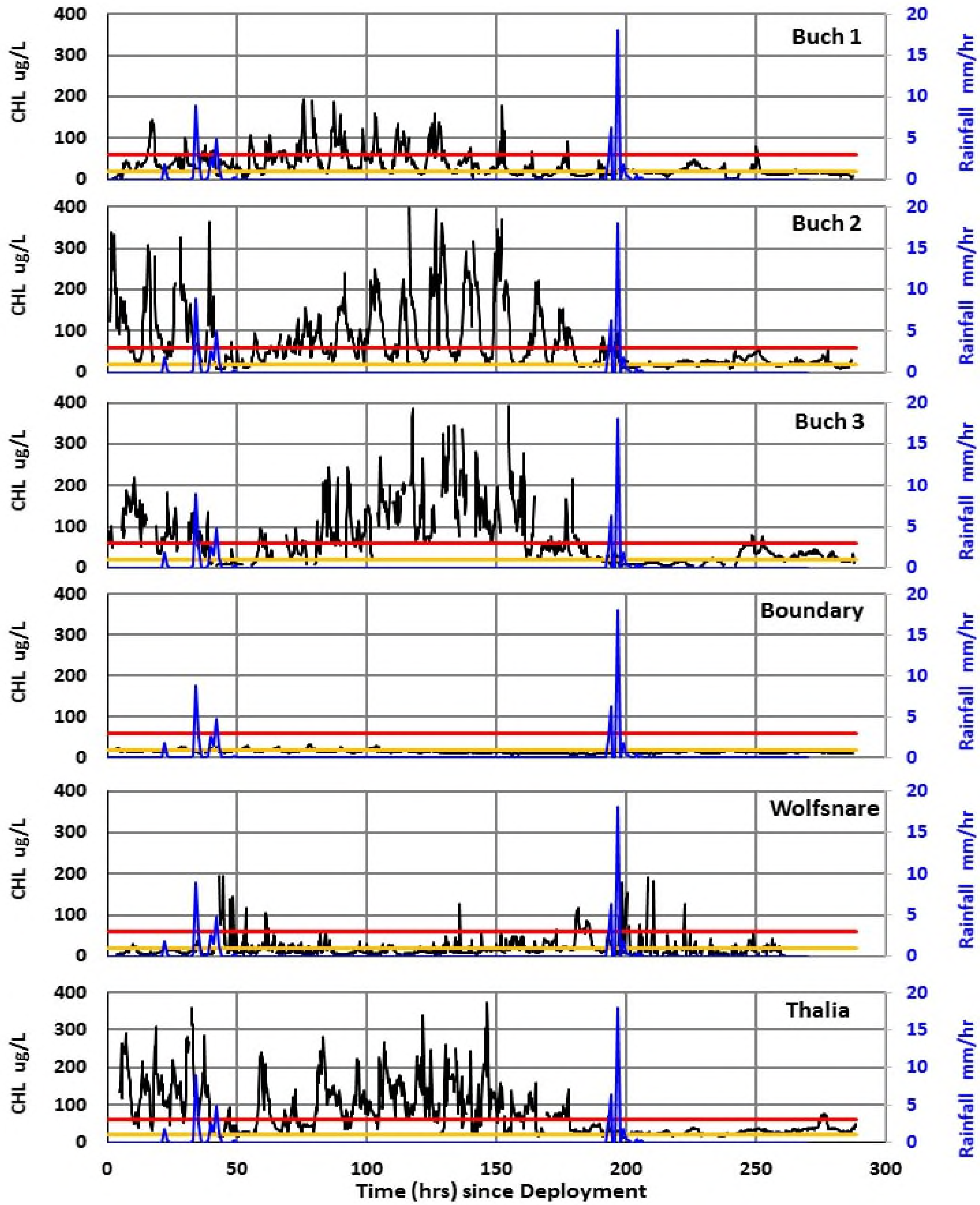


Figure 2.27. Continuous monitoring unadjusted chlorophyll concentration (µg/L) and hourly precipitation (mm) time series during fourth (4/18/2019 - 4/30/2019) deployment period. Note: orange and red lines represent lower limit of high (20-60 ug/L) and hyper (> 60 ug/L) chlorophyll eutrophic index, respectively.

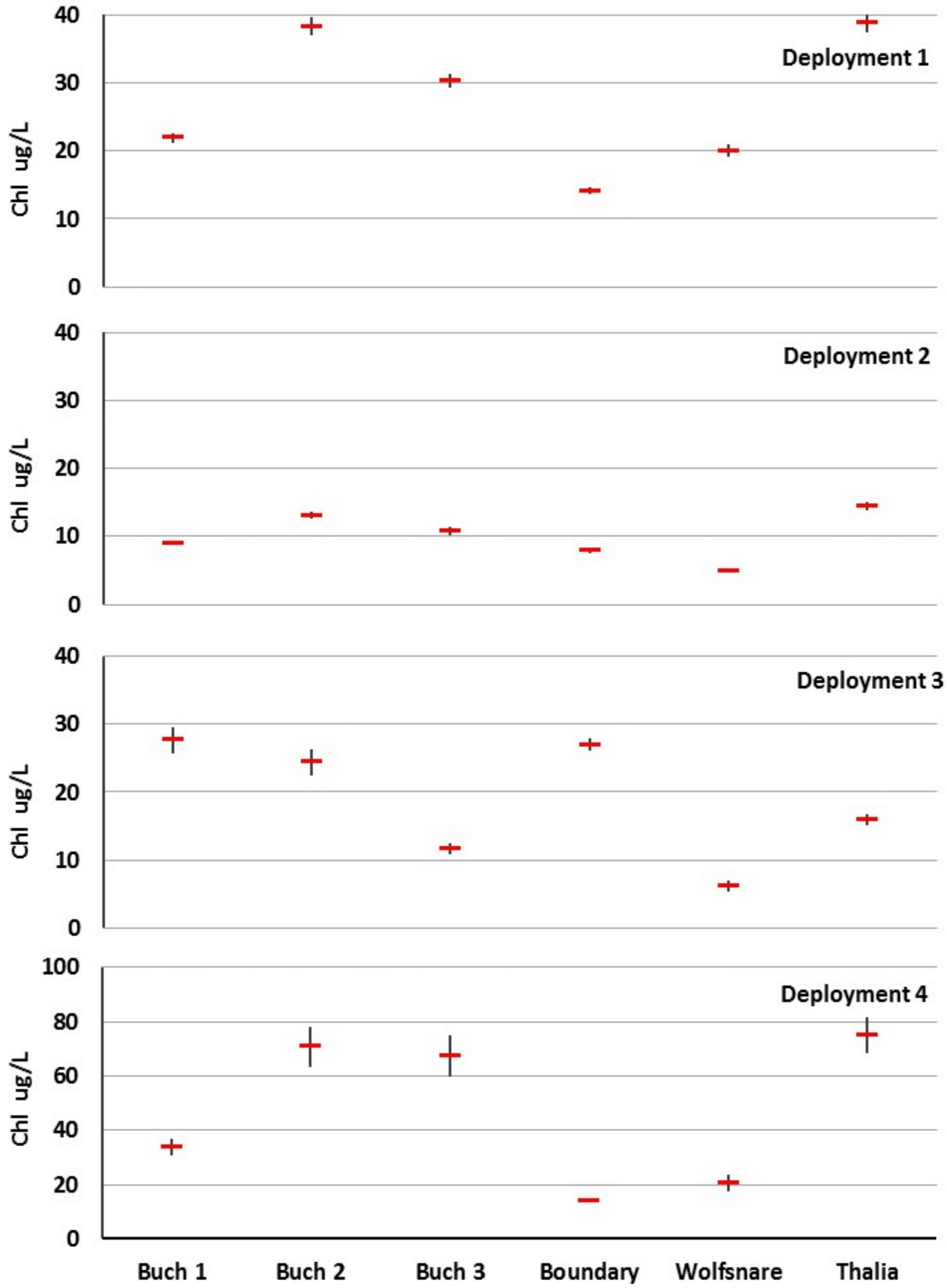


Figure 2.28. Average continuous monitoring chlorophyll (ug/L) with ± 3.5 SEM confidence bars by station and deployment interval.

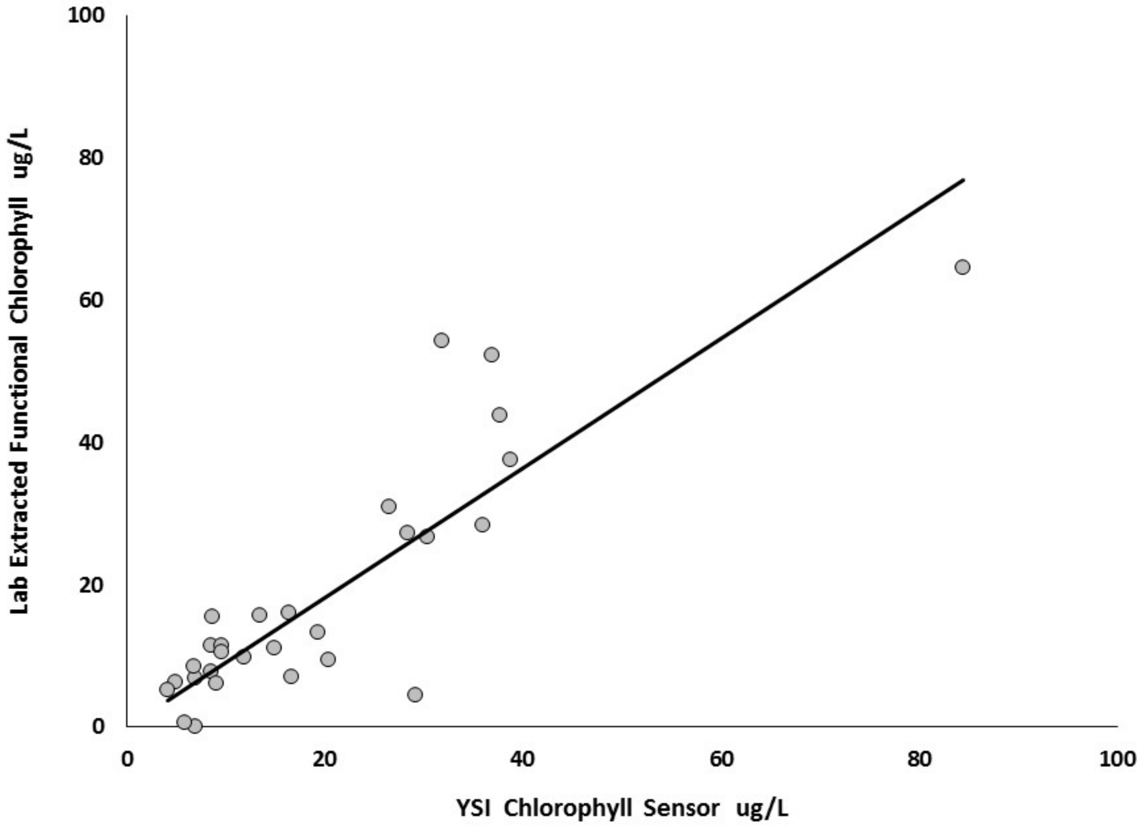


Figure 2.29. Linear relationship between YSI Chl sensor and lab extracted function Chl a using Buchanan Creek and Boundary stations: Functional Chl a = 0.91 x YSI sensor Chl (r^2=0.88; N=29; p=0.000). Note: a single identified outlier sample was not included in the regression analysis. Linear relationship with lab extracted total Chl a: Total Chl a = 1.22 x YSI sensor Chl (r^2=0.82; N=29; p=0.000).

As with dissolved oxygen, Chl patterns within Buchanan Creek, the Western Branch of the Lynnhaven River, and the reference tidal creek stations (Wolfsnare and Thalia) were relatively dynamic with concentrations ranging from 0.1 to 397.9 µ/L. With respect to a commonly used estuarine chlorophyll eutrophic index (Bricker et. al. 1999), mean Chl levels within Buchanan Creek and at the reference creek stations were within the high (20-60 ug/L) condition index range for deployments 1 (representative of fall) and 4 (representative of spring); with stations Buch 2, Buch 3 and Thalia in the hypereutrophic (> 60 ug/L) condition range during deployment 4. During deployment 2, average Chl levels at all stations remained within medium (> 5 to ≤ 20 µg/L) to low (> 0 to ≤ 5 µg/L) eutrophic index range. Deployment 3 was of interest as the more downstream stations (Boundary and Buch 3) exhibited average Chl levels within the high index range, whereas the upper tidal creek stations (Buch 3, Wolfsnare and Thalia) displayed concentrations within the medium index range. The general pattern of change from higher eutrophic indices associated with upstream portions of the tidal creeks appears to coincide with a sustained precipitation event early in the deployment period; significantly depressed upstream salinities (most notably Buch 3 and Wolfsnare) lasted for approximately 4 days and would serve to flush the system with fresher streamflow and associated runoff.

Table 2.11. Summary statistics for chlorophyll (ug/L) by continuous monitoring (ConMon) water quality station and deployment period.

ConMon Station ID	Deployment 1 (9/18/18 - 9/27/18)	Deployment 2 (11/28/18 - 12/12/18)	Deployment 3 (2/21/2019 - 3/4/19)	Deployment 4 (4/18/19 - 4/30/19)
Buch 1	Avg: 21.9 Min: 10.4 Max: 44.7 Std Dev: 5.9 N: 869	Avg: 9.0 Min: 2.9 Max: 41.0 Std Dev: 3.7 N: 1340	Avg: 27.6 Min: 0.1 Max: 152.6 Std Dev: 18.1 N: 1012	Avg: 33.6 Min: 0.4 Max: 194.5 Std Dev: 29.7 N: 1133
Buch 2	Avg: 38.3 Min: 19.2 Max: 79.3 Std Dev: 10.9 N: 864	Avg: 13.1 Min: 4.9 Max: 44.3 Std Dev: 5.6 N: 1341	Avg: 24.4 Min: 4.8 Max: 137.0 Std Dev: 17.5 N: 983	Avg: 70.7 Min: 8.5 Max: 397.9 Std Dev: 72.3 N: 1122
Buch 3	Avg: 30.2 Min: 15.9 Max: 59.9 Std Dev: 8.7 N: 864	Avg: 10.8 Min: 2.3 Max: 41.2 Std Dev: 5.5 N: 1112	Avg: 11.7 Min: 1.0 Max: 40.3 Std Dev: 7.3 N: 911	Avg: 67.1 Min: 3.2 Max: 393.4 Std Dev: 66.7 N: 939
Boundary	Avg: 14.1 Min: 6.2 Max: 26.4 Std Dev: 3.7 N: 486	Avg: 7.9 Min: 2.9 Max: 46.4 Std Dev: 3.4 N: 1342	Avg: 27.0 Min: 13.8 Max: 90.1 Std Dev: 9.0 N: 1043	Avg: 14.2 Min: 8.3 Max: 33.6 Std Dev: 3.9 N: 1143
Wolfsnare	Avg: 20.0 Min: 6.0 Max: 47.0 Std Dev: 7.5 N: 867	Avg: 4.9 Min: 2.0 Max: 32.6 Std Dev: 2.2 N: 1361	Avg: 6.2 Min: 0.5 Max: 134.3 Std Dev: 7.9 N: 1056	Avg: 20.6 Min: 0.1 Max: 283.5 Std Dev: 25.7 N: 936
Thalia	Avg: 38.8 Min: 19.2 Max: 79.1 Std Dev: 11.9 N: 866	Avg: 14.4 Min: 1.0 Max: 54.4 Std Dev: 6.2 N: 1103	Avg: 16.0 Min: 3.8 Max: 60.6 Std Dev: 7.6 N: 1070	Avg: 74.9 Min: 11.2 Max: 372.5 Std Dev: 63.6 N: 1116

ConMon Turbidity

Turbidity, measured in nephelometric turbidity units (NTUs), is a measure of water clarity and is influenced by the scattering of light by fine sediments, organic matter (dissolved and particulate), algae and other planktonic forms. Turbidity (NTU) time series plots for each ConMon water quality station are shown in Figures 2.30, 2.31, 2.32 and 2.33 for deployment periods 1 through 4, respectively. Summary statistics for individual stations and deployment period are provided in Table 2.12. Typical background levels for estuarine systems is on the order of ≤ 10 nephelometric turbidity units (NTUs). Background levels can easily be increased to levels that have negative impacts with respect to light availability to rooted underwater vegetation, and siltation/filtration issues for selected organisms. Mean deployment NTU levels varied between 29-41 NTUs for deployment 1, 2-11 NTUs for deployment 2, 5-39 NTUs for deployment 3, and 14-47 NTUs for the fourth deployment. There existed a general pattern of elevated NTU levels associated with the tidal creek systems as compared to the open water boundary station within the Western Branch of the Lynnhaven River, where mean deployment and maximum values varied from 2 to 31 NTUs and 10-54 NTUs, respectively. Tidal creek peak values ranged from 300-929 NTUs at the Buchanan Creek stations, 698 NTUs in Wolfsnare, and 124 NTUs in Thalia Creek. Due to the shallowness and fine grained sediment nature of the tidal creek systems, storm influence on NTU levels was evident with contributing factors including resuspension from waves and currents and possibly direct material contribution from stormwater runoff. Given the residential nature of the studied system, boat activity could also play a significant role in sediment resuspension over various timescales.

Continuous Monitoring (ConMon) pH

pH (standard units) time series plots for each ConMon water quality station are shown in Figures 2.34, 2.35, 2.36 and 2.37 for deployment periods 1 through 4, respectively. Summary statistics for individual stations and deployment period are provided in Table 2.13. As would be expected, there was a general trend of decreasing pH levels with distance upstream. Deployment mean values ranged from 7.8-8.3 for the boundary station located in the Western Branch of the Lynnhaven River, 7.4-8.0 for the downstream Buch1 station, 7.1-7.4 at the Buch 2 station and 6.8-7.1 at the Buch 3 station. Wolfsnare and Thalia Creek station mean deployment pH values ranged from 6.8-7.1 and 7.2-7.5, respectively. The primary explanation for the upstream gradient pattern is that freshwater typically has a lower pH range (on the order of 6-8) than higher salinity coastal waters (range on the order of 8 or greater). Superimposed on diurnal end-member water mixing, driven by tidal action, is pH changes as a result of metabolic activity, where primary production increase pH and respiration decreases pH. With respect to water quality standards, at no time during the four deployment periods did observed pH levels exceed Virginia's high (9.0 su) and low (6.0 su) standards for Chesapeake Bay and its tidal tributaries (VAC 2017).

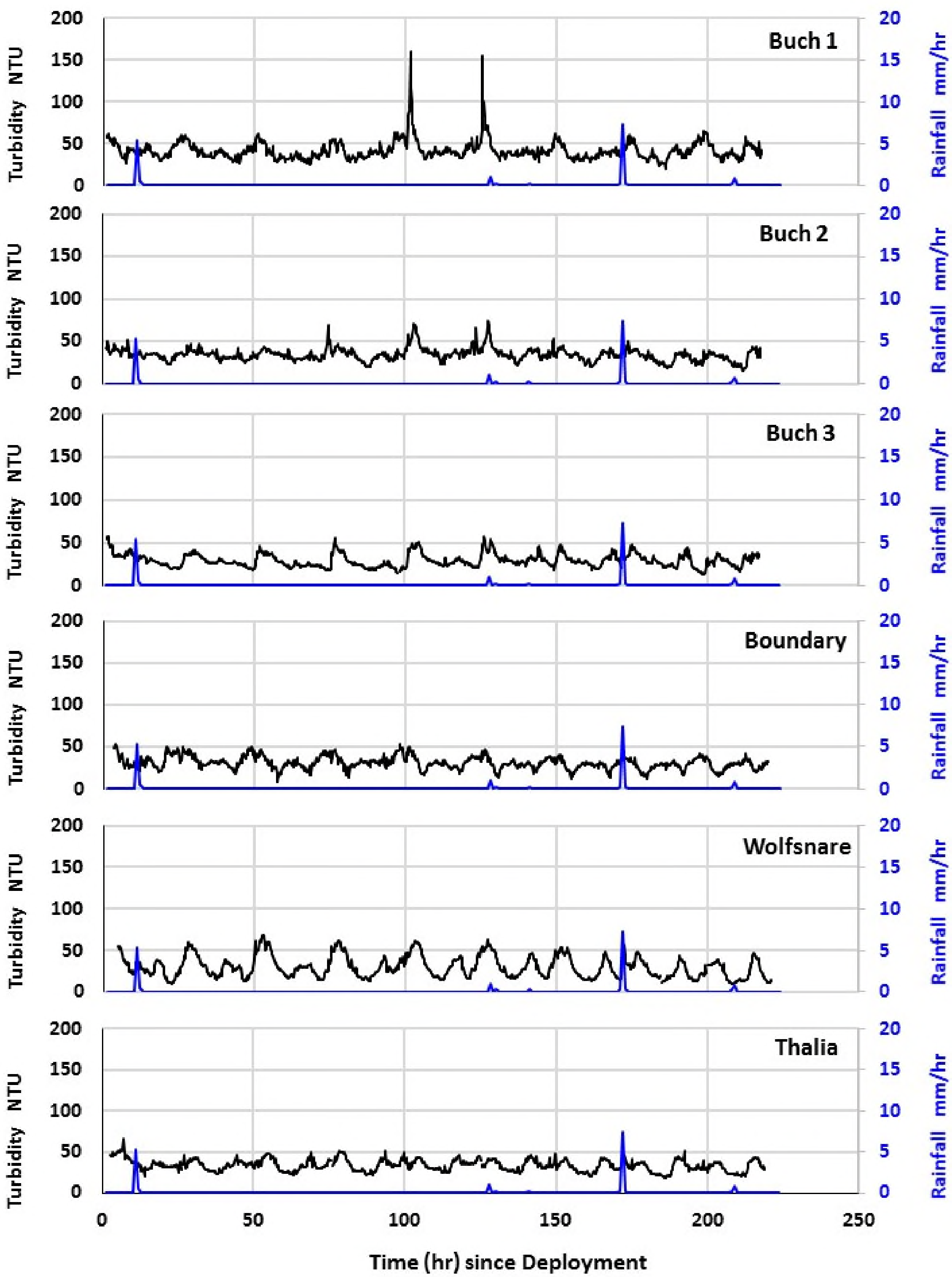


Figure 2.30. Continuous monitoring turbidity level (NTU) and hourly precipitation (mm) time series during first (9/18/2018 - 9/27/2018) deployment period.

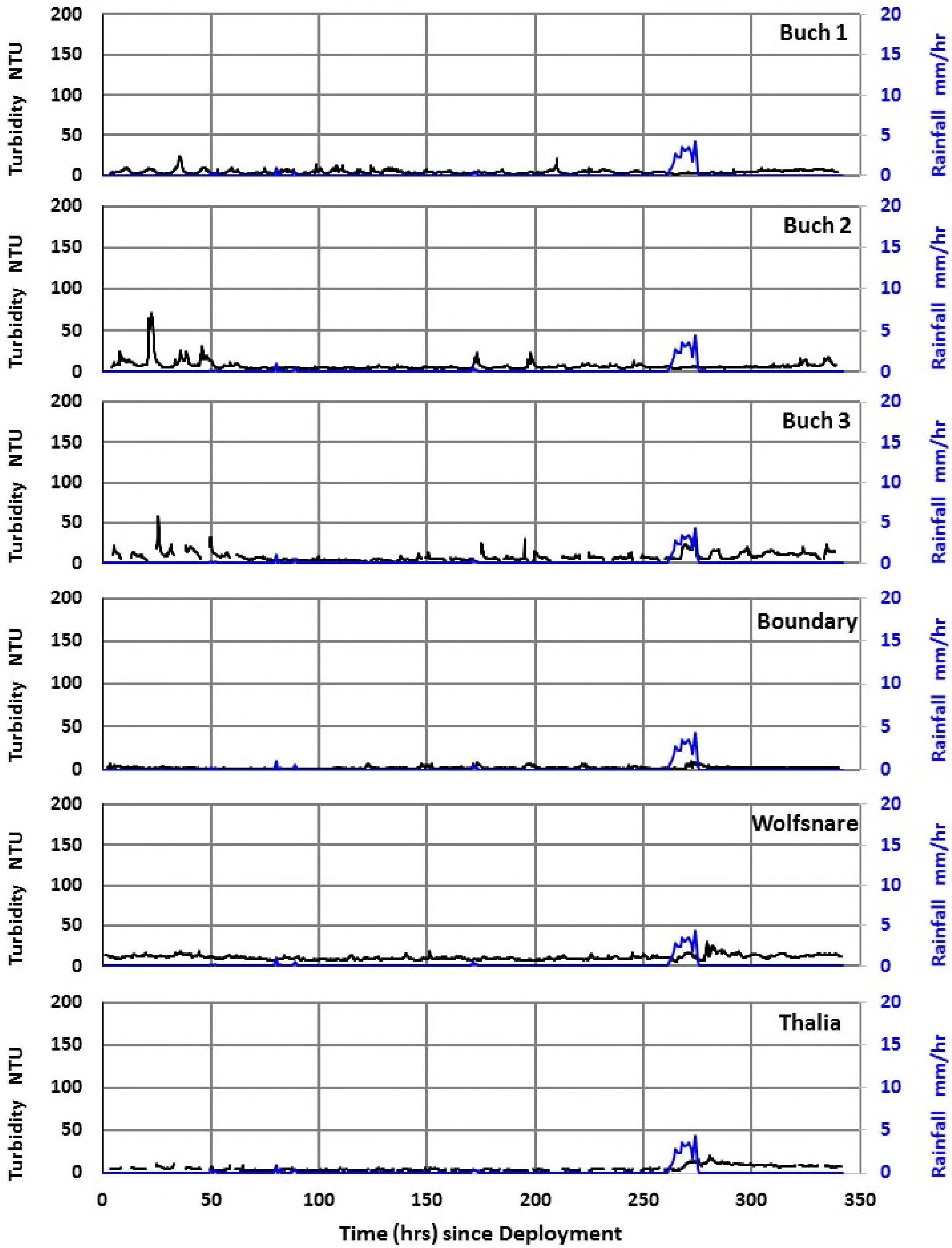


Figure 2.31. Continuous monitoring turbidity level (NTU) and hourly precipitation (mm) time series during second (11/28/2018 - 12/12/2018) deployment period.

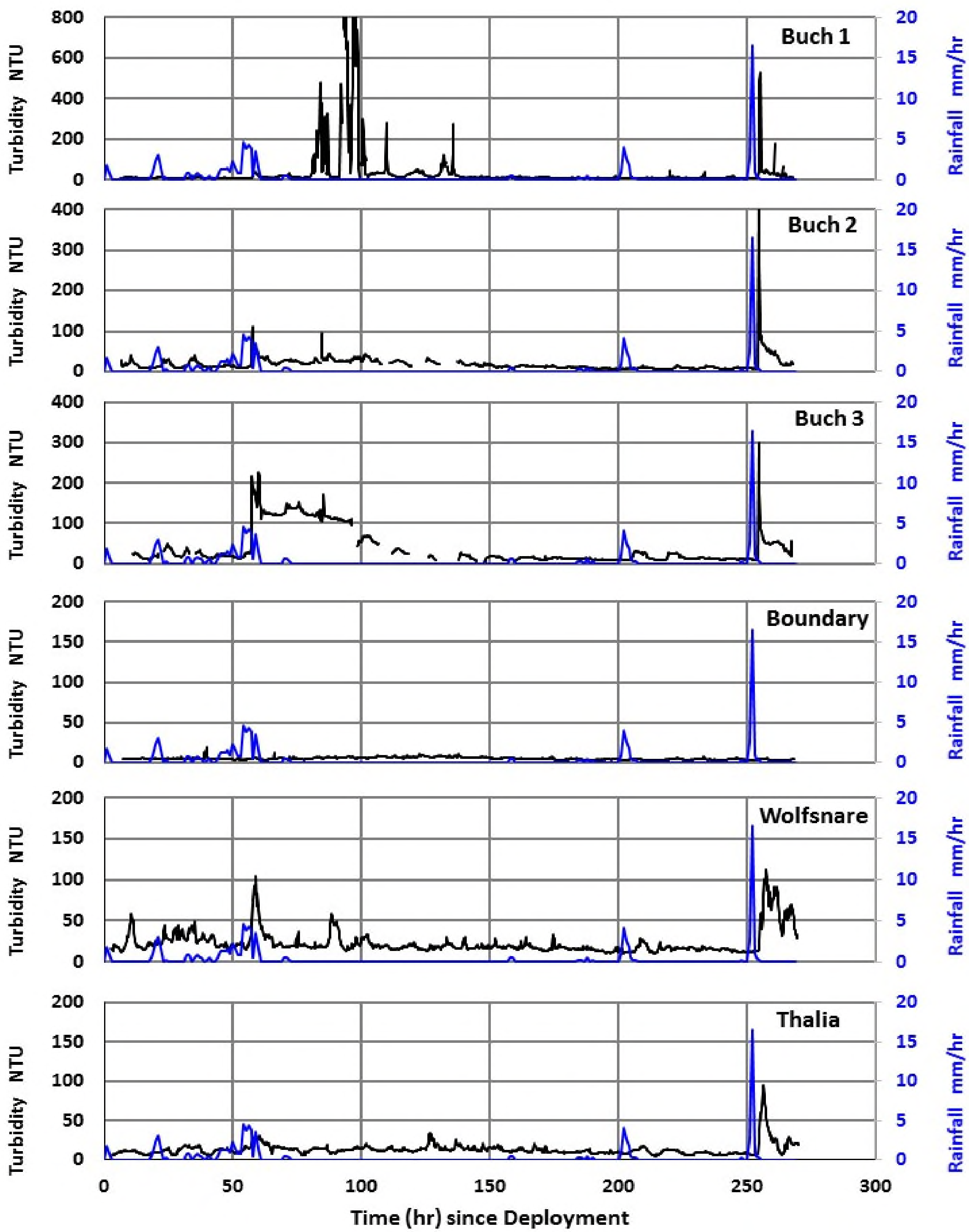


Figure 2.32. Continuous monitoring turbidity level (NTU) and hourly precipitation (mm) time series during third (2/21/2019 - 3/4/2019) deployment period.

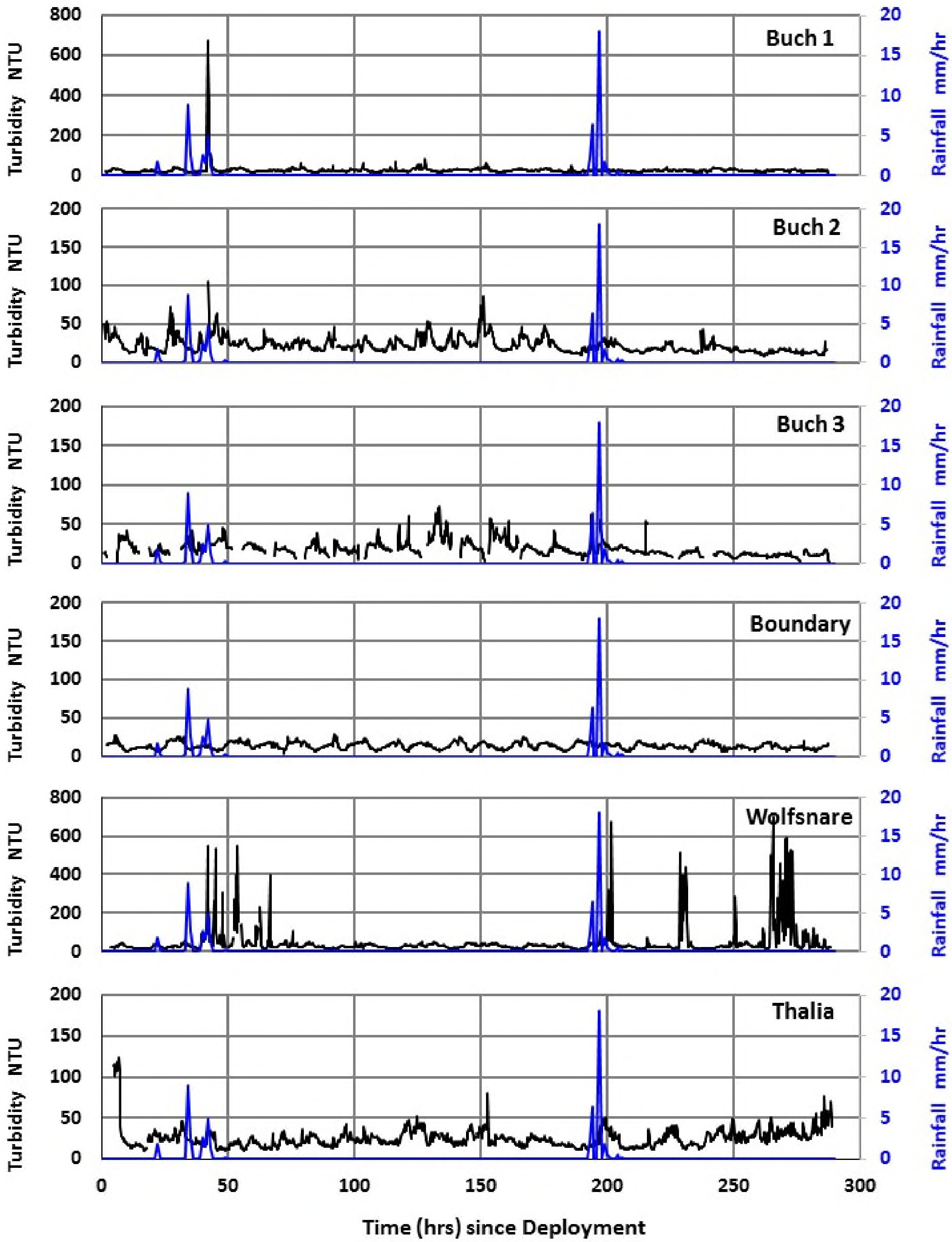


Figure 2.33. Continuous monitoring turbidity level (NTU) and hourly precipitation (mm) time series during fourth (4/18/2019 - 4/30/2019) deployment period.

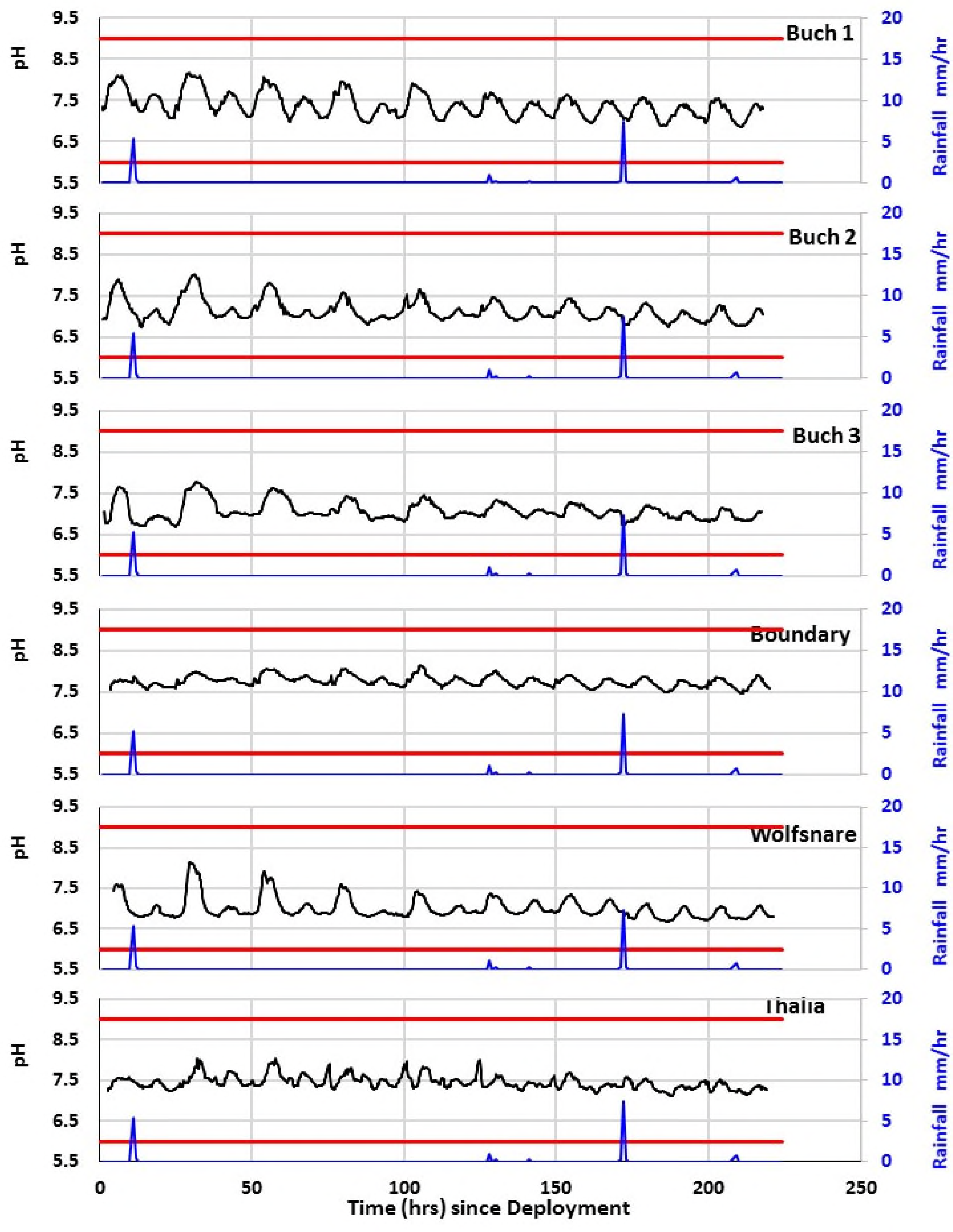


Figure 2.34. Continuous monitoring pH (standard units) and hourly precipitation (mm) time series during first (9/18/2018 - 9/27/2018) deployment period. Note: red dashed lines represent Virginia high (9.0 su) and low (6.0 su) water quality standards for Chesapeake Bay and its tidal tributaries (VAC 2017).

Table 2.12. Summary statistics for turbidity (NTU) by continuous monitoring (ConMon) water quality station and deployment period.

ConMon Station ID	Deployment 1 (9/18/18 - 9/27/18)	Deployment 2 (11/28/18 - 12/12/18)	Deployment 3 (2/21/19 - 3/4/19)	Deployment 4 (4/18/19 - 4/30/19)
Buch 1	Avg: 41.3 Min: 20.4 Max: 160.6 Std Dev: 11.4 N: 866	Avg: 4.7 Min: 1.4 Max: 23.9 Std Dev: 2.4 N: 1345	Avg: 35.7 Min: 4.5 Max: 928.5 Std Dev:106.6 N: 1033	Avg: 26.9 Min: 10.8 Max: 671.3 Std Dev: 28.7 N: 1133
Buch 2	Avg: 34.3 Min: 15.9 Max: 73.4 Std Dev: 7.6 N: 864	Avg: 6.9 Min: 2.8 Max: 71.5 Std Dev: 5.8 N: 1340	Avg: 18.9 Min: 5.4 Max: 456.3 Std Dev: 20.2 N: 985	Avg: 22.7 Min: 9.2 Max: 105.8 Std Dev: 10.00 N: 1139
Buch 3	Avg: 29.2 Min: 12.8 Max: 57.6 Std Dev: 7.7 N: 862	Avg: 8.2 Min: 2.1 Max: 57.9 Std Dev: 5.3 N: 1121	Avg: 39.0 Min: 4.7 Max: 300.7 Std Dev: 44.6 N: 908	Avg: 19.0 Min: 1.5 Max: 72.4 Std Dev: 9.8 N: 952
Boundary	Avg: 30.7 Min: 9.0 Max: 53.5 Std Dev: 7.5 N: 864	Avg: 2.3 Min: 0.7 Max: 10.1 Std Dev: 1.2 N: 1352	Avg: 5.0 Min: 2.6 Max: 18.9 Std Dev: 1.6 N: 1046	Avg: 14.0 Min: 5.7 Max: 29.7 Std Dev: 4.3 N: 1143
Wolfsnare	Avg: 30.1 Min: 9.7 Max: 68.4 Std Dev: 13.0 N: 861	Avg: 10.5 Min: 5.6 Max: 30.0 Std Dev: 2.8 N: 1363	Avg: 22.8 Min: 9.6 Max: 112.1 Std Dev: 14.59 N: 1068	Avg: 46.5 Min: 9.9 Max: 698.4 Std Dev: 79.5 N: 1108
Thalia	Avg: 33.6 Min: 18.6 Max: 65.3 Std Dev: 7.2 N: 863	Avg: 5.5 Min: 2.5 Max: 20.0 Std Dev: 2.9 N: 1119	Avg: 13.3 Min: 5.1 Max: 94.7 Std Dev: 7.6 N: 1067	Avg: 25.0 Min: 10.1 Max: 124.2 Std Dev: 12.42 N: 1127

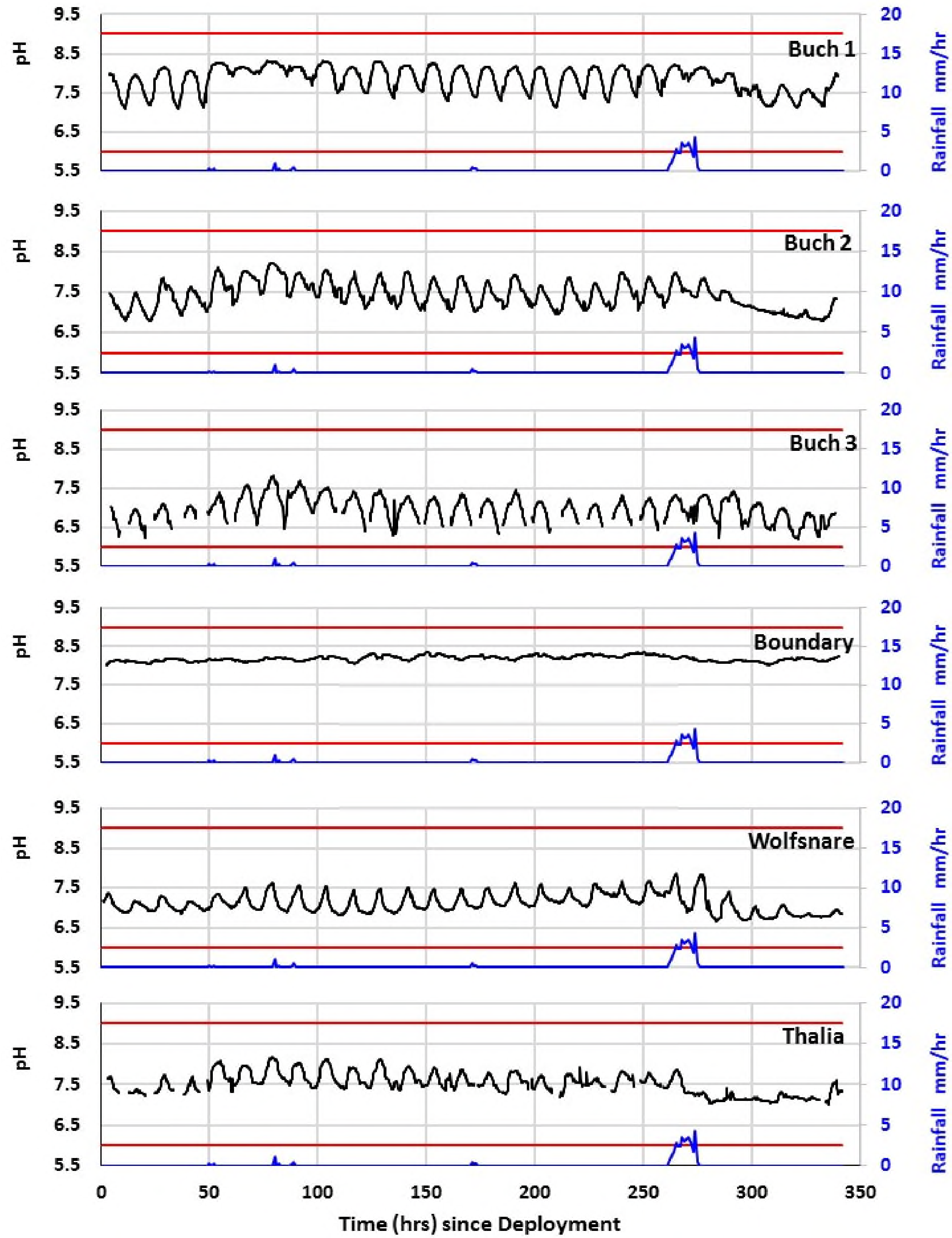


Figure 2.35. Continuous monitoring pH (standard units) and hourly precipitation (mm) time series during second (11/28/2018 - 12/12/2018) deployment period. Note: red dashed lines represent Virginia high (9.0 su) and low (6.0 su) water quality standards for Chesapeake Bay and its tidal tributaries (VAC 2017).

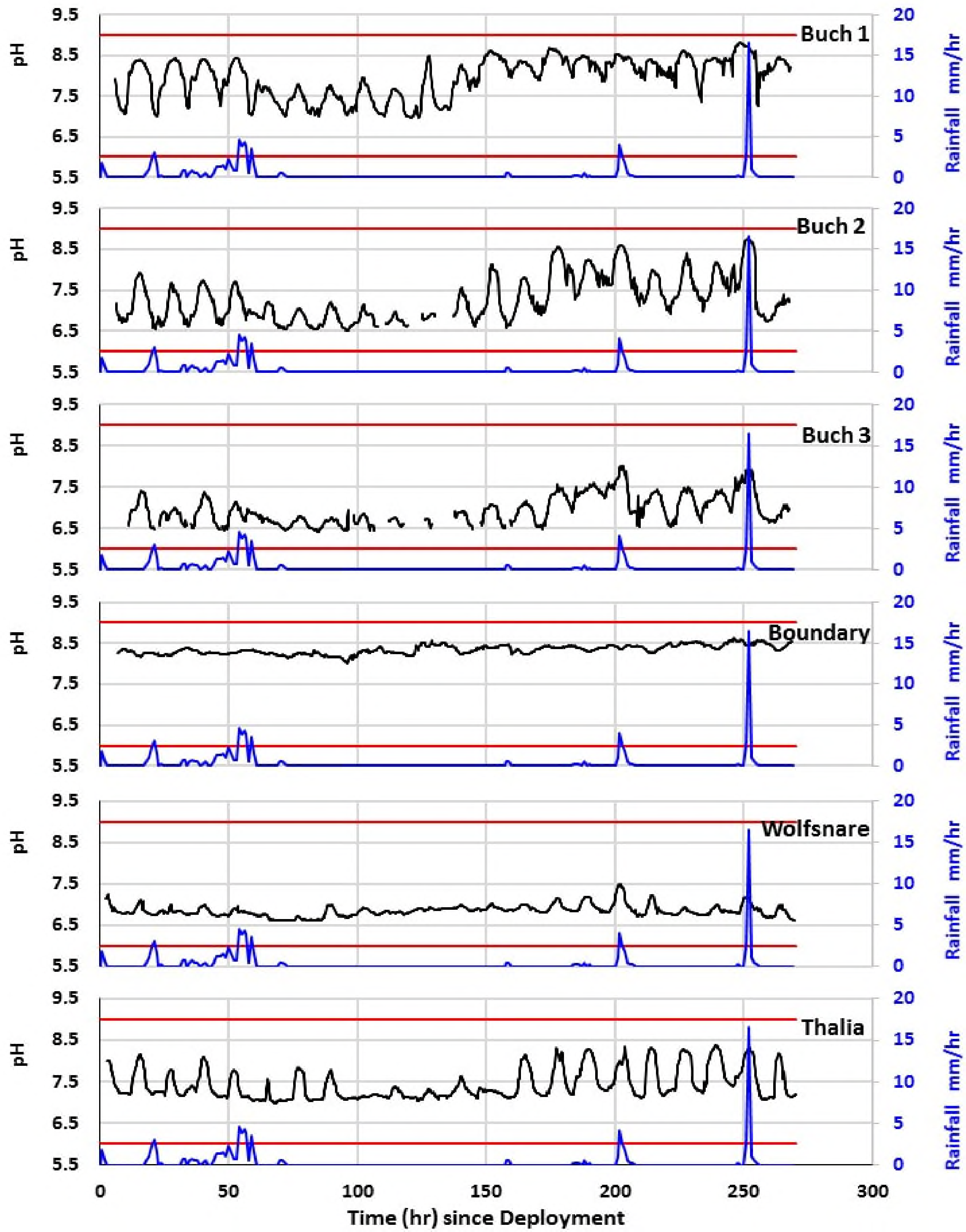


Figure 2.36. Continuous monitoring pH (standard units) and hourly precipitation (mm) time series during third (2/21/2019 - 3/4/2019) deployment period. Note: red dashed lines represent Virginia high (9.0 su) and low (6.0 su) water quality standards for Chesapeake Bay and its tidal tributaries (VAC 2017).

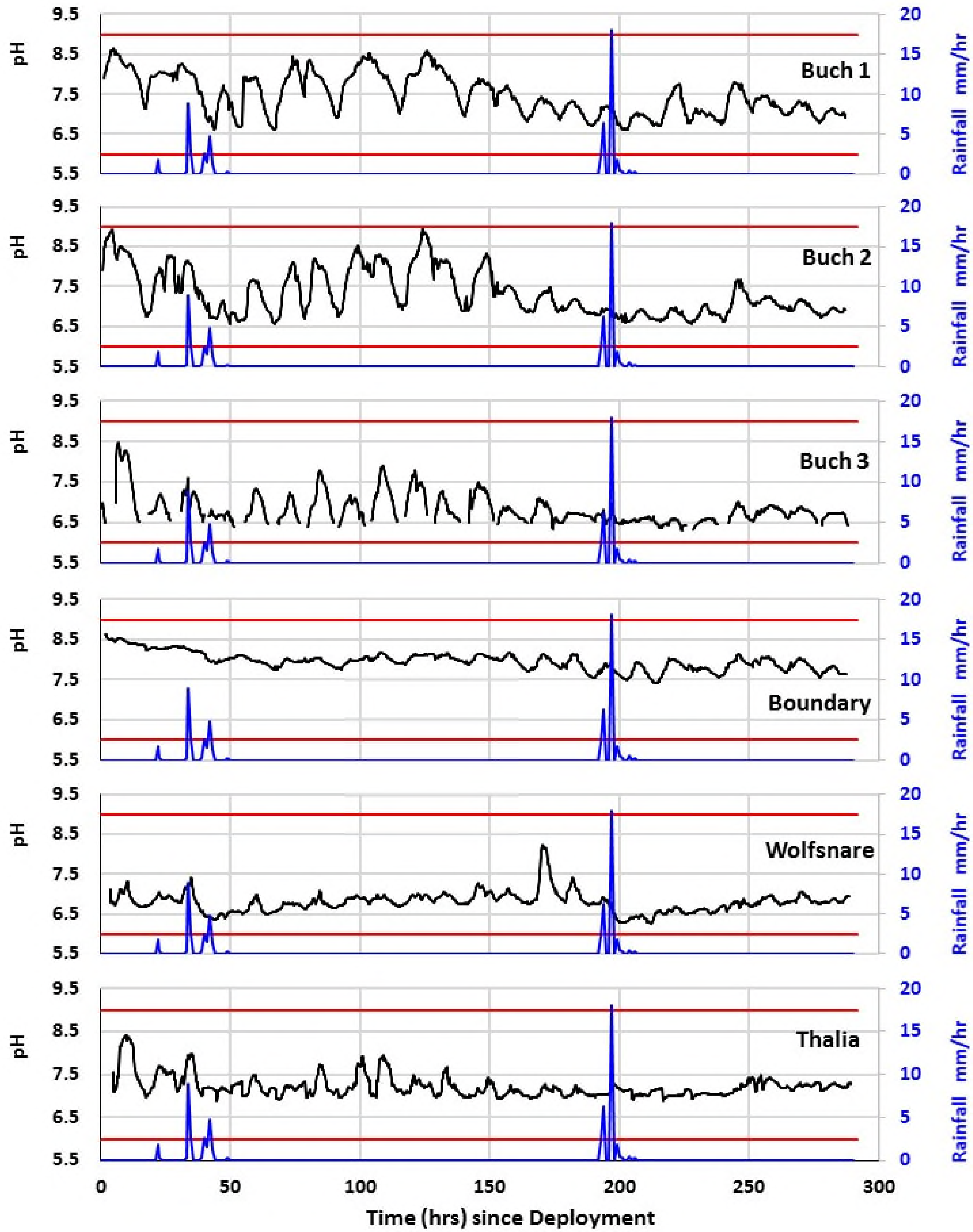


Figure 2.37. Continuous monitoring pH (standard units) and hourly precipitation (mm) time series during fourth (4/18/2019 - 4/30/2019) deployment period. Note: red dashed lines represent Virginia high (9.0 su) and low (6.0 su) water quality standards for Chesapeake Bay and its tidal tributaries (VAC 2017).

Table 2.13. Summary statistics for pH (standard units) by continuous monitoring (ConMon) water quality station and deployment period.

ConMon Station ID	Deployment 1 (9/18/18 - 9/27/18)	Deployment 2 (11/28/18 - 12/12/18)	Deployment 3 (2/21/19 - 3/4/2019)	Deployment 4 (4/18/19 - 4/30/19)
Buch 1	Avg: 7.38 Min: 6.86 Max: 8.16 Std Dev: 0.29 N: 869	Avg: 7.83 Min: 7.08 Max: 8.31 Std Dev: 0.33 N: 1345	Avg: 7.95 Min: 6.98 Max: 8.81 Std Dev: 0.49 N: 1050	Avg: 7.47 Min: 6.6 Max: 8.66 Std Dev: 0.51 N: 1144
Buch 2	Avg: 7.13 Min: 6.75 Max: 8.01 Std Dev: 0.25 N: 867	Avg: 7.41 Min: 6.79 Max: 8.2 Std Dev: 0.33 N: 1341	Avg: 7.28 Min: 6.51 Max: 8.74 Std Dev: 0.55 N: 986	Avg: 7.32 Min: 6.56 Max: 8.97 Std Dev: 0.57 N: 1145
Buch 3	Avg: 7.07 Min: 6.69 Max: 7.77 Std Dev: 0.2 N: 864	Avg: 6.97 Min: 6.20 Max: 7.81 Std Dev: 0.31 N: 1093	Avg: 6.96 Min: 6.41 Max: 8.02 Std Dev: 0.36 N: 913	Avg: 6.84 Min: 6.3 Max: 8.49 Std Dev: 0.36 N: 964
Boundary	Avg: 7.76 Min: 7.47 Max: 8.15 Std Dev: 0.12 N: 867	Avg: 8.18 Min: 8.00 Max: 8.35 Std Dev: 0.07 N: 1352	Avg: 8.34 Min: 8.01 Max: 8.64 Std Dev: 0.11 N: 1047	Avg: 7.96 Min: 7.42 Max: 8.63 Std Dev: 0.22 N: 1143
Wolfsnare	Avg: 7.00 Min: 6.66 Max: 8.12 Std Dev: 0.26 N: 867	Avg: 7.11 Min: 6.65 Max: 7.86 Std Dev: 0.24 N: 1363	Avg: 6.85 Min: 6.61 Max: 7.48 Std Dev: 0.14 N: 1071	Avg: 6.80 Min: 6.26 Max: 8.24 Std Dev: 0.25 N: 1141
Thalia	Avg: 7.45 Min: 7.11 Max: 8.04 Std Dev: 0.17 N: 866	Avg: 7.52 Min: 7.01 Max: 8.19 Std Dev: 0.27 N: 1219	Avg: 7.44 Min: 6.97 Max: 8.38 Std Dev: 0.37 N: 1070	Avg: 7.22 Min: 6.89 Max: 8.41 Std Dev: 0.25 N: 1139

Tidal Water Grab Sample Survey

Nutrient grab sample data and summary statistics for tidal water nutrients are provided in Tables 2.15, 2.17, 2.19, 2.21, 2.23 and 2.25 for stations Buch 1, Buch 2, Buch 3, the Western Branch of the Lynnhaven River boundary, Wolfsnare and Thalia Creeks, respectively. TDN levels depicted a general increasing pattern with distance upstream within Buchanan Creek. Average TDN levels at the Western Branch of the Lynnhaven River station was 0.3169 mg/L-N as N, 0.4338 mg/L as N at Buch 1, 0.5717 mg/L as N at Buch 2 and 0.6929 mg/L as N at the upper Buchanan Creek station (Buch 3). Mean TDN concentrations were 0.7758 and 0.5583 mg/L as N at the reference Wolfsnare and Thalia Creek stations, respectively. Overall, TDN levels within tidal creek stations were approximately two-fold greater than the open water boundary station level. A national estuarine eutrophication assessment criteria (Bricker et al. 1999) was used to classify TDN concentrations; nitrogen criteria range classes were low (≥ 0 to < 0.1 mg/L), medium (≥ 0.1 to < 1.0 mg/L) and high (≥ 1.0 mg/L). TDN concentrations were reflective of the medium range; exception occurred on two occasions at the Buch 3 station when TDN levels were reflective of high levels. While soluble inorganic nitrogen salts (primarily NO_3 and NH_4) are generally recognized as the primary nitrogen source for the growth of phytoplankton and benthic algae, recent evidence shows that labile forms (e.g., urea, amino acids) of dissolved organic nitrogen (DON) can stimulate productivity in estuarine phytoplankton and bacteria. On average, DON comprised the majority of the TDN pool at all stations; individual station DON percent contribution to TDN varied from 57.1 to 87.7%. These results, both in terms of concentration and percent contribution to TDN pools, are similar to reported values within similar Virginia Beach tidal creek systems (Sisson et al. 2009; Sisson et al. 2010).

As with TDN, estuarine eutrophication assessment criteria (Bricker et al. 1999) were used to classify TDP concentrations; classification ranges were low (≥ 0 to < 0.01 mg/L), medium (≥ 0.01 to < 0.1 mg/L) and high (≥ 0.1 mg/L). Similar to TDN, tidal creek total dissolved phosphorus (TDP) levels were elevated, on the order of fourfold, relative to the Western Branch of the Lynnhaven River station. Mean TDP concentration at the Western Branch of the Lynnhaven River station 0.0188 mg/L as P as compared to mean concentration values of 0.0542 mg/L as P at Buch 1, 0.0722 mg/L as P at Buch 2, 0.0616 mg/L as P at the Buch 3 station, 0.0844 mg/L as P at the Wolfsnare Creek station, and 0.0556 mg/L as P at the Thalia Creek station; TDP concentrations were classified as medium at all locations. High TDP concentrations were observed at the three Buchanan Creek and Wolfsnare Creek station on a single occasion. In contrast to TDN, inorganic fractions of phosphorus (DIP) comprised the majority of the TDP pool at most stations, with the more open water Buch 3 and boundary station being the exception. Examination of TDN:TDP ratios can provide some insight as to nutrient limitation of primary productivity in coastal waters. While the literature provides a broad range of guidance, nutrient limitation ratios for this report are based on a review by Guildford and Hecky (2000) indicating that nitrogen limitation of growth can occur at TDN:TDP ratios < 20, and phosphorus limitation occurs at much higher ratios on the order of > 50. It should be noted that there was a high degree of variability in TDN and TDP relationships at each station. With that cautionary note, stations leaning toward N limitation during sampled seasons associated with elevated productivity (fall and spring) include Buch 2, the reference creek stations (Wolfsnare and Thalia) with stations Buch 1 and Buch 3 with slightly elevated ratios. The Western Branch of the Lynnhaven River boundary station exhibited TDN:TDP ratios suggestive of phosphorus limitation.

Plant pigment concentrations, including total Chl a, pheopigments and functional Chl-a over the study period by station are provided in Tables 2.14 (Buch 1), 2.16 (Buch 2), 2.18 (Buch 3), 2.20 (Boundary), 2.22 (Wolfsnare) and 2.24 (Thalia). Total Chl a levels at the Buchanan and reference tidal creek stations varied from low (> 0 to ≤ 5 µg/L) to medium (> 5 to ≤ 20 µg/L) in winter 2018-2019, to hyper-eutrophic (> 60 µg/L) in early fall 2018. Study averaged total Chl a levels at tidal creek associated stations were classified as high (range: 26.0-47.9 µg/L) and showed a minor increasing upstream trend. Total Chl a levels varied from 7.8-33.2 µg/L at the Western Branch of the Lynnhaven River station with an overall moderate (19.9 µg/L) mean value. Percent contribution of pheopigments to total Chl provide a measure of degraded plant components. Pheopigments generally represented 30-40% of total Chl estimates at all stations, with the exception of the Wolfsnare Creek station where pheopigment contributions were elevated.

While turbidity is an optical determination of water clarity, total suspended solids (TSS) provides a direct measurement of solids including inorganic materials (ex. silts and clays), plankton, algae and bacteria cells that can attenuate light. Many pollutants, such as bacteria, nutrients and other contaminants have a high affinity for particulates, therefore, elevated TSS may be indicative of higher concentration of bacteria and nutrients. TSS can be subcategorized as fixed suspended solids (FSS) comprised of inorganic material and volatile suspended solids (VSS) that represent organic solids in the water column. Average TSS concentrations, ranging from 24.2-35.4 mg/L, were relatively similar across the six ConMon stations as was the average percent contribution of FSS (range: 60-69%) and VSS (30-40%). While there is not TSS standard for Virginia's tidal waters, TSS values > 15 mg/L are considered detrimental to select estuarine ecosystems such as underwater grasses, and values > 20 mg/L are considered to have more general negative impacts.

The existence of pathogens is one of the most cited water quality problem associated with nonpoint sources of pollution in Virginia. The Lynnhaven Bay and its tributaries are currently listed as impaired due to fecal coliform bacteria standard violations for shellfish growing waters (City of VA Beach, 2018). Criteria for shellfish waters are < 14 MPN/100 ml and single sample maximum criteria for recreational contact is 104 cfu/100 ml. For reference, Entercocci bacteria concentrations in urban and agricultural runoff is on the order of 10^2-10^3 cfu/100 ml, 10-10^5 cfu/100 ml for stormwater runoff, and 10^5 for raw sewage. Enterococci bacteria densities over the study period by station are provided in Tables 2.14 (Buch 1), 2.16 (Buch 2), 2.18 (Buch 3), 2.20 (Boundary), 2.22 (Wolfsnare) and 2.24 (Thalia). Enterococci bacteria densities varied over 3 orders of magnitude, 20 to 24,196 MPN/100 ml, over the study period. The low value was associated with the Western Branch of the Lynnhaven River boundary station and the peak value was at Buch 2 station where recent (24 hr prior to sampling) rainfall resulted in creek salinity of 0.3 psu. Geometric mean densities of *Enterococcus* sp. showed an increasing trend with distance upstream Buchanan Creek; geometric mean densities were 38 MPN/100 ml at the Western Branch of the Lynnhaven River boundary station, 952 MPN/100 ml at Buch 1, 1,878 MPN/100 ml at Buch 2, and 2,175 MPN/100 ml at the upstream Buch 3 station. Reference creeks, Wolfsnare and Thalia, exhibited 1,664 and 571 MPN/100 ml. Sources of pathogenic bacteria vary depending on the existence of relevant point sources and watershed characteristics. Assuming all residences are on the public sewer system and there exist no damaged pipes or misconnections with stormwater drainage infrastructure, bacteria sources to Buchanan Creek would include point source stormwater drainage that may include seepage, nonpoint source runoff from urbanized and natural lands, and direct domestic and wild animal loadings. The relatively large marsh system in Buchanan Creek, as well riparian and residential lawns utilized by domestic and wildlife, add complexity to the problem. In such developed areas, wildlife populations tend to migrate to the limited forested and marsh edge regions thereby increasing bacterial loadings from such areas (Simmons et al., 1995; Siewicki et al., 2007). In most cases, diffuse nonpoint sources of pathogen microbes are difficult to reduce in developed landscapes. If there is a desire to pursue reductions, a source tracking study would be warranted to help guide development and implementation of remediation strategies.

Table 2.14. Physical, plant pigment, suspended solids and *Enterococcus* results from grab samples collected at the Buch 1 continuous station. Note: WT: water temperature, Sal: salinity, DO_{conc}, % DO_{sat}, Chl: chlorophyll, Pheo: pheophytin, Func. Chl: functional Chl, TSS: total suspended solids, FSS: fixed suspended solids, VSS: volatile suspended solids, and * denotes geometric mean.

Date	WT ºC	Sal ppt	pH SU	DO mg/L	%DO sat	Chl μg/L	Pheo ug/L	Func. Chl ug/L	TSS mg/L	FSS mg/L	VSS mg/L	Enterococcus MPN/100 ml
9/18/2018	27.5	13.7	7.37	7.3	100.0	72.2	19.8	52.3	45.0	32.5	12.5	
9/27/2018	27.0	26.4	7.19	4.0	57.8	26.4	15.3	11.1	52.4	43.3	9.0	
11/28/2018	8.3	12.6	7.80	10.7	98.2	12.6	6.2	6.3	31.5	24.0	7.5	
12/12/2018	6.3	6.5	7.65	11.5	97.2	14.0	2.6	11.4	18	13.8	4.2	
1/23/2019	3.9	4.1	6.49	8.3	65.3							1,565
2/21/2019	8.6	7.5	7.43	10.8	96.8	12.4	3.0	9.4	13.5	6.0	7.5	480
3/4/2019	8.8	2.9	7.22	11.1	96.4	37.1	6.1	31.0	51.8	23.3	28.5	13,524
4/18/2019	22.1	13.8	8.10	11.0	136.0	43.9	6.5	37.5	32.0	15.3	16.7	464
4/30/2019	21.1	9.9	6.88	4.1	48.3	14.1	14.1	0.0	39.3	31.3	8.0	166
Average	16.2	11.7	7.46	8.8	91.3	29.1	9.2	19.9	35.4	23.7	11.7	952*
Std. Dev.	9.1	7.1	0.38	3.2	27.2	21.2	6.3	18.2	14.5	12.0	7.8	
Count	8	8	8	8	8	8	8	8	8	8	8	5

Table 2.15. Nutrient (nitrogen and phosphorus) results from grab samples collected at the Buch 1 continuous monitoring station. Concentrations are expressed as mg/L of nitrogen or phosphorus. Note: Ammonium (NH_4), nitrate+nitrite (NO_{23}), nitrite (NO_2), nitrate (NO_3), dissolved inorganic nitrogen (DIN), dissolved organic nitrogen (DON), total dissolved nitrogen (TDN), phosphate (PO_4), dissolved organic phosphorus (DOP), and total dissolved phosphorus (TDP).

Date	NH_4	NO_{23}	NO_2	NO_3	DIN	DON	TDN	PO_4	DOP	TDP
09/18/2018	0.0561	0.0226	0.0036	0.0190	0.0787	0.4303	0.5090	0.0548	0.0411	0.0959
09/27/2018	0.0192	0.0027	0.0027	0.0000	0.0219	0.3822	0.4040	0.0155	0.0260	0.0415
11/28/2018	0.0777	0.1576	0.0042	0.1533	0.2353	0.2465	0.4818	0.0357	0.0125	0.0482
12/12/2018	0.0031	0.0907	0.0023	0.0884	0.0938	0.2842	0.3779	0.0294	0.0149	0.0443
02/21/2019	0.0020	0.0270	0.0018	0.0252	0.0290	0.0104	0.0394	0.0030	0.0104	0.0134
03/04/2019	0.0778	0.2218	0.0064	0.2154	0.2995	0.4373	0.7368	0.0748	0.0283	0.1031
04/18/2019	0.0031	0.0027	0.0008	0.0019	0.0058	0.3595	0.3653	0.0008	0.0164	0.0172
04/30/2019	0.0173	0.0237	0.0008	0.0229	0.0410	0.5155	0.5565	0.0259	0.0442	0.0701
Average	0.0320	0.0686	0.0028	0.0658	0.1006	0.3332	0.4338	0.0300	0.0242	0.0542
Std. Dev.	0.0332	0.0814	0.0019	0.0799	0.1083	0.1562	0.1997	0.0253	0.0130	0.0332
Count	8	8	8	8	8	8	8	8	8	8

Table 2.16. Physical, plant pigment, suspended solids and *Enterococcus* results from grab samples collected at the Buch 2 continuous monitoring station. Note: Abbreviations as in Table 2.14.

Date	WT ºC	Sal ppt	pH SU	DO mg/L	%DO sat	Chl µg/L	Pheo ug/L	Func. Chl ug/L	TSS mg/L	FSS mg/L	VSS mg/L	Enterococcus MPN/100 ml
09/18/2018	28.4	12.6	6.91	4.9	68.0	70.2	26.5	43.7	95.0	78.5	16.5	
09/27/2018	26.7	20.0	6.94	2.5	35.6	29.6	16.3	13.3	32.0	24.0	8.0	
11/28/2018	7.4	10.4	7.35	9.7	86.5	10.6	2.8	7.8	10.0	5.5	4.5	
12/12/2018	5.9	5.8	7.15	9.9	82.8	9.8	2.9	6.9	16.2	10.8	5.3	
01/23/2019	5.4	4.7	6.77	10.3	84.1							1,391
02/21/2019	10.6	1.8	7.14	9.6	86.7	12.6	5.5	7.1	20.0	9.3	10.7	4,352
03/04/2019	8.3	0.3	7.23	10.5	90.2	9.1	4.7	4.4	45.0	34.0	11.0	24,196
04/18/2019	23.8	10.6	7.30	8.5	111.8	59.4	8.5	50.9	28.7	11.4	17.4	362
04/30/2019	21.0	8.7	6.77	4.1	48.7	42.3	15.6	26.7				441

Table 2.17. Nutrient (nitrogen and phosphorus) results from grab samples collected at the Buch 2 continuous monitoring station. Concentrations are expressed as mg/L of nitrogen or phosphorus. Note: Abbreviations as in Table 2.15.

Date	NH_4	NO_{23}	NO_2	NO_3	DIN	DON	TDN	PO_4	DOP	TDP
09/18/2018	0.0786	.0295	0.0044	0.0252	0.1081	0.4554	0.5634	0.0546	0.0350	0.0896
09/27/2018	0.0355	.0027	0.0027	0.0000	0.0382	0.4525	0.4907	0.0336	0.0310	0.0646
11/28/2018	0.0031	.0618	0.0037	0.0581	0.0649	0.2618	0.3267	0.0193	0.0128	0.0322
12/12/2018	0.0031	0.1866	0.0033	0.1833	0.1897	0.3264	0.5161	0.0723	0.0214	0.0937
01/23/2019	0.2302	0.2549	0.0046	0.2503	0.4851	0.3318	0.8169	0.0392	0.0231	0.0623
02/21/2019	0.1056	0.2710	0.0065	0.2645	0.3766	0.3881	0.7647	0.0490	0.0120	0.0610
03/04/2019	0.1615	0.1615	0.0041	0.1574	0.3230	0.3812	0.7042	0.0942	0.0246	0.1188
04/18/2019	0.0031	0.0049	0.0008	0.0041	0.0080	0.4207	0.4286	0.0132	0.0301	0.0433
04/30/2019	0.0160	0.0328	0.0046	0.0282	0.0488	0.4852	0.5340	0.0444	0.0397	0.0841
Average	0.0707	0.1117	0.0039	0.1079	0.1825	0.3892	0.5717	0.0466	0.0255	0.0722
Std. Dev.	0.0813	0.1077	0.0016	0.1067	0.1723	0.0726	0.1607	0.0252	0.0094	0.0269
Count	9	9	9	9	9	9	9	9	9	9

Table 2.18. Physical, plant pigment, suspended solids and *Enterococcus* results from grab samples collected at the Buch 3 continuous monitoring station. Note: Abbreviations as in Table 2.14.

Date	WT °C	Sal ppt	pH SU	DO mg/L	DO %sat	Chl µg/L	Pheo ug/L	Func. Chl ug/L	TSS mg/L	FSS mg/L	VSS mg/L	Enterococcus MPN/100 ml
09/18/2018	27.8	12.6	7.04	5.5	75.4	83.8	21.8	62.0	61.0	47.5	13.5	
09/27/2018	26.8	14.9	7.01	2.9	39.4	31.9	15.9	16.0	45.0	35.5	9.5	
11/28/2018	7.8	7.3	7.10	8.1	72.0	11.0	2.5	8.5	7.2	3.9	3.3	
12/12/2018	6.1	4.3	7.13	8.0	66.9	4.1	3.5	0.7	16.5	11.0	5.5	
01/23/2019	3.9	4.1	6.49	8.3	65.3							1,565
02/21/2019	10.5	0.6	7.23	9.7	87.7	11.3	5.1	6.2	26.9	15.6	11.4	4,345
03/04/2019	8.8	0.1	7.46	10.4	89.2							19,863
04/18/2019	20.2	7.8	6.89	5.0	57.6	70.1	5.5	64.6	31.3	12.7	18.7	496
04/30/2019	25.6	4.1	6.43	2.7	34.6	23.5	8.0	15.5	9.3	5.3	4.0	726

Table 2.19. Nutrient (nitrogen and phosphorus) results from grab samples collected at the Buch 3 continuous monitoring station. Concentrations are expressed as mg/L of nitrogen or phosphorus. Note: Abbreviations as in Table 2.15.

Date	NH_4	NO_{23}	NO_2	NO_3	DIN	DON	TDN	PO_4	DOP	TDP
09/18/2018	0.0031	0.0027	0.0008	0.0019	0.0058	0.4099	0.4157	0.0265	0.0332	0.0596
09/27/2018	0.0632	0.0071	0.0032	0.0039	0.0703	0.4586	0.5289	0.0365	0.0333	0.0698
11/28/2018	0.0031	0.0454	0.0044	0.0410	0.0485	0.2367	0.2853	0.0069	0.0106	0.0175
12/12/2018	0.0357	0.2609	0.0034	0.2575	0.2966	0.3939	0.6905	0.1073	0.0290	0.1362
01/23/2019	0.3286	0.5895	0.0079	0.5817	0.9182	0.3318	1.2500	0.0314	0.0141	0.0455
02/21/2019	0.1201	0.2356	0.0067	0.2291	0.3558	0.2979	0.6537	0.0484	0.0152	0.0636
03/04/2019										
04/18/2019	0.721	0.1058	0.0112	0.0946	0.1779	0.4181	0.5960	0.0171	0.0263	0.0434
04/30/2019	0.2708	0.4818	0.0121	0.4697	0.7526	0.3702	1.1228	0.0325	0.0573	0.0573
Average	0.1932	0.2161	0.0062	0.2099	0.3282	0.3646	0.6929	0.0383	0.0274	0.0616
Std. Dev.	0.2456	0.2213	0.0040	0.2191	0.3383	0.0722	0.3329	0.0305	0.0150	0.0342
Count	8	8	8	8	8	8	8	8	8	8

Table 2.20. Physical, plant pigment, suspended solids and *Enterococcus* results from grab samples collected at the Boundary continuous monitoring station. Note: Abbreviations as in Table 2.14.

Date	WT ºC	Sal ppt	pH SU	DO mg/L	DO %sat	Chl µg/L	Pheo ug/L	Func. Chl ug/L	TSS mg/L	FSS mg/L	VSS mg/L	Enterococcus MPN/100 ml
09/18/2018	26.9	17.4	7.55	5.7	78.4	26.0	10.4	15.6	62.0	54.0	8.0	
09/27/2018	26.7	17.6	7.52	5.3	72.4	18.1	10.1	8.1	55.5	48.0	7.5	
11/28/2018	8.7	16.2	7.79	10.5	99.7	7.8	2.6	5.2	6.5	2.5	4.1	
12/12/2018	6.6	12.1	8.05	12.1	107.1	13.4	1.9	11.5	12.5	9.3	3.3	
02/21/2019	8.1	12.3	8.32	11.3	103.3	29.0	1.9	27.2	8.6	2.9	5.7	63
03/04/2019	8.2	10.9	8.31	12.3	111.5	33.2	4.9	28.3	33.0	23.0	10.0	52
04/18/2019	19.5	17.4	8.12	9.8	118.1	16.8	6.3	10.6	30.3	22.4	8.0	20
04/30/2019	19.6	14.7	7.57	7.4	88.2	15.2	5.5	9.7	33.9	22.3	11.5	31

Table 2.21. Nutrient (nitrogen and phosphorus) results from grab samples collected at the Boundary continuous monitoring station. Concentrations are expressed as mg/L of nitrogen or phosphorus. Note: Abbreviations as in Table 2.15

Date	NH_4	NO_{23}	NO_2	NO_3	DIN	DON	TDN	PO_4	DOP	TDP
09/18/2018	0.0320	0.0567	0.0352	0.0215	0.0887	0.3155	0.4042	0.0175	0.0201	0.0376
09/27/2018	0.0504	0.0027	0.0072	BDL	0.0531	0.3689	0.4220	0.0159	0.0194	0.0352
11/28/2018	0.0031	0.0761	0.0058	0.0703	0.0792	0.2509	0.3301	0.0046	0.0070	0.0116
12/12/2018	0.0031	0.0313	0.0008	0.0305	0.0344	0.2299	0.2643	0.0015	0.0033	0.0047
02/21/2019	0.0044	0.0065	0.0008	0.0057	0.0109	0.2348	0.2457	0.0036	0.0069	0.0105
03/04/2019	0.0031	0.0415	0.0008	0.0407	0.0446	0.2799	0.3245	0.0017	0.0106	0.0123
04/18/2019	0.0031	0.0027	0.0008	0.0019	0.0058	0.2396	0.2454	0.0008	0.0039	0.0047
04/30/2019	0.0167	0.0027	0.0008	0.0019	0.0194	0.2793	0.2987	0.0008	0.0154	0.0162
Average	0.0145	0.0275	0.0065	0.0246	0.0420	0.2749	0.3169	0.0058	0.0108	0.0166
Std. Dev.	0.0178	0.0286	0.0119	0.0251	0.0306	0.0478	0.0678	0.0069	0.0067	0.0182
Count	8	8	8	7	8	8	8	8	8	8

Table 2.22. Physical, plant pigment, suspended solids and *Enterococcus* results from grab samples collected at the Wolfsnare Creek continuous monitoring station. Note: Abbreviations as in Table 2.14.

Date	WT ºC	Sal ppt	pH SU	DO mg/L	DO %sat	Chl μg/L	Pheo ug/L	Func. Chl ug/L	TSS mg/L	FSS mg/L	VSS mg/L	Enterococcus MPN/100 ml
09/18/2018	29.7	9.3	7.43	7.7	106.5	110.2	20.3	89.9	57.0	42.5	14.5	
09/27/2018	25.0	5.4	7.18	2.0	24.9	9.9	6.2	3.7	17.5	11.0	6.5	
11/28/2018	6.4	3.8	6.12	9.8	81.8	4.8	3.7	1.1	14.3	9.2	5.1	
12/12/2018	5.9	0.6	7.24	8.8	68.2	2.0	1.8	0.2	9.0	4.7	4.4	
02/21/2019	8.2	3.1	7.17	9.2	79.8	10.9	6.5	4.5	20.0	13.3	6.7	2,603
03/04/2019	9.0	0.1	7.77	9.9	86.5							19,863
04/18/2019	23.1	0.3	6.92	7.0	81.7	17.3	13.6	3.7	28.0	22.7	5.3	266
04/30/2019	19.7	0.3	6.94	7.3	79.8	27.0	10.3	16.7	23.3	20.0	3.3	557

Table 2.23. Nutrient (nitrogen and phosphorus) results from grab samples collected at the Wolfsnare Creek continuous monitoring station. Concentrations are expressed as mg/L of nitrogen or phosphorus. Note: Abbreviations as in Table 2.15.

Date	NH_4	NO_{23}	NO_2	NO_3	DIN	DON	TDN	PO_4	DOP	TDP
09/18/2018	0.1504	0.0553	0.0134	0.0419	0.2057	0.5003	0.7060	0.0467	0.0452	0.0919
09/27/2018	0.1582	0.0855	0.0103	0.0752	0.2437	0.5210	0.7647	0.0947	0.0490	0.1437
11/28/2018	0.0344	0.1555	0.0055	0.1500	0.1899	0.3645	0.5544	0.0430	0.0141	0.0571
12/12/2018	0.0791	0.3804	0.0061	0.3743	0.4595	0.3723	0.8318	0.0520	0.0274	0.0793
02/21/2019	0.0801	0.1711	0.0056	0.1655	0.2512	0.4060	0.6572	0.0243	0.0140	0.0383
03/04/2019										
04/18/2019	0.1714	0.3490	0.0185	0.3305	0.5204	0.4794	0.9998	0.0644	0.0320	0.0964
04/30/2019	0.1174	0.4285	0.0258	0.4027	0.5459	0.3705	0.9164	0.0610	0.0229	0.0839
Average	0.1130	0.2322	0.01217	0.2200	0.3452	0.4306	0.7758	0.0552	0.0292	0.0844
Std. Dev.	0.0505	0.1509	0.0077	0.1417	0.1564	0.0676	0.1534	0.0219	0.0139	0.0332
Count	7	7	7	7	7	7	7	7	7	7

Table 2.24. Physical, plant pigment, suspended solids and *Enterococcus* results from grab samples collected at the Thalia Creek continuous monitoring station. Note: Abbreviations as in Table 2.14.

Date	WT ºC	Sal ppt	pH SU	DO mg/L	DO %sat	Chl µg/L	Pheo ug/L	Func. Chl ug/L	TSS mg/L	FSS mg/L	VSS mg/L	Enterococcus MPN/100 ml
09/18/2018	26.9	14.8	7.25	2.3	31.0	69.8	23.5	46.3	53.5	40.5	13.0	
09/27/2018	27.0	27.8	7.13	3.3	48.1	43.0	24.3	18.6	43.0	32.5	10.5	
11/28/2018	8.9	7.7	7.61	9.7	88.4	17.4	3.0	14.5	7.5	2.5	5.0	
12/12/2018	7.1	5.5	7.56	9.9	85.0	22.4	3.7	18.7	14.0	8.5	5.5	
02/21/2019	8.2	5.2	7.81	10.8	94.4	34.5	8.0	26.5	13.3	4.0	9.3	683
03/04/2019	9.4	0.7	7.66	10.9	96.3	25.0	8.8	16.2	20.7	16.0	4.7	4,226
04/18/2019	23.7	5.2	7.79	10.0	122.4	89.2	13.4	75.8	42.7	23.0	19.7	215
04/30/2019	22.0	4.0	7.23	6.9	81.6	81.9	11.1	70.8	20.7	14.7	6.0	171

Table 2.25. Nutrient (nitrogen and phosphorus species) results from grab samples collected at the Thalia Creek continuous monitoring station. Concentrations are expressed as mg/L of nitrogen or phosphorus. Note: Abbreviations as in Table 2.15.

Date	NH_4	NO_{23}	NO_2	NO_3	DIN	DON	TDN	PO_4	DOP	TDP
09/18/2018	0.0766	0.0092	0.0104	BDL	0.0858	0.4075	0.4932	0.0457	0.0319	0.0775
09/27/2018	0.0333	0.0027	0.0021	0.0006	0.0360	0.4755	0.5115	0.0274	0.0356	0.0630
11/28/2018	0.0527	0.0944	0.0106	0.0838	0.1471	0.3549	0.5020	0.0290	0.0140	0.0430
12/12/2018	0.0774	0.2855	0.0060	0.2795	0.3629	0.4151	0.7780	0.0544	0.0236	0.0780
02/21/2019	0.0257	0.0931	0.0031	0.0900	0.1188	0.3426	0.4614	0.0065	0.0125	0.0190
03/04/2019	0.0318	0.2582	0.0051	0.2531	0.2900	0.449	0.7390	0.0440	0.0239	0.0679
04/18/2019	0.0031	0.0051	0.0030	0.0022	0.0082	0.4693	0.4775	0.0241	0.0275	0.0515
04/30/2019	0.0031	0.0304	0.0049	0.0255	0.0335	0.4703	0.5038	0.0201	0.0250	0.0451
Average	0.0380	0.0973	0.0057	0.1050	0.1353	0.4230	0.5583	0.0314	0.0243	0.0556
Std. Dev.	0.0290	0.1140	0.0033	0.1161	0.1282	0.0524	0.1250	0.0157	0.0079	0.0200
Count	8	8	8	7	8	8	8	8	8	8

Birchwood Malibu Park Survey

As opportunities presented themselves, efforts were made to survey water runoff from Birchwood Malibu Park. This effort focused on three discharge outlet structures and included a lake sample site; see Figure 2.5 for station locations. DO-1 was a large diameter pipe that was semi-exposed at low tide and submerged at high tide (see Figure 2.38). DO-1 appeared to be under maintenance at the time of the study and discharge was not noticeable except on one occasion where a slight surface density gradient could be observed. The degree of connectivity between the DO-1 outlet in Buchanan Creek and an up-gradient stormwater retention basin is uncertain (see Figure 2.39) and will be discussed below. DO-2 is a small concrete pipe located midway up the hillslope to the maintained lawn at the park. Discharge was never observed from this outlet and samples were collected in a small pool in front of the outlet. DO-3, a small diameter pipe located near the downstream edge of the park and lake, exhibited low and intermittent flow over the study period. While sampling was limited, it does provide basic information to characterize pollutant discharge from the park into headwaters of Buchanan Creek. Bacteria (*Enterococcus* sp.) and supplemental information for DO-2 is presented in Table 2.26 with nutrient information presented in Table 2.27, Tables 2.28 and 2.29 for DO-3, and Tables 2.30 and 2.31 for the lake sampling station.

Relative to the adjacent Buchanan Creek station (Buch 3; 2,175 MPN/100 ml), geometric mean densities of E*nterococcus* associated with discharge from DO-2 (262 MPN/100 ml) and DO-3 (213 MPN/100 ml) were significantly reduced. In comparison, averaged TDN and TDP levels associated with DO-2 and DO-3 effluent was 2 and 5 times greater than observed in Buchanan Creek. Origin of the discharge is suspected to be upland groundwater seepage into the DO-2 pipe network and a mix of upland seepage and lake overflow/drainage into the DO-3 pipe network. Of note was the high (330.9 μg/L) Chl-a level in DO-3 effluent on April 18, 2019 when the lake was experiencing bloom conditions. Initial assessment would indicate that identified drainage (DO-2 and DO-3) at Birchwood Malibu Park would have limited impact on Buchanan Creek given its low and intermittent discharge coupled to moderate effluent concentrations of nutrient and Enterococci bacteria. Additional effort may be warranted to assess pollutant concentrations and flow rates under storm event conditions. Of note, on the initial survey date of January 23, 2019, maintenance activities were occurring on the street stormwater drainage system near the park's entrance. Water was being pumped from the drainage system and being discharge in the Park's parking lot drain which subsequently discharged through an unmarked discharge pipe creek-ward of the assumed upland retention basin for DO-1 (see Figure 2.41). Discharge and creek samples were collected and analyzed for Enterococci bacteria densities and nutrients. The discharge water was characterized by elevated enterococci (GM: 3,039 MPN/100 ml) and TDN (1.4 mg/L as N) levels; TDP levels were in comparison low (0.03 mg/L as P). Bacterial survey results for this event are provided in Figure 2.42. Impacts from maintenance activities may warrant additional observations and, at minimum, be planned to minimize impact to Buchanan Creek.

Figure 2.38. Image of DO-1.

Figure 2.39. Image of stormwater retention basin upland from DO-1. Connectivity with the DO-1 outlet in Buchanan Creek is uncertain.

Figure 2.40. Image of DO-3. Flow rate is estimated at 200 ml/sec.

Figure 2.41. Image of unmarked discharge pipe during January 23, 2019 sampling survey.

Figure 2.42. Enterococci bacteria levels (MPN/100 ml) for the January 23, 2019 survey sampling. Arrows denote known path of discharged stormwater system water

Table 2.26. Physical, plant pigment, suspended solids and Enterococci bacteria results from grab samples collected at Birchwood-Malibu Park Outfall #2 (36.85144°, -76.09943°). Note: Abbreviations as in Table 2.16. * denotes geometric mean.

Date	WT ºC	Sal ppt	pH SU	DO mg/L	DO %sat	Chl µg/L	Pheo ug/L	Func. Chl ug/L	TSS mg/L	FSS mg/L	VSS mg/L	Enterococcus MPN/100 ml
1/23/2019	8.4	0.23	6.53	3.53	31.0							120
2/21/2019	8.3	0.06	7.25	9.0	79.1							571
Average	8.35	0.15	6.89	6.3	55.1							262*
Std. Dev.	0.0707	0.12	0.51	3.9								
Count	2	2	2	2	2							2

Table 2.27. Nutrient (nitrogen and phosphorus) results from grab samples collected at Birchwood-Malibu Park Outfall #2 (36.85144°, -76.09943). Concentrations are expressed as mg/L of N or P. Note: Abbreviations as in Table 2.15.

Date	NH_4	NO_{23}	NO_2	NO_3	DIN	DON	TDN	PO_4	DOP	TDP
1/23/2019	0.0396	0.0027*	0.0008*	0.0035	0.0423	0.9783	1.0206	0.1962	0.1236	0.3198
Average	0.0396	0.0027	0.0008	0.0035	0.0423	0.9783	1.0206	0.1962	0.1236	0.3198
Std. Dev.										
Count	1	1	1	1	1	1	1	1	1	1

Table 2.28. Physical, plant pigment, suspended solids and Enterococci bacteria results from grab samples collected at Birchwood-Malibu Park Outfall #3 (36.85225°, -76.10027). Note: Abbreviations as in Table 2.16. * denotes geometric mean. Flow estimated at 200 ml/sec on 1/23/2019.

Date	WT ºC	Sal ppt	pH SU	DO mg/L	DO %sat	Chl µg/L	Pheo ug/L	Func. Chl ug/L	TSS mg/L	FSS mg/L	VSS mg/L	Enterococcus MPN/100 ml
01/23/2019	8.0	0.06	7.67	11.0	93.0							31
02/21/2019	9.3	0.03	7.01	9.9	85.9							63
04/18/2019	23.1	0.1	6.87	5.7	67.3	330.9	39.0	291.9	52.4	10.8	37.0	1,503
04/30/2019	25.1	0.07	7.07	4.6	56.9	87.0	35.2	51.8	20.0	5.6	14.4	700
Average	16.4	0.07	7.16	7.8	75.8	209.0	37.1	171.9	36.2	8.2	25.7	213*
Std. Dev.	9.0	0.03	0.35	3.1	16.6	172.5	2.7	169.8	22.9	3.7	16.0	
Count	4	4	4	4	4	2	2	2	2	2	2	4

Table 2.29. Nutrient (nitrogen and phosphorus) results from grab samples collected at Birchwood-Malibu Park Outfall #3 (36.85225°, -76.10027). Concentrations are expressed as mg/L of N or P. Note: Abbreviations as in Table 2.15. Flow estimated at 200 ml/sec on 1/23/2019.

Date	NH_4	NO_{23}	NO_2	NO_3	DIN	DON	TDN	PO_4	DOP	TDP
1/23/2019	0.0031*	0.0027*	0.0008*	0.0019	0.0058	0.7511	0.7569	0.0600	0.0426	0.1026
4/18/2019	0.3128	0.2436	0.0333	0.2499	0.5959	1.4750	2.0708	0.3547	0.1444	0.4991
4/30/2019	0.4249	0.2436	0.0460	0.1976	0.6685	1.6107	2.2792	0.4844	0.1315	0.6159
Average	0.2469	0.1633	0.0267	0.1498	0.4234	1.2789	1.7023	0.2997	0.1062	0.4059
Std. Dev.	0.2185	0.1391	0.0233	0.1307	0.3635	0.4624	0.8253	0.2175	0.0554	0.2690
Count	3	3	3	3	3	3	3	3	3	3

Table 2.30. Physical, plant pigment, suspended solids and Enterococci bacteria results from grab samples collected at Birchwood-Malibu Park lake (36.85204°, -76.10038). Note: Abbreviations as in Table 2.16. * denotes geometric mean.

Date	WT ºC	Sal ppt	pH SU	DO mg/L	DO %sat	Chl µg/L	Pheo ug/L	Func. Chl ug/L	TSS mg/L	FSS mg/L	VSS mg/L	Enterococcus MPN/100 ml
1/23/2019	6.8	0.05	8.69	12.8	104.4							31
2/21/2019	9.2	0.03	7.06	10.1	87.3							10
4/18/2019	27.0	0.04	10.28	15.0	188.4	471.0	0.0	471.0	53.0	5.8	47.2	241
4/30/2019	27.5	0.03	7.11	10.7	133.3	138.0	13.7	124.3	53.6	8.0	45.6	2,851
Average	17.6	0.04	8.29	12.1	128.4	304.5	6.9	297.7	53.0	5.8	47.2	120.8*
Std. Dev.	11.2	.01	1.53	2.2	44.3	235.5	9.7	245.2	53.6	8.0	1.1	
Count	4	4	4	4	4	2	2	2	2	2	2	4

Table 2.31. Nutrient (nitrogen and phosphorus) results from grab samples collected at Birchwood-Malibu Park lake (36.85204°, -76.10038). Concentrations are expressed as mg/L of N or P. Note: Abbreviations as in Table 2.15. * denotes ½ MDL.

Date	NH_4	NO_{23}	NO_2	NO_3	DIN	DON	TDN	PO_4	DOP	TDP
1/23/2019	0.0031*	0.0027*	0.0008*	0.0019	0.0058	0.7760	0.7818	0.0629	0.0482	0.1111
4/18/2019	0.0031*	0.0027*	0.0008*	0.0019	0.0058	1.5301	1.5359	0.3008	0.1403	0.4411
4/30/2019	0.2414	0.0027*	0.0034	-	0.2448	1.9462	2.1910	0.5023	0.1274	0.6297
Average	0.0825	0.0027	0.0017	0.0010	0.0855	1.4174	1.5029	0.28867	0.1053	0.3940
Std. Dev.	0.1376		0.0015	0.0015	0.1380	0.5932	0.7052	0.2211	0.0499	0.2625
Count	3	3	3	3	3	3	3	3	3	3

Chapter 3
Numerical Modeling Study of Buchanan Creek

Key Findings

- Our modeling built off the water quality monitoring data reported in Chapter II and is consistent with the picture provided by those data.

Contributions to pollution loading

- Modeling indicates that the dominant contributions of pollutant sources (nutrients and bacteria) are nonpoint sources and storm water discharge. The dominant nutrient sources in the model are fertilizer applied to lawns and atmospheric deposition. The dominant bacterial sources in the model are wildlife and pets.

- The amount of pollutant loadings is within the range of typical urban dominated areas.

- Particle tracking studies show that pollutants can be transported between Thalia and Buchanan creeks, indicating that the pollutants in Buchanan Creek are not solely discharged from that watershed.

Predicted changes from channel deepening

- Water age (residence time) is long (> 20 days) in Buchanan Creek during typical low runoff conditions, which is favorable for algal growth and nutrient recycling, but the system can be flushed out quickly when surface runoff is higher.

- Water residence time will increase and the flushing effect will decrease if the channel of Buchanan Creek is deepened by 2 ft (0.6 m) . If the channel is deepened, the decrease in current and flushing capability during high runoff events could induce rapid sediment deposition.

- Water quality model simulations predict that deepening of the channel will result in a slight decrease in Chl-a, but there will be no obvious change in DO because of the continued high contribution of the benthic community.

Comparisons with reference sites

- Comparison of monitoring analysis of DO and Chl-a between Buchanan Creek and two reference sites, Thalia Creek and Wolfsnare Creek, shows that the characteristics of headwater creeks are similar in terms of DO, total ecosystem primary production, net ecosystem metabolism, and pelagic versus benthic contributions to total ecosystem primary production.

- Water quality model simulations using identical kinetic parameters can reproduce DO and Chl-a variation and nutrient dynamics observed in all three creeks, also suggesting the similarity of systems.

Introduction

Buchanan Creek is located upstream of the Western Branch of the Lynnhaven River, where it splits into Thurston Branch and Buchanan Creek (Fig. 3.1). About 1.3 km (0.8 mi) up Thurston Branch, Thurston splits into the upper Thurston Branch and Thalia Creek. Because the tide propagates from the Western Branch of the Lynnhaven River to this region, the water and associated pollutants that transport into and out of Buchanan Creek are highly influenced by the Western Branch, Thurston Branch, and Thalia Creek. Pollutant transport processes in Buchanan Creek depends both on the dynamics in Western Branch/Thurston Branch and Thalia Creek, as well as discharge from the drainage watershed. To investigate the controls on water quality and the role of transport processes inside Buchanan Creek, VIMS assisted DEQ by developing numerical models to assess the hydrodynamic and water quality conditions of the system. The modeling study focused on four topics: (1) The existing water quality conditions in Buchanan Creek and surrounding portions of the system; (2) Contributions of pollutant sources causing water quality problems (runoff, transport from outside, hidden sources, etc.); (3) Changes of dynamics, transport, and water quality conditions due to local channel geometry modifications such as changes in channel depth; and (4) Comparisons of current channel conditions to reference sites with similar properties in other sections of the Lynnhaven system. Detailed descriptions of the modeling process and major results are documented here.

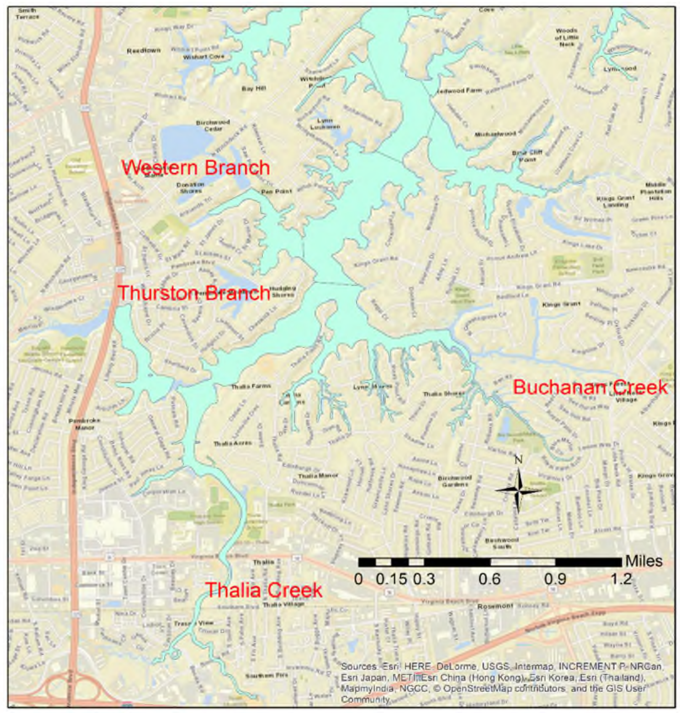


Figure 3.1. Map of the Buchanan Creek and surrounding area

Existing water quality condition

Chapter II provided details of the water quality sampling that we conducted in Buchanan Creek and the reference sites. In this section we further explore some of those data to characterize existing water conditions in Buchanan Creek and the reference sites (see Fig. 2.? in the preceding chapter), prior to discussing our Modeling efforts and results.

September measurements of chlorophyll a (Chl-a) and dissolved oxygen (DO) at five of the stations show typical shallow water characteristics with high variation in space and time (Table2 3.1 & 3.2, Fig. 3.2). Chl-a concentrations range from 6-79 ug/L and DO ranges from 0.3-12 mg/L. DO can often be higher than saturation DO during the daytime, which suggests active biological processes occur in these creeks. In September, Chl-a concentration is higher at Thalia Creek compared with other sites, and DO has the greatest range at the Wolfsnare site. The time-series for DO distributions at Buchanan Creek (Buch. 3) and at Wolfsnare are very similar, although Chl-a time-series are relatively different at these two stations (Fig 2-3a). The statistical t-test shows that no difference in mean DO at these two stations (α = 0.05). Since their mean Chl-a levels are different, this suggests that DO variation is not totally contributed by phytoplankton. Although measurement stations Buch. 2 and Buch. 3 are located very close to each other, Chl-a and DO distribution are relatively different, indicating a high spatial variation in the creek due to biological processes.

Table 3.1. Statistics for Chl-a measurement (µg/L).

	Station	Thalia	Buch. 1	Buch. 2	Buch. 3	Wolfsnare	Boundary
	Mean	38.8	21.9	38.3	30.2	20.1	14.1
	Min	19.2	10.4	19.2	15.9	6.0	6.2
Sep.	Max	79.1	44.7	79.3	59.9	47.0	26.4
	STD	11.9	5.9	10.9	8.7	7.5	3.7
	Count	1103.0	1340.0	1341.0	1111.0	1361.0	1342.0
	Mean	14.4	9.0	12.9	10.8	4.9	7.9
	Min	1.0	0.0	4.8	2.3	2.0	2.9
Dec.	Max	54.4	41.0	44.2	41.2	32.6	46.5
	STD	6.2	3.7	5.6	5.5	2.2	3.4
	Count	1103.0	1340.0	1341.0	1111.0	1361.0	1342.0
	Mean	16.0	27.6	24.4	11.8	6.2	27.0
	Min	3.8	0.1	4.8	1.0	0.5	13.8
Feb.	Max	60.6	152.6	137.0	40.3	134.3	90.1
	STD	7.6	18.1	17.5	7.3	7.9	9.0
	Count	1070	1012	983	898	1056	1043

Table 3.2 Statistics for DO measurements by sampling period (mg/L).

	Station	Thalia	Buch. 1	Buch. 2	Buch. 3	Wolfsnare	Boundary
	Mean	4.4	5.2	4.0	3.4	3.5	6.4
	Min	2.1	1.4	0.3	0.3	0.7	4.3
Sep.	Max	9.0	10.0	9.8	10.0	11.6	8.8
	STD	1.2	1.7	2.2	2.1	2.1	0.9
	Count	863	869	867	864	867	486
	Mean	9.9	10.4	8.7	7.9	8.3	11.0
	Min	7.3	7.4	2.8	5.0	4.4	9.5
Dec.	Max	12.8	12.6	12.5	11.8	10.8	12.3
	STD	0.9	1.0	1.8	1.5	1.3	0.4
	Count	1162	1345	1341	1159	1363	1352
	Mean	9.6	11.3	10.6	9.7	8.8	12.2
	Min	6.4	1.0	6.8	5.7	6.9	10.4
Feb.	Max	13.0	17.1	15.6	13.7	11.2	14.6
	STD	1.2	2.0	1.7	1.6	0.8	0.8
	Count	1070	1049	986	897	1071	1047

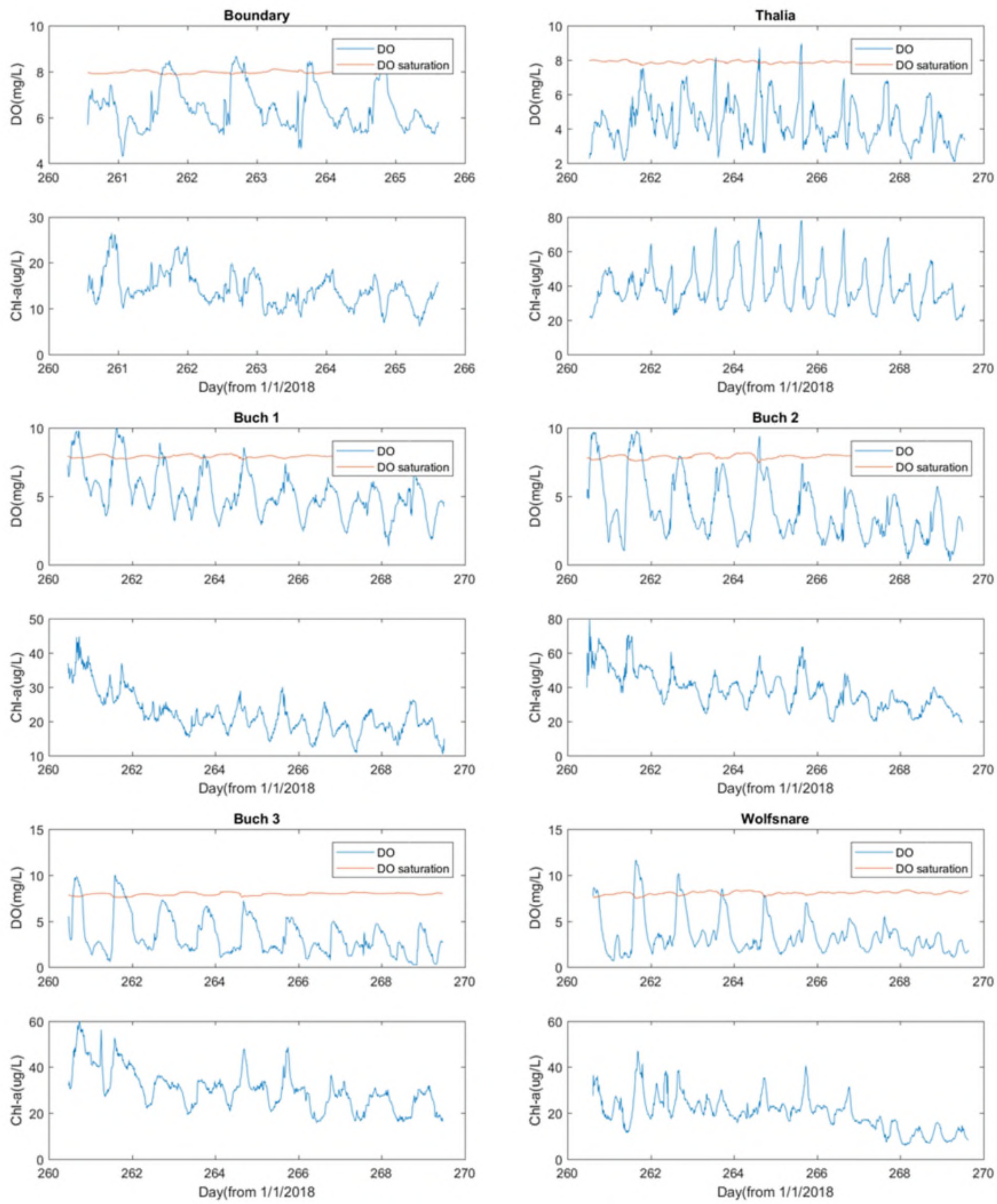


Figure 3.2. Chl-a and DO measured at the Boundary location, 3 stations in Buchanan Creek, and reference stations in Thalia and Wolfsnare creeks during Sept. 2018.

Turbidity at these stations are quite similar and of the same order of magnitude. Turbidity ranges from 12 to 41 NTU (Fig. 3.4). pH values are high at Thalia station in association with high Chl-a concentrations, but all pH values are within the range of 6.7-8.2, a typical variation in a shallow water waterbody (Fig. 3.4). For other stations, pH variations are very similar.

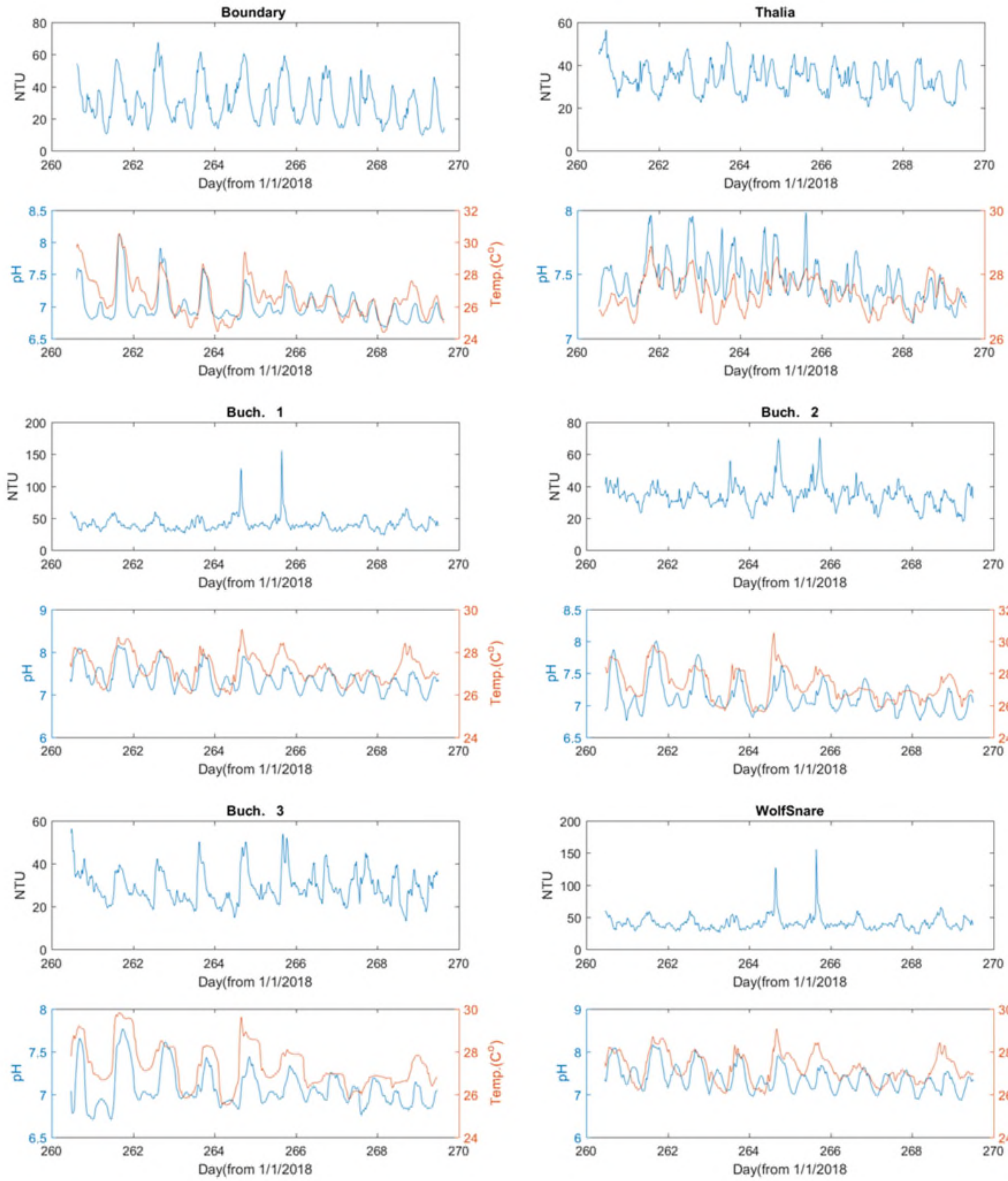


Figure 3.3. Turbidity (NTU), pH and temperature measured at the Boundary location, 3 stations in Buchanan Creek, and reference stations in Thalia and Wolfsnare creeks during Sept. 2018.

For December measurements, DO concentrations increase compared with September because of a decrease in temperature (Table 3.2). DO below 5 mg/L only occurred a couple of times during the observation period, and the lowest observed DO was 4.4 mg/L at Wolfsnare (Table 3.2, Fig. 3.4). The mean concentration of Chl-a was lower in December compared to September.

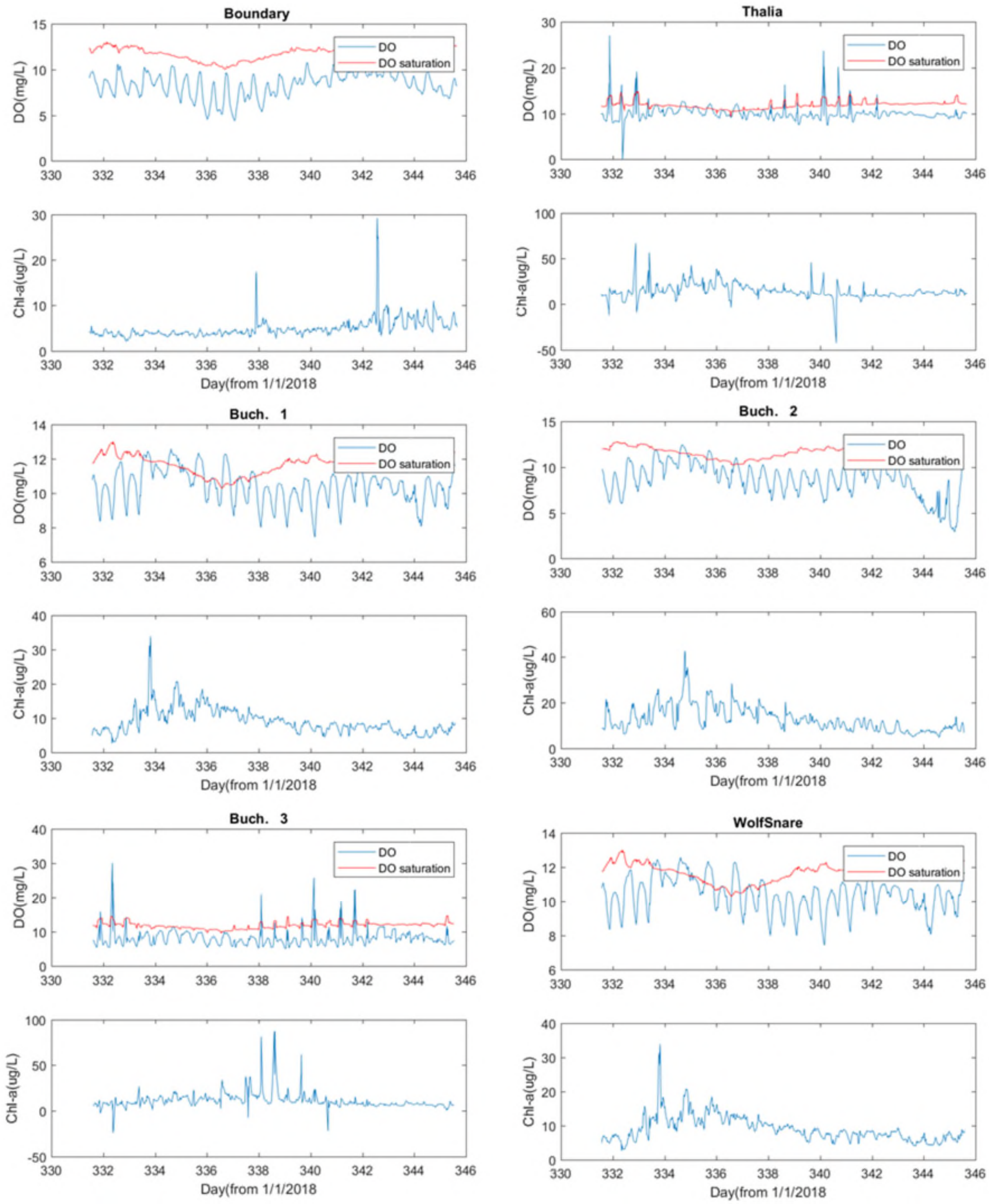


Figure 3.4. Chl-a and DO measured at the Boundary location, 3 stations in Buchanan Creek, and reference stations in Thalia and Wolfsnare creeks during Dec. 2018.

Turbidity was also comparatively low during December (Fig. 3.5).

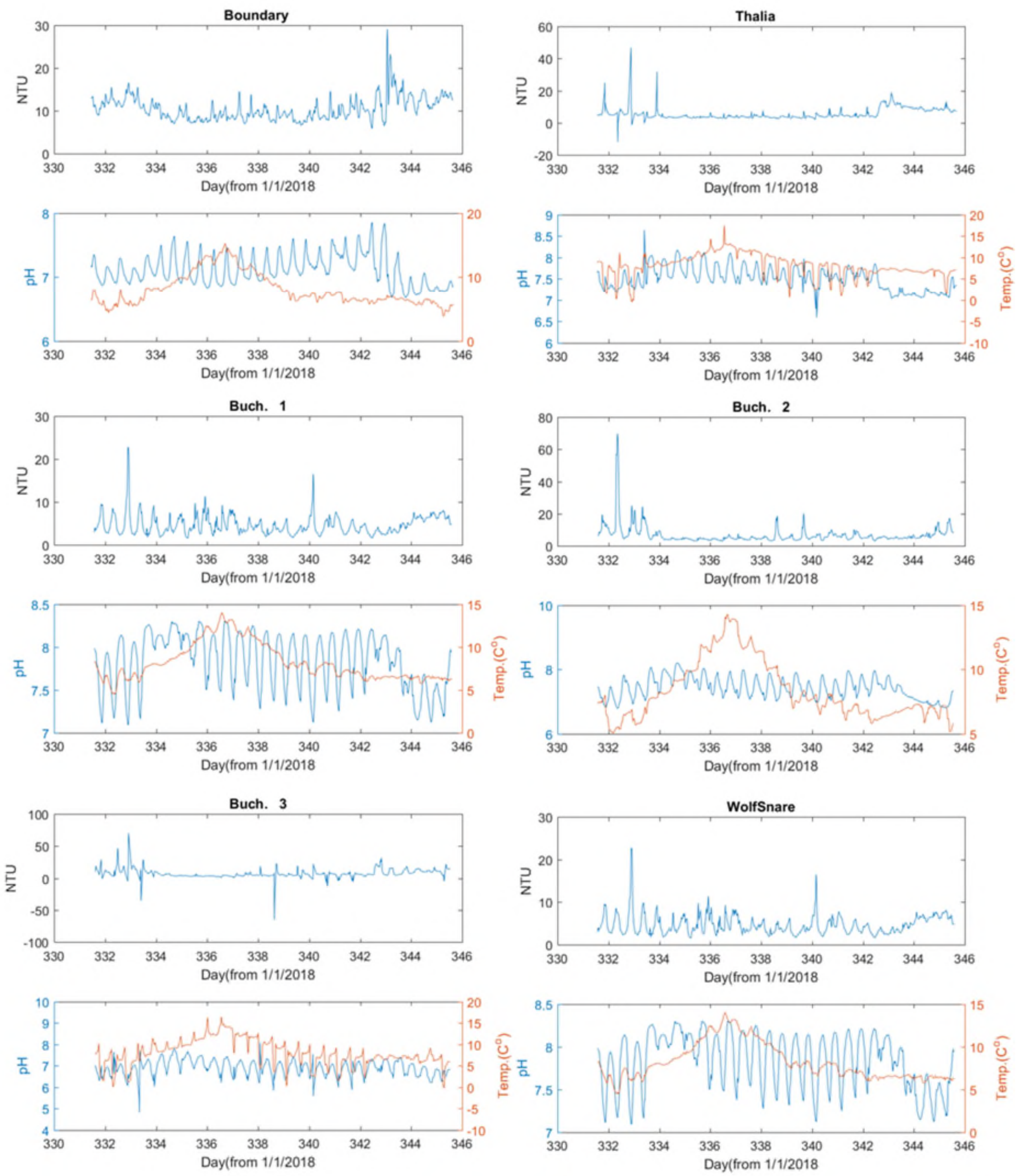


Figure 3.5. Turbidity (NTU), pH and temperature measured at the Boundary location, 3 stations in Buchanan Creek, and reference stations in Thalia and Wolfsnare creeks during Dec. 2018.

For February measurements, DO was generally higher than 5 mg/L. (Table 3.2, Fig. 3.6) However, Chl-a concentrations were very high at some stations (Table 3.1, Fig. 3.6); however, mean Chl-a concentration in February was lower than September in general (Table 3.1). Compared to September, large fluctuations in DO and Chl-a were observed in February, which can be due to periods of high freshwater discharge.

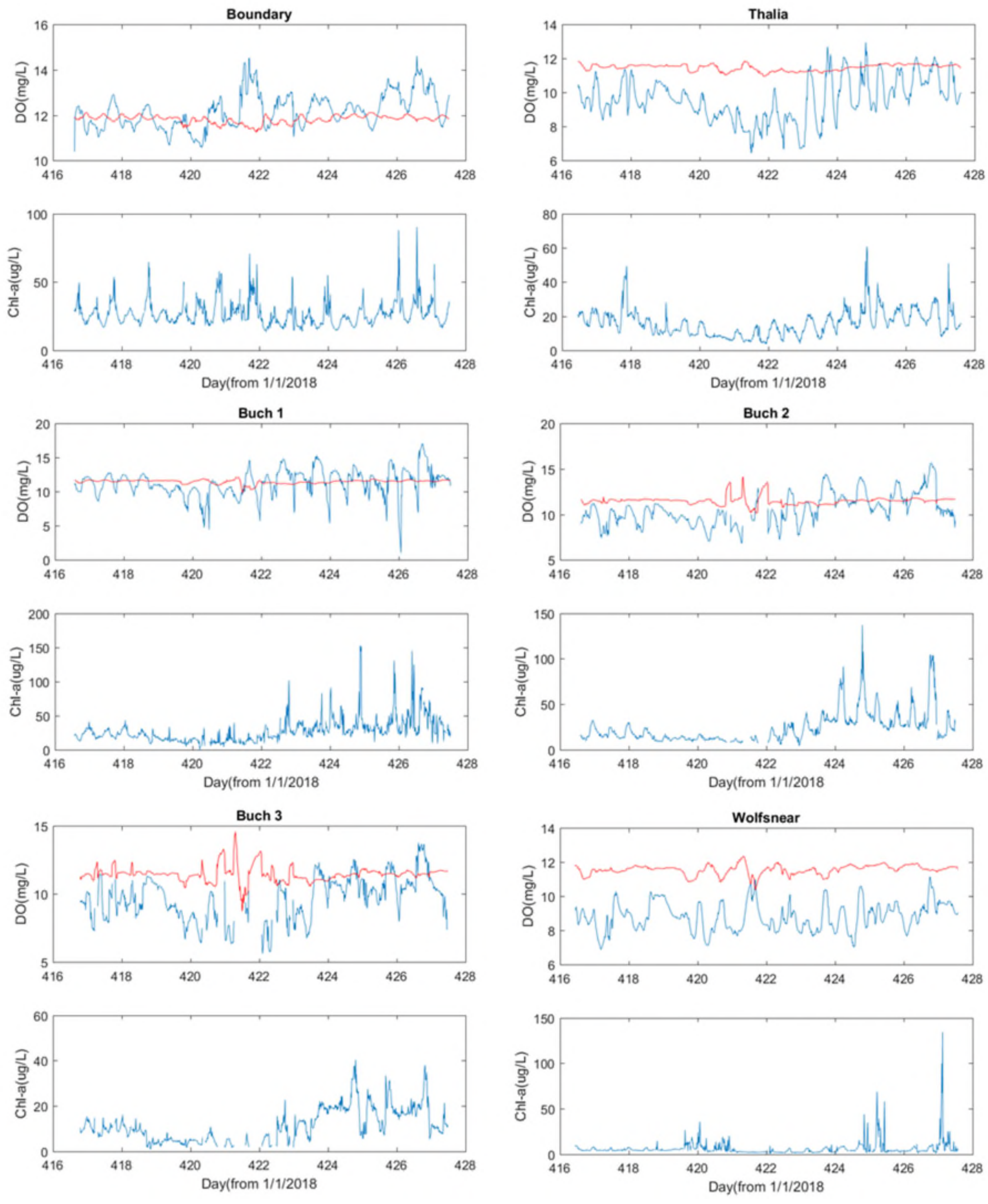


Figure 3.6. Chl-a and DO measured at the Boundary location, 3 stations in Buchanan Creek, and reference stations in Thalia and Wolfsnare creeks during Feb. 2019.

Turbidity was higher in February than December, but lower than September in general. pH variations were very similar at all stations. (Fig. 3.7).

Figure 3.7. Turbidity (NTU), pH and temperature measured at the Boundary location, 3 stations in Buchanan Creek, and reference stations in Thalia and Wolfsnare creeks during Feb. 2019.

One of the typical shallow water characteristics of DO and Chl-a variation is a diurnal cycle, with concentrations peaking toward the end of daylight hours (Caffrey, 2004, Shen et al., 2008). Both pelagic (phytoplankton) and benthic communities (benthic microalgae, macroalgae, and submerged aquatic vegetation) perform photosynthesis during the daytime and respire during day and night. Phytoplankton and macrophyte respiration, decay of organic carbon (OC), and sediment oxygen demand (SOD) can deplete DO, resulting in DO generally increasing during daytime and DO decreasing at night. These typical patterns of diurnal cycles in DO and Chl-a are particularly evident in the September data (Fig. 3.8). However, the diurnal cycles are modulated by tides, indicating the influence of tides in these shallow locations. The tidal effect is more pronounced at the Western Branch (open boundary) and Thalia Creek sites.

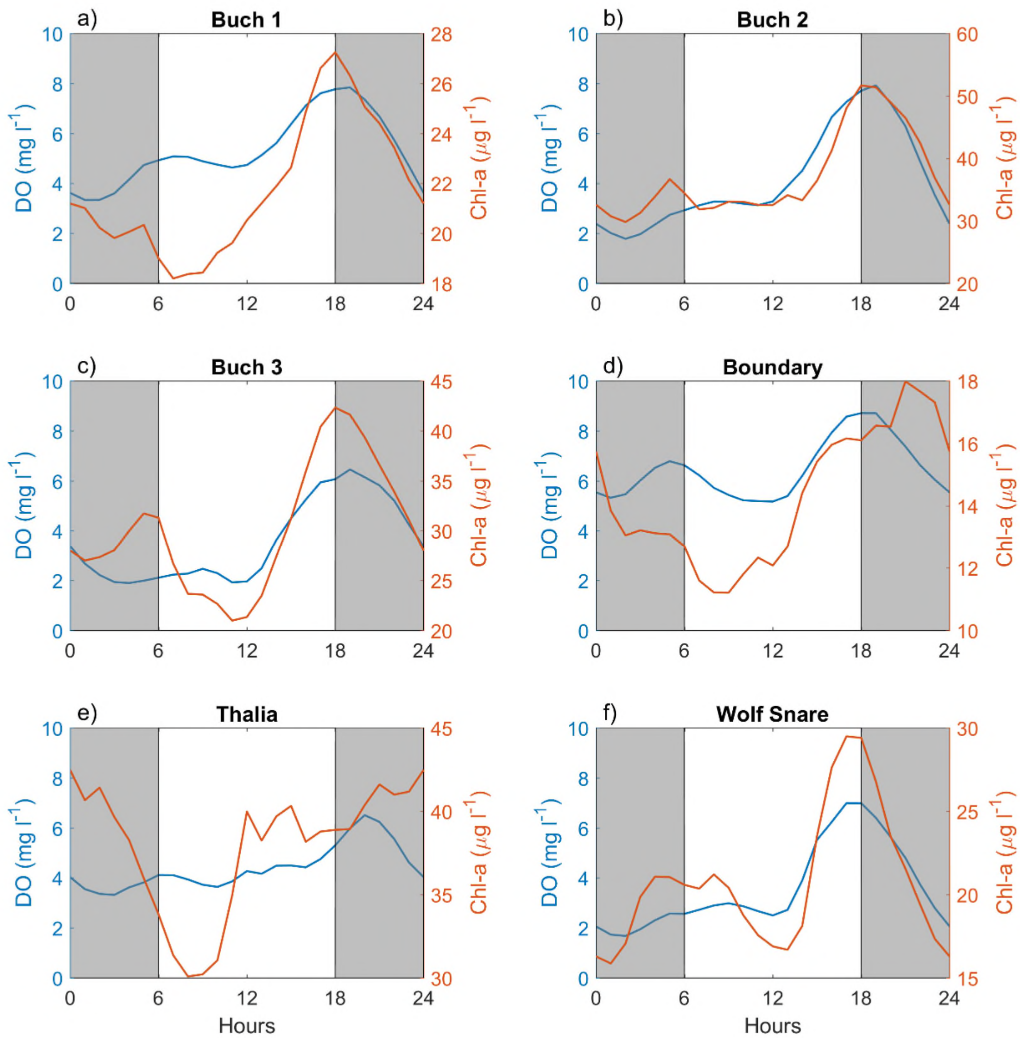


Figure 3.8. Averaged observed daily variation of Chl-a and DO at the measurement locations for Sept. 2018.

Comparisons of current channel condition to a reference site

For this study, two reference sites were selected for comparison, which are the Thalia Creek station and Wolfsnare Creek stations. One is located in the upstream portion of Thalia Creek and one is located in the upstream portion of Eastern Branch. Chapter 2 provides details of the data collected in these creeks and compares them to Buchanan, reaching the general conclusion that water quality in these reference creeks do not differ substantially from Buchanan Creek. In this section we use some of these data compute important ecosystem rates indicative of eutrophication.

In high eutrophication waterbodies, primary production is dominated by phytoplankton (Valiela et al., 1997). The ecosystem condition with respect to eutrophication can be assessed by comparing the individual rate of primary production due to the benthic community versus phytoplankton and also by examining the net ecosystem metabolism (NEM). Both total gross primary production (GPP) of phytoplankton (pelagic GPP) and of the whole ecosystem (pelagic GPP and benthic GPP combined) are computed using Continuous Monitoring (ConMon) data based on the open water methods (Caffrey, 2004; Qin and Shen, 2019). These results are listed in Tables 3.3 – 3.5, respectively, for September 2018, December 2018, and February 2019.

Table 3.3. Mean of gross primary production and respiration by station in September 2018

Station	**Ecosystem GPP**	**Ecosystem GPP**	**Pelagic GPP**	**Pelagic contribution**	**Respiration**	**Net Ecosystem Metabolism**
	g O_2 m^{-2} d^{-1}	g C m^{-2} d^{-1}	g C m^{-2} d^{-1}		g O_2 m^{-2} d^{-1}	g O_2 m^{-2} d^{-1}
Buch. 1	8.406	3.152	0.439	13.7%	11.369	-2.963
Buch. 2	8.662	3.248	0.563	20.8%	13.276	-4.614
Buch. 3	10.281	3.855	0.598	28.3%	15.736	-5.455
Boundary	12.151	4.557	0.806	17.3%	12.826	-0.675
Thalia	4.387	1.876	0.531	37.1%	8.313	-3.926
Wolfsnare	18.362	6.886	1.042	14.9%	24.073	-5.712

Table 3.4. Mean of gross primary production and respiration by station in December 2018

Station	**Ecosystem GPP**	**Ecosystem GPP**	**Pelagic GPP**	**Pelagic contribution**	**Respiration**	**Net Ecosystem Metabolism**
	g O_2 m^{-2} d^{-1}	g C m^{-2} d^{-1}	g C m^{-2} d^{-1}		g O_2 m^{-2} d^{-1}	g O_2 m^{-2} d^{-1}
Buch. 1	5.400	2.422	0.235	13.0%	7.489	-2.089
Buch. 2	5.742	2.568	0.712	28.4%	11.130	-5.388
Buch. 3	2.911	1.092	0.198	41.2%	5.144	-2.233
Boundary	5.203	1.951	0.302	22.1%	4.847	0.357
Thalia	4.518	1.694	0.434	28.3%	5.834	-1.316
Wolfsnare	7.471	2.802	0.179	3.3%	12.963	-5.492

Table 3.5. Mean of gross primary production and respiration by station in February 2019

Station	Ecosystem GPP	Ecosystem GPP	Pelagic GPP	Pelagic contribution	Respiration	Net Ecosystem Metabolism
	$g\ O_2\ m^{-2}\ d^{-1}$	$g\ C\ m^{-2}\ d^{-1}$	$g\ C\ m^{-2}\ d^{-1}$		$g\ O_2\ m^{-2}\ d^{-1}$	$g\ O_2\ m^{-2}\ d^{-1}$
Buch. 1	6.189	2.365	0.727	17.1%	8.864	-2.675
Buch. 2	3.337	1.184	0.749	25.4%	4.905	-1.569
Buch. 3	3.256	1.240	0.330	15.5%	5.997	-2.741
Boundary	4.867	2.006	1.086	55.7%	4.597	0.269
Thalia	3.070	1.151	0.471	54.5%	8.298	-5.229
Wolfsnare	4.738	1.777	0.336	23.3%	8.059	-3.321

In general, ecosystem GPP was higher than pelagic GPP (Figs. 3.9 – 3.11) and the contribution of pelagic GPP is less than 50% of ecosystem GPP, which is similar to the shallow water region of York River (Qin and Shen, 2019), suggesting that a large portion of the organic carbon (OC) and consumption of DO comes from the benthic community. The estimated NEM ranges from -0.7 to -5.7 g O_2/m^2 per day. The highest NEM is observed at the Buchanan 3 and Wolfsnare sites in September. The range of NEM is within the same range of those observed in the coastal estuaries in the Atlanta Region (Caffrey, 2004). The pelagic GPP at both upstream stations (Buch. 3 and Wolfsnare) are very similar.

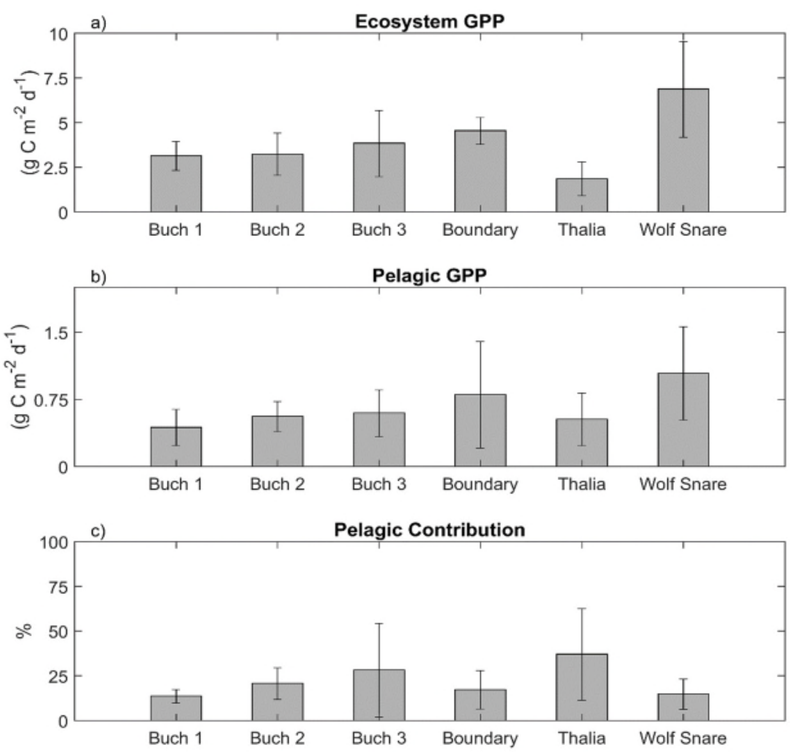


Figure 3.9. Comparison of total GPP and pelagic (phytoplankton) GPP for the measurement sites during Sept. 2018.

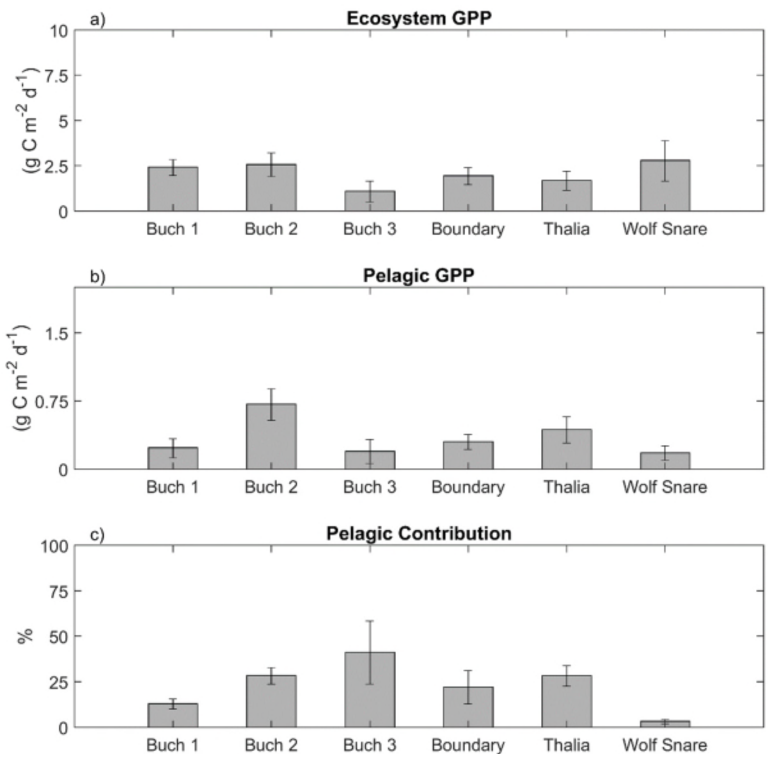


Figure 3.10. Comparison of total GPP and pelagic (phytoplankton) GPP for the measurement sites during Dec. 2018.

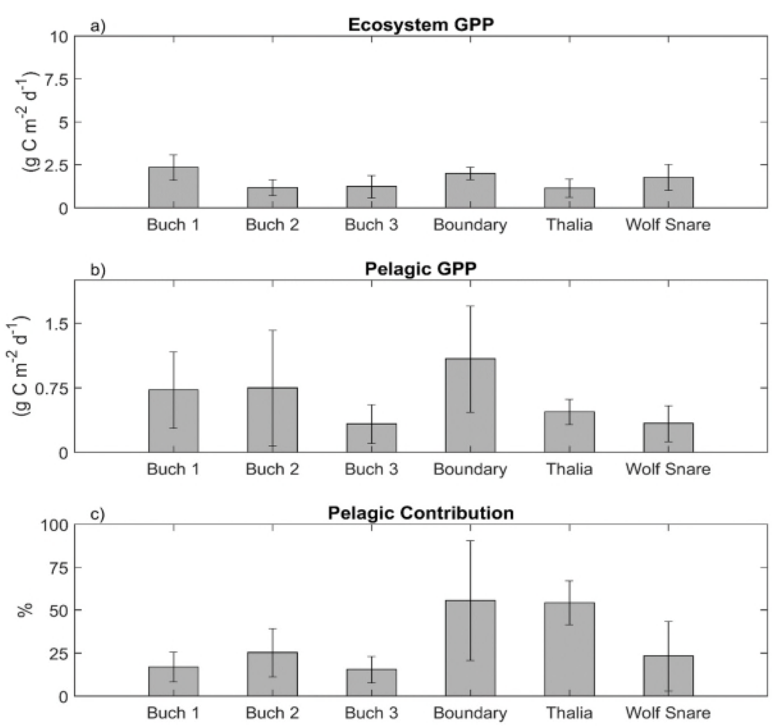


Figure 3.11. Comparison of total GPP and pelagic (phytoplankton) GPP for the measurement sites during Feb. 2019.

Comparing the stations located in Buchanan Creek with the stations located in the upstream portion of Thalia Creek and Wolfsnare Creek (i.e., the reference sites) suggests that Buchanan Creek is similar to Thalia and Wolfsnare in terms of concentration of phytoplankton, DO, and ecosystem GPP versus pelagic GPP. The low contribution of pelagic GPP to ecosystem GPP indicates that the benthic community contributes highly to diurnal DO variation, and Buchanan Creek has not been in a stage of high eutrophication because of the large contributions from benthic community (Valiela et al., 1997; Qin and Shen, 2019).

Comparing the distributions of DO, Chl-a, turbidity, and pH in Buchanan Creek with the stations located in upstream portion of Thalia Creek and Wolfsnare (reference sites), Buchanan Creek is not substantially different from Wolfsnare for DO, turbidity, and pH (Figs. 3.12 - 3.14). However, Chl-a distribution in Wolfsnare is lower for all our measurement periods. This is also clear if comparing daily average values (Fig. 3.15).

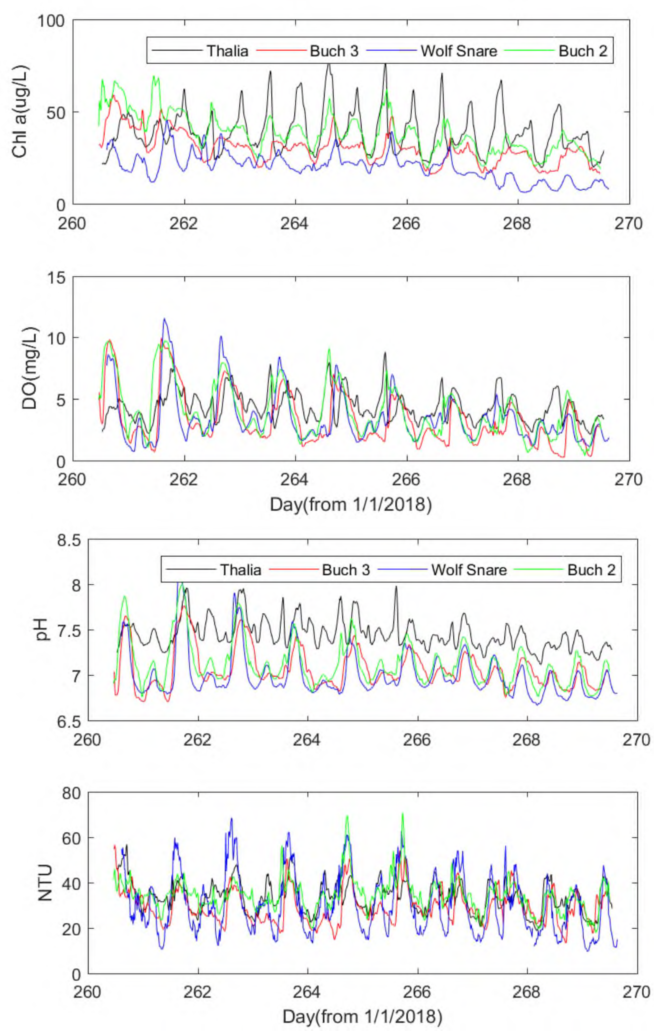


Figure 3.12. Comparison of Thalia, Buchanan 3, and Wolfsnare sites (Chl-a, DO, pH, NTU) distribution during Sept. 2018.

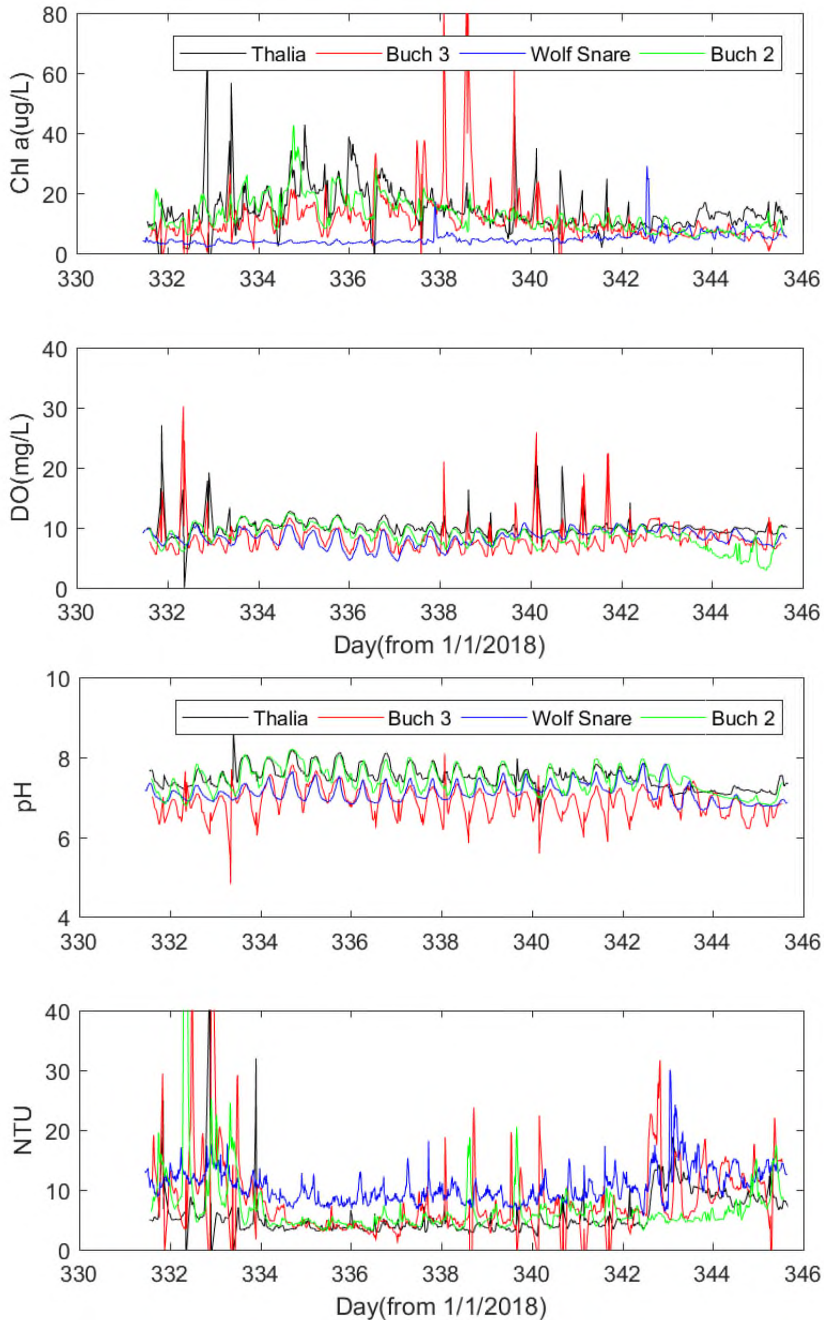


Figure 3.13. Comparison of Thalia, Buchanan 3, and Wolfsnare sites (Chl-a, DO, pH, NTU) distribution during Dec. 2018.

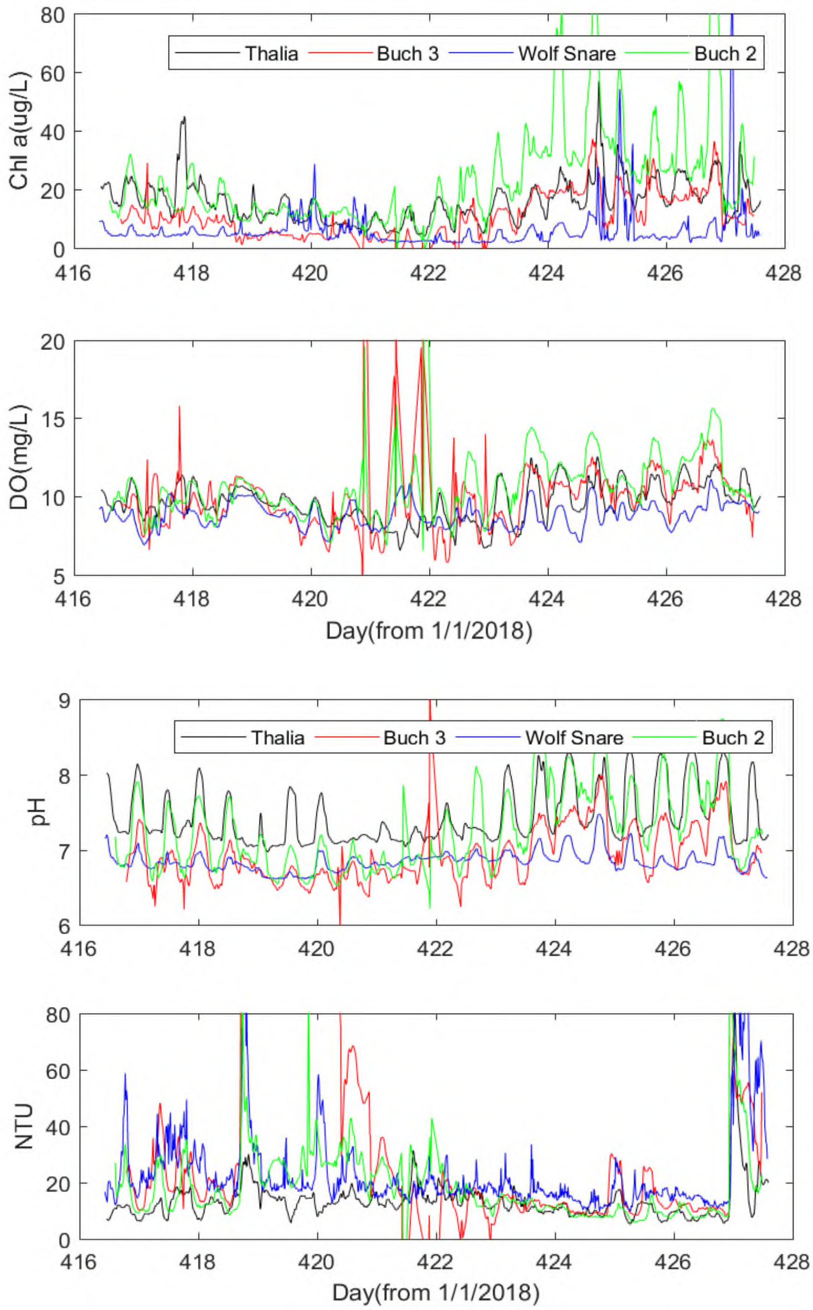


Figure 3.14. Comparison of Thalia, Buchanan 3, and Wolfsnare sites (Chl-a, DO, pH, NTU) distribution during Feb. 2019.

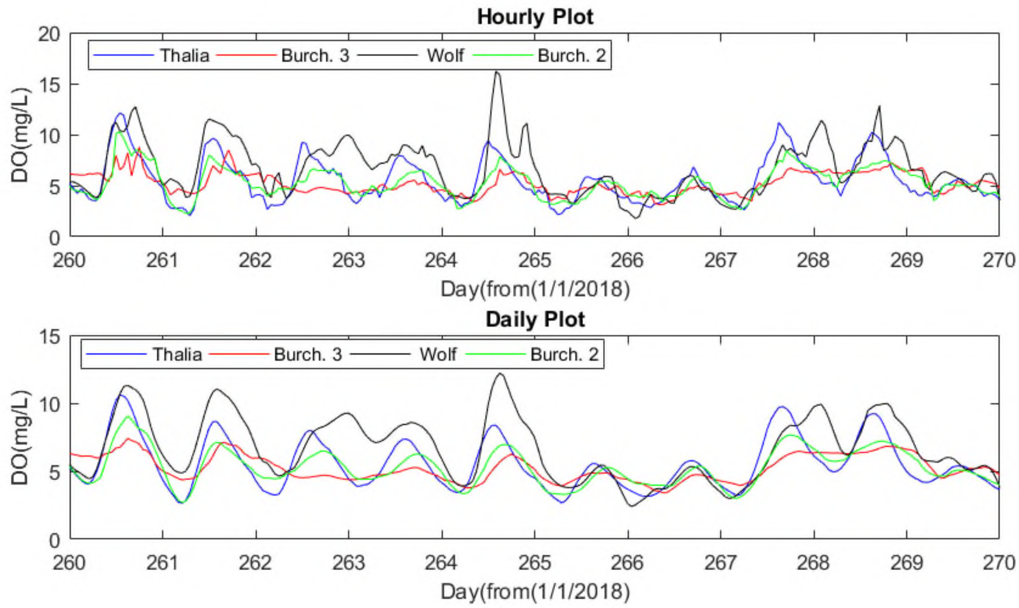


Figure 3.15. Comparison of DO during summer period at 4 observation sites during Sept. 2018.

We used the same model kinetic parameters to run the water quality model and compared the model results to observational data, which is shown in Fig. 3.16. It can be seen that the model results are very similar and agree with the observations reasonably well. Low DO can be observed at all three stations during September.

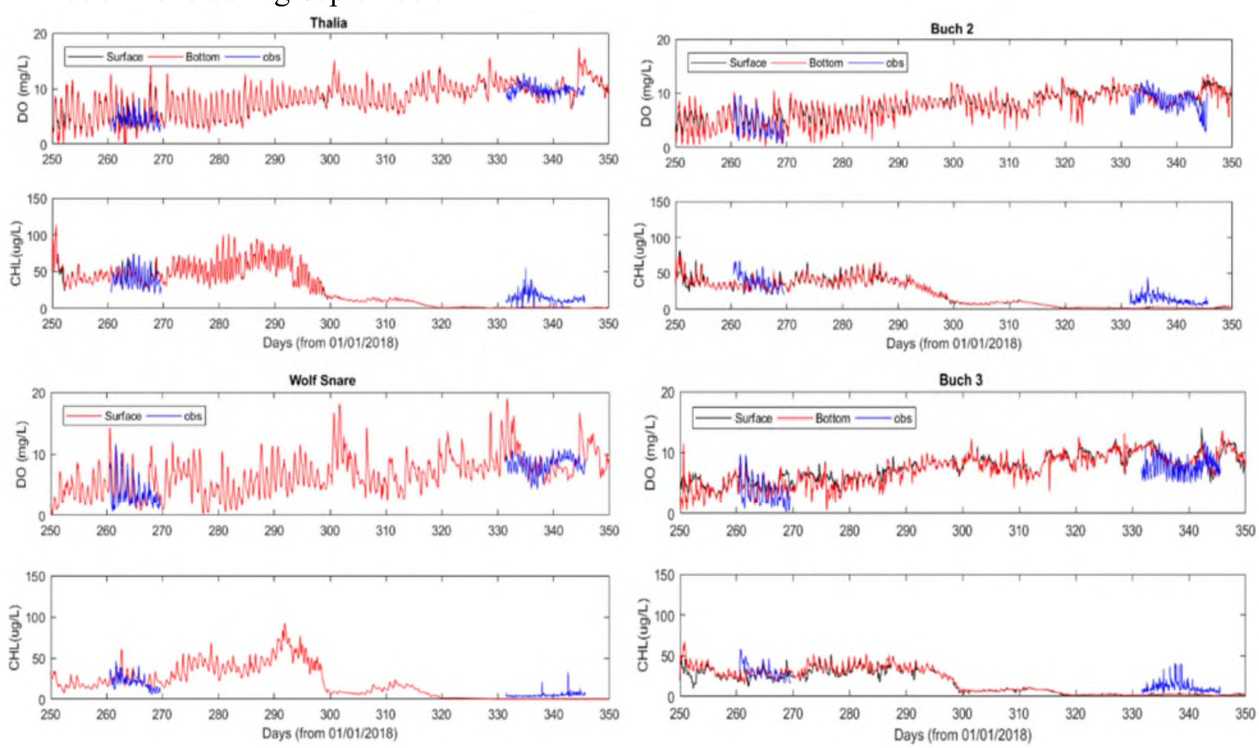


Figure 3.16. Model simulation of DO and Chl-a compared to observations at 4 observation sites during 2018.

Contributions of pollutant sources

A watershed approach was applied for source assessment for Buchanan Creek and Thalia Creek watersheds. The source assessment is based on the land use distribution, which does not include site specific sources as there are no sufficient information to obtain detail pollutant sources during the short period. The entire drainage area is divided into 230 sub-watersheds (Fig. 3.17. The source assessment is conducted on the sub-watershed level. Land use information was extracted from Virginia Geographic Information Network (https://www.vita.virginia.gov/integrated-services/vgin-geospatial-services/) and was used to determine the habitat area/location of each wildlife type within each sub-watershed. The land use distribution is shown in Fig. 3.18. The largest land use is urban impervious (45%) followed by grassland (31%) and forest (19%). These land use data provide a high resolution of urban pervious and impervious land uses, and turf grass from forest, but it does not separate a wetland (category) for the Lynnhaven River watershed.

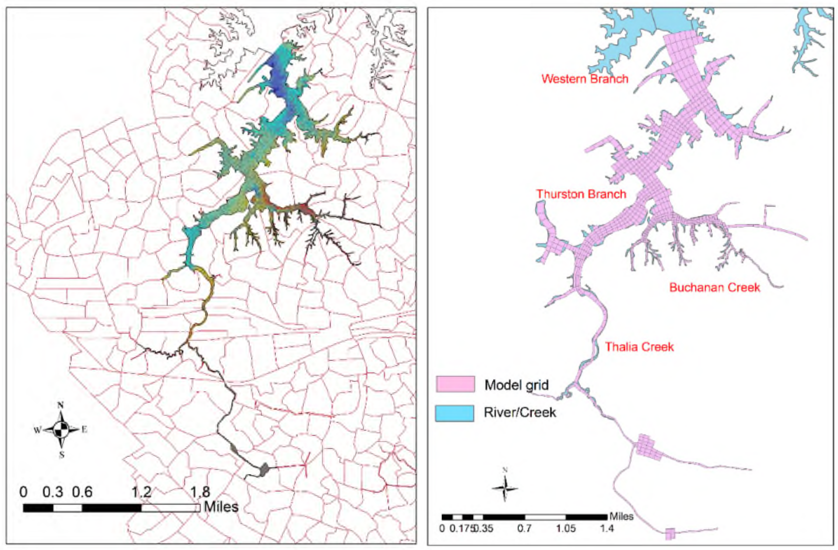


Figure 3.17. Watershed delineation, unstructured (left panel) and structured model grids (right panel).

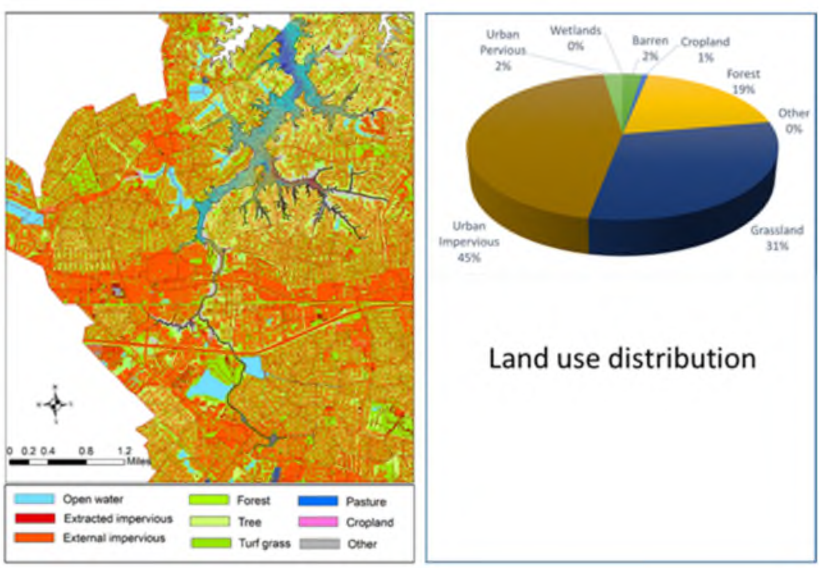


Figure 3.18. Land use (USGS 2018) distribution in the Thalia and Buchanan creek area of the Lynnhaven.

In the evaluation of sources, a watershed approach is applied and loads are characterized by using the best available information from landowner and citizen input, literature values, and local government agencies. The source assessment is conducted on the sub-watershed level, while only the total numbers and loadings of the whole watershed are presented here. As the study is focused on Buchanan Creek, which branches off of Thalia Creek, the information for Buchanan Creek and Thalia Creek is presented as well.

Permitted Point Sources

The discharge of pollutants from point sources is regulated through Virginia Pollutant Discharge Elimination System (VPDES) permits. There are no permitted point sources that discharge to the surface waters in the Thalia Creek and Buchanan Creek watersheds. The permitted MS4 associated with urban land use is included in the nonpoint sources for this modeling study.

Nonpoint Sources

In the Thalia Creek and Buchanan watershed, nonpoint sources of bacteria and nutrients include recreational boating, pets, septic tanks, and wildlife. In addition, lawn fertilizer application and atmosphere deposition are important sources of nutrient loading.

Recreational Boating

Boating activities can contribute to bacteria and nutrient loadings when sewage wastes are not adequately collected in pump stations. For the Thalia Creek and Buchanan Creek area, however, the loading contributions of boating activity are not estimated as there is no sufficient data available at this moment.

Pets

As the fecal coliform and nutrients daily loadings of dogs are much higher (~106 counts higher) than that of cats, dogs are the only pet considered in this study. The number of households in the City of Virginia Beach was obtained from United States Census Bureau (USCB). As most of the land-use in the area is urban, the number of households of the City is divided by the urban area of the City and multiplied by that of the Thalia Creek and Buchanan Creek watersheds to get the number of households of the Thalia Creek and Buchanan Creek watersheds. Assuming the average number of dogs per household is 0.58, the number of dogs in each sub-watershed can be calculated (Table 3.6). The production rate for fecal coliform, TN, and TP are 4.00E+09 counts/day/dog, 8.3E-03 lbs/day/dog, and 3.3E-03 lbs/day/dog. Assuming that the dog feces pickup rates in pervious and impervious lands are 51% and 83% (based on information from Rudee TMDL Technical Advisory Committee), the loads in each subwatershed is calculated as the product of the dog number, the non-pickup rate, and the production rate.

Table 3.6. Total number of dogs in Thalia Creek and Buchanan Creek Watersheds.

Watershed	Total # of Households	Total # of Dogs
Buchanan Creek	342	251
Thalia Creek	10,129	5,875

Septic Tanks

Conventional septic tank systems are only effective where the soil is adequately porous to allow percolation of liquids, and the groundwater level is low enough to avoid contamination. Leaking pipes or treatment tanks (i.e., leakage losses) can allow wastewater to return to the groundwater, or discharge to the surface, without adequate treatment. The loading for the contaminants in each sub-watershed is estimated as the product of pollutant concentration, number of septic tanks, failure rate, daily wastewater discharge per person, the number of persons for each tank, and the unit conversion factor.

For this study, the contribution of septic tanks is not estimated as there is not sufficient data available at the time the report was written. However, as urban land use is a major percentage of the total watershed land use, it can be estimated that the septic tank discharge, and therefore the bacteria and nutrients loadings from it, are minimal.

Wildlife

Wildlife populations in the Thalia Creek and Buchanan Creek watersheds were estimated by combining typical wildlife densities with available stream habitats, which were generated based on GIS data of land use and streams. The land use information from Virginia Geographic Information Network (VGIN, 2016) was used to determine the habitat area/location of each wildlife type within each sub-watershed. The density and production rates of each species are listed in Table 3.7. A summary of wildlife numbers is provided in Table 3.8.

Table 3.7. Wildlife Population Densities, and Bacteria and Nutrients Production Rates

Species	Density	Fecal Coliform Production Rate (CFU/Animal/Day)	TN Production Rate[b] (lb/Animal/Day)	TP Production Rate[b] (lb/Animal/Day)
Deer	0.1032 animals/acre[a]	5.00E+08[c]	8.25E-03	3.25E-03
Ducks	0.0652 animals/acre[a]	2.43E+09[d]	4.60E-03	1.66E-03
Geese	0.032 animals/acre[a]	4.90E+10[e]	4.60E-03	1.66E-03
Beavers	4.8 animals/mile[b]	2.50E+08[b]	4.00E-03	5.00E-04
Raccoons	0.0703 animals/acre[a]	1.25E+08[f]	4.00E-03	5.00E-04
Muskrats	0.3128 animals/acre[a]	3.40E+07[3]	4.00E-03	5.00E-04

[a]VA-DEQ, 2016; [b]ASAE, 1998; [c]VA-DEQ, 2007; [d]VA-DEQ, 2009; [e]USEPA, 2001; [f]VA-DEQ,2017b

Table 3.8. Estimated Numbers of Wildlife in the Buchanan Creek and Thalia Creek sub-watersheds.

Watershed	Deer	Ducks	Geese	Beavers	Raccoons	Muskrats
Buchanan Creek	34	21	5	10	23	47
Thalia Creek	922	582	158	150	630	1400

Deer

The deer habitat is the entire watershed. The total number of deer in each sub-watershed equals to the deer density multiplied by its habitat area. The total contaminant loadings are calculated as the number of deer multiplied by its production rates.

Ducks and Geese

The duck and geese habitats are the entire watershed except urban impervious land use. The density was multiplied by the sub-watershed habitat area to get the total number in each sub-watershed. The total contaminant loadings are calculated as the total numbers of ducks/geese multiplied by their production rates.

Beavers

The habitat of beavers is the riparian zone, which is the interface between land and a stream. The number of river miles was determined by measuring the total length of water edges using GIS software. The number of beavers equals the density multiplied by the total length of the water edges. The total contaminant loadings are calculated as the number of beaver multiplied by its production rates.

Raccoons

The raccoon habitat is the entire watershed, except open waters. The loadings are calculated as the products of the number of raccoons in each sub-watershed and their production rates.

Muskrats

The muskrat habitat is the entire watershed, except urban, open waters, and barren land uses. The density was multiplied by the area to get the total muskrat number in each sub-watershed. The loadings are calculated as the total muskrat population multiplied by the production rates.

Fertilizer Application

Approximately 50 lbs/acre of nitrogen and 1.5 lbs/acre of phosphorus are applied annually to urban lawns in the Chesapeake Bay watershed. The area of urban pervious land-use of each sub-watershed is multiplied by these two numbers to get the nitrogen and phosphorus loads, respectively.

Atmospheric Deposition

Atmospheric deposition of air-borne nutrients has been estimated using the value from the literature for the Chesapeake Bay region shown in Table 3.9

Table 3.9. Nutrient contributions from atmospheric deposition

Nutrient	**Loading** (lbs/acre/year)
TN	11.48
TP	0.71

Nutrient loading and bacterial loading for the Buchanan Creek and Thalia Creek watersheds by source categories are listed in Tables 3.10 and 3.11, respectively. Both fertilizer application and atmospheric deposition dominate the nutrient deposition and runoff on the land, while wildlife is the major source of bacteria.

Table 3.10. Summary of Bacteria and Nutrient Loadings of Buchanan Creek by Source Category

Nonpoint Source		**Fecal Coliform Loading** (counts/day)	**TN Loading** (lb/day)	**TP Loading** (lb/day)
Pets (Dogs)		2.2E+11	0.53	0.21
Wildlife	Deer	1.7E+10	0.28	0.11
	Ducks	5.2E+10	0.98	0.035
	Geese	2.5E+11	0.024	0.0086
	Beaver	2.5E+09	0.040	0.0050
	Raccoon	2.9E+09	0.092	0.011
	Muskrat	1.6E+09	0.19	0.023
Sum of Wildlife		5.6E+09	2.14	0.40
Fertilizer Application		NA	1.2	0.035
Atmospheric Deposition		NA	12,0	0.72
TOTALS		**5.5E+11**	**1.5E+01**	**1.2E+00**

Table 3.11. Summary of Bacteria and Nutrient Loadings of Thalia Creek by Source Category

Nonpoint Source		**Fecal Coliform Loading** (counts/cay)	**TN Loading** (lb/day)	**TP Loading** (lb/day)
Pets (Dogs)		4.6E+12	9.4	3.7
Wildlife	Deer	4.6E+11	7.6	3.0
	Ducks	1.4E+12	2.7	0.97
	Geese	7.7E+12	0.73	0.26
	Beaver	3.7E+10	0.60	0.075
	Raccoon	7.8E+10	2.50	0.31
	Muskrat	4.8E+10	5.70	0.71
Sum of Wildlife				
Fertilizer Application		NA	20.9	0.86
Atmospheric Deposition		NA	280.0	17.0
TOTALS		**1.4E+13**	**340**	**27.0**

Model development

A system of numerical models was applied to simulate the loadings of organic matter and nutrients from the watersheds, and the resulting response of in-stream water quality processes (Fig. 3.19). The watershed model, Loading Simulation Program in C++ (LSPC), developed by the US EPA (Shen et al., 2005) was selected to simulate the watershed hydrology and nutrient loads. The Environmental Fluid Dynamics Computer Code (EFDC/HEM3D) developed at VIMS was used to simulate the eutrophication processes in the receiving water (Park et al, 1995c; Shen et al., 2016). The water column processes were coupled to the bottom sediment diagenesis model, which simulates the remineralization of particulate organic matter deposited from the overlying water column, the resulting fluxes of inorganic substances, and the sediment oxygen demand (SOD) back to the water column. Because of the high contribution of the benthic community, the attached algal group is used to simulate the combined effect of the benthic community.

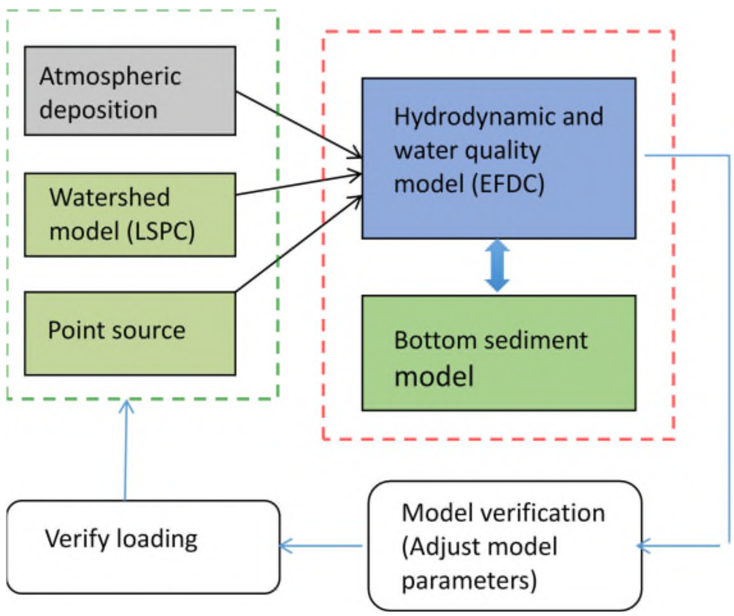


Figure 3.19. Diagram of linked watershed and water quality modeling system

In order to accurately simulate transport of water and pollutants surrounding small tributaries, and to make the model grids accurately follow the shoreline and bathymetry, a very fine spatial resolution model grid using the unstructured grid model (SCHISM) (Zhang et. al., 2016) was developed for evaluating complex interactions of geometry and hydrodynamics to assess channel modification, such as channel deepening. The model grids for water quality model and unstructured grid model are shown in Figs. 3.20 and 3.21, respectively. This high-resolution model enables us to use the particle tracking technique to investigate the pathway of water movement and its associated transport time (water age).   A more detailed discussion of t model development is presented in Appendix D.

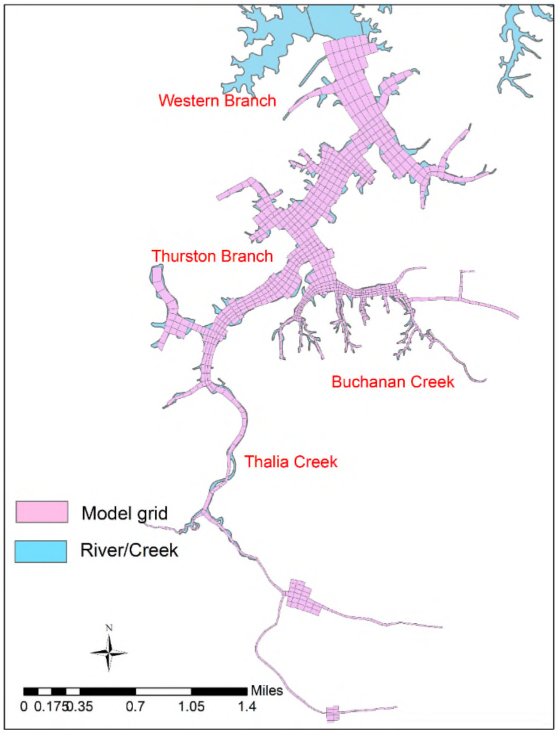


Figure 3.20. DC/HEM3D water quality model grid

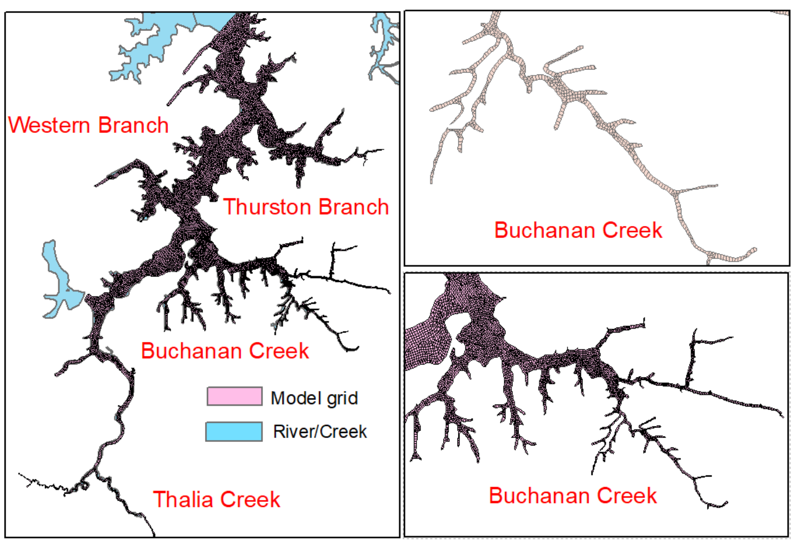


Figure 3.21. Unstructured grid model of Buchanan Creek and the Western Branch to Thalia Creek.

The LSPC watershed model is driven by hourly precipitation collected at the Norfolk airport and data collected at USGS station located in Thalia Creek. The pollutant loadings to the watershed were determined based on the source assessment for each land use category. Because there are no direct measurements of bacteria data in Buchanan Creek, bacterial abundance was not simulated by the watershed model for this study. Because there are no nutrient data in the Buchanan Creek watershed, the model was calibrated for TN and TP, respectively, based on limited observations at watersheds located in the Lynnhaven River near Thalia Creek. Other nutrient species, dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP), were estimated based on the product of the TN/TP loadings and the fraction of each species. The watershed loadings were discharged to the receiving water model at model grids adjacent to the watersheds. The water quality model simulates both particulate and dissolved nutrients together with DO and Chl-a. Municipal Separate Storm Sewer System (MS4) was not simulated separately. Instead, it was simulated together with the urban land use category for this urban-land-use-dominated watershed.

The hydrodynamic and water quality models are calibrated using 2009 and 2018 data for tide, salinity, temperature, DO and Chl-a. A detailed description of model and model calibration results are included in Appendix D. An example of the calibration of DO and Chl-a during 2018 is shown in **Fig. V-5-4**. It can be seen that the model simulates seasonal variations of both DO and Chl-a at the observation stations. **Fig. V-5-5** shows detailed model simulations of DO and Chl-a during September 2018. High-frequency data have large variation, and the Chl-a variation is highly dependent on light, in-stream turbidity, and shading. Because we do not have *in situ* observations of light in the watershed and also because runoff is simulated by the model rather than observed, it is not possible to simulate high-frequency fluctuations in Chl-a and DO with high accuracy. But seasonal variation, the diurnal cycle, and overall magnitudes of DO and Chl-a variation are appropriately simulated by the model, which is suitable for conducting model experiments for this assessment.

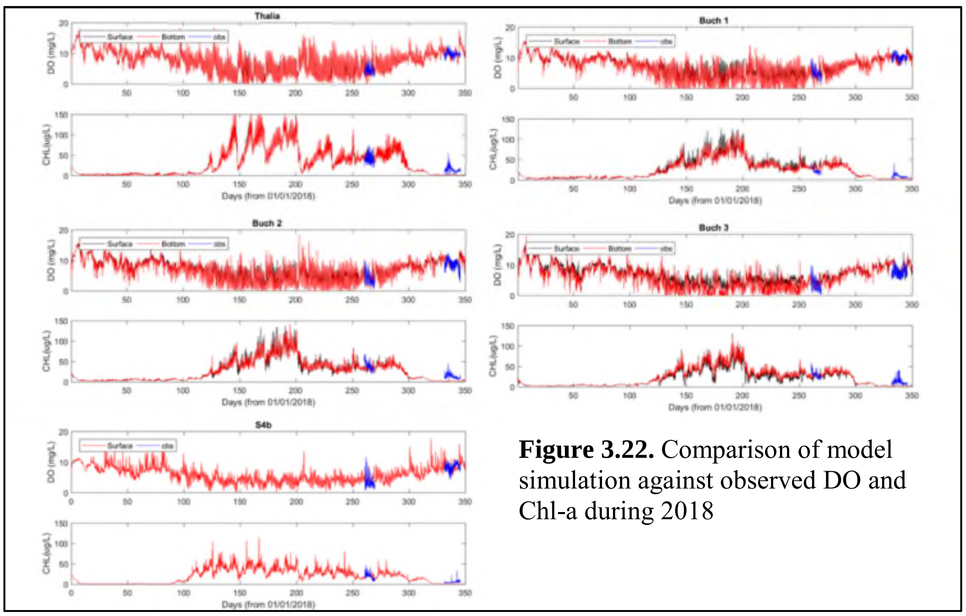


Figure 3.22. Comparison of model simulation against observed DO and Chl-a during 2018

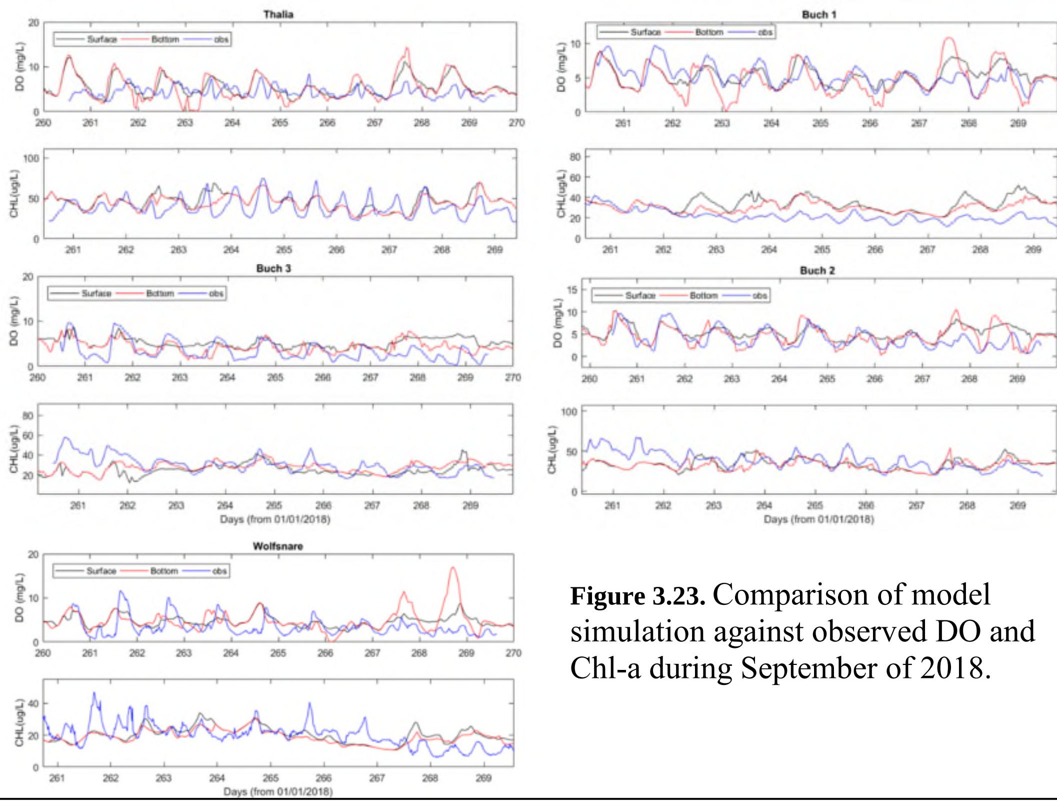


Figure 3.23. Comparison of model simulation against observed DO and Chl-a during September of 2018.

Changes in dynamics and transport conditions due to local channel geometry modifications

Buchanan Creek was deepened and heavily modified from a much smaller natural channel and unchannelized tidal marsh during the period of the development of this urban community. Over the years, sedimentation has occurred due to both watershed runoff of sediments and transport of sediments from outside in response to tides. To possibly improve the current condition, channel deepening has been suggested as an option. However, as water depth increases, the volume of the waterbody increases as well. If the tidal range does not simultaneously increase, the flushing capability can decrease because the overall flushing capacity is the ratio of the tidal prism plus freshwater discharge relative to the waterbody volume. When high freshwater discharge occurs, the presently very shallow creek can be washed out very rapidly. When freshwater discharge is low, flushing is controlled by the strength of the tide, and the pollutants and nutrients discharged outside of Buchanan Creek can be transported into the creek by tidal currents. Several model experiments have been conducted for assessing channel deepening and its impacts on hydrodynamics. Because Buchanan Creek is very shallow, the water column is generally well mixed for most of the time. The change in transport processes in response to deepening is a major concern as it can affect the retention and transport of pollutants out of the creek. The transport processes can be quantified by tidal flushing of the creek and the movement of water in and out of the creek. The particle tracking method is used for this assessment, which provides a way to visually examine the movement of the water. The water age is a good timescale to show the time required to transport dissolved pollutants out of the estuary and tidal creek (Shen and Lin, 2006). A change of water age is indicative of change of transport processes. Two scenarios were evaluated:

Scenario I: Deepening channel by 2 ft in the region between headwater of Buchanan Creek (near Royal Palm Arch) to 400 m downstream of the creek; and

Scenario II: Deepening channel by 2 ft in the region between headwater of Buchanan Creek (near Royal Palm Arch) to 740 m downstream of the creek.

Water Movement (particle tracking)

To help understand how water and pollutants are transported in this complex system, we conducted model simulations using the particle tracking module of the SCHISM model. Water parcel movement can be represented by particles. Particles were input continually for 30 days (May 31, 2009 to June 29, 2009) at the headwaters of Buchanan Creek near Royal Palm Arch, at Buchanan Creek near Little Neck Rd., and in the upstream portion of Thalia Creek, respectively. The input rate of particles is proportional to river discharge. In total, 3001 particles are released into the creek, and the first particle enters the creek at 4:30 am May 31, 2009 (150 days after Jan. 1, 2009).

The visual movement of water can be observed through these particle movements. For a better illustration, particles are divided into three groups in terms of release time. Group 1-3 correspond to the first, second, and last 10 days of the 30-day release period, respectively. The model results provide information on the material transport processes in the Thalia and Buchanan system.

Figure 3.24 shows the water movement that is discharged at the headwater of Buchanan Creek near Royal Palm Arch starting from June 1. It takes about one day for the first water particles to move to the downstream end when freshwater discharge is large at the beginning of the simulation. But some water will be moved back into the creek due to the tide. After 6 days, it can be seen that a large fraction of the water has moved downstream with some entering the second branch of Buchanan Creek. On June 12, water particles are observed to be transported into the upstream portion of Thalia Creek. The distance for material transport depends on the tide and freshwater discharge. On June 18, most of water moves to Thalia Creek, but less to the branch of the Buchanan. On June 23, more water from the headwaters of Buchanan has moved into upper Thalia Creek and Western Branch and to many small creeks. It can be seen that the water discharged from Buchanan Creek can be transported to many small creeks downstream.

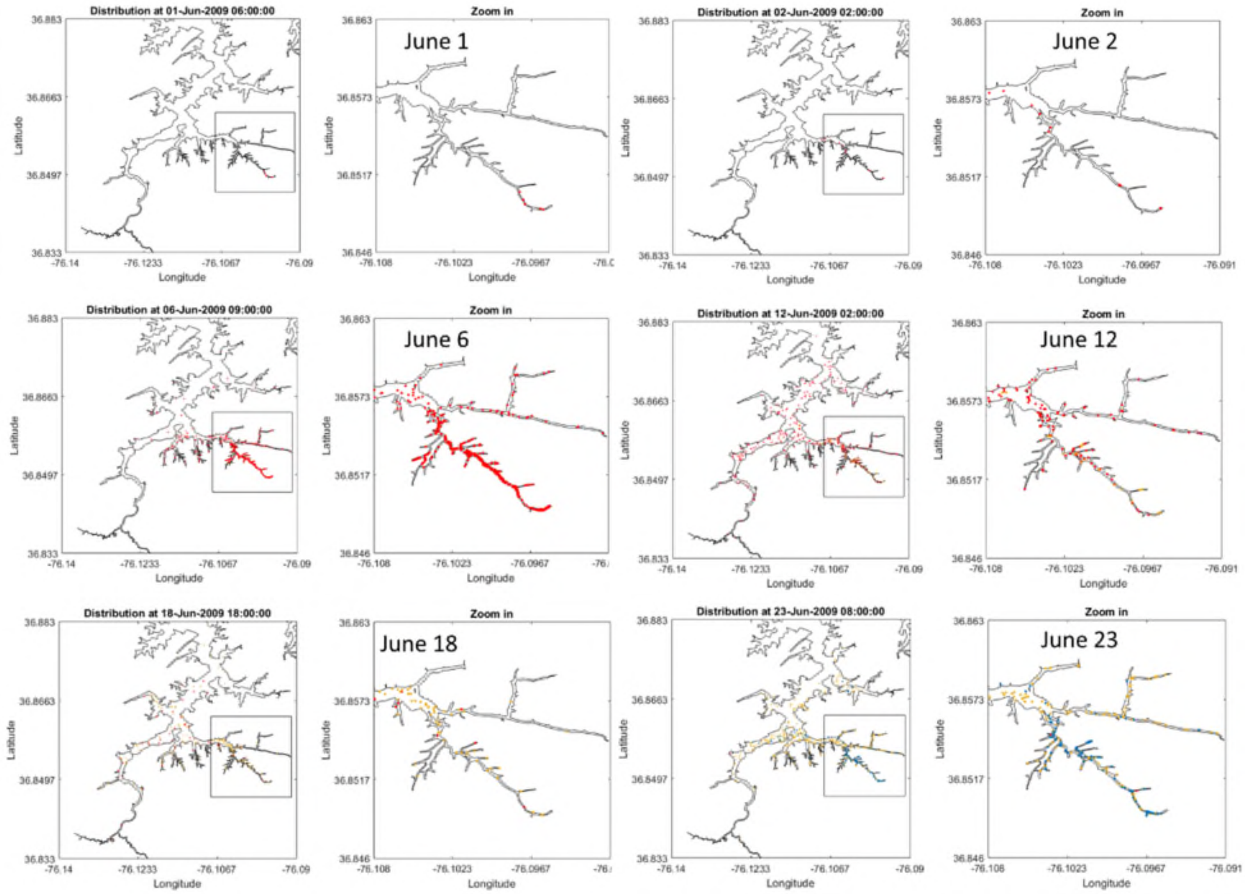


Figure 3.24. Distribution of freshwater discharged from Buchanan Creek near Royal Palm Arch (red, yellow, and blue dots are particles representing water parcel, discharged in 1-10, 11-20, 20-30 days, respectively).

Figure 3.25 shows discharge of freshwater from the second branch of Buchanan Creek near Little Neck Rd. After 6 days, water moves to the downstream end of this branch. On June 12, a notable portion of the water moves to Buchanan Creek near Royal Palm Arch and to the upstream section of Thalia Creek. On day 23, water has been transported to many small downstream small creeks due to the tide.

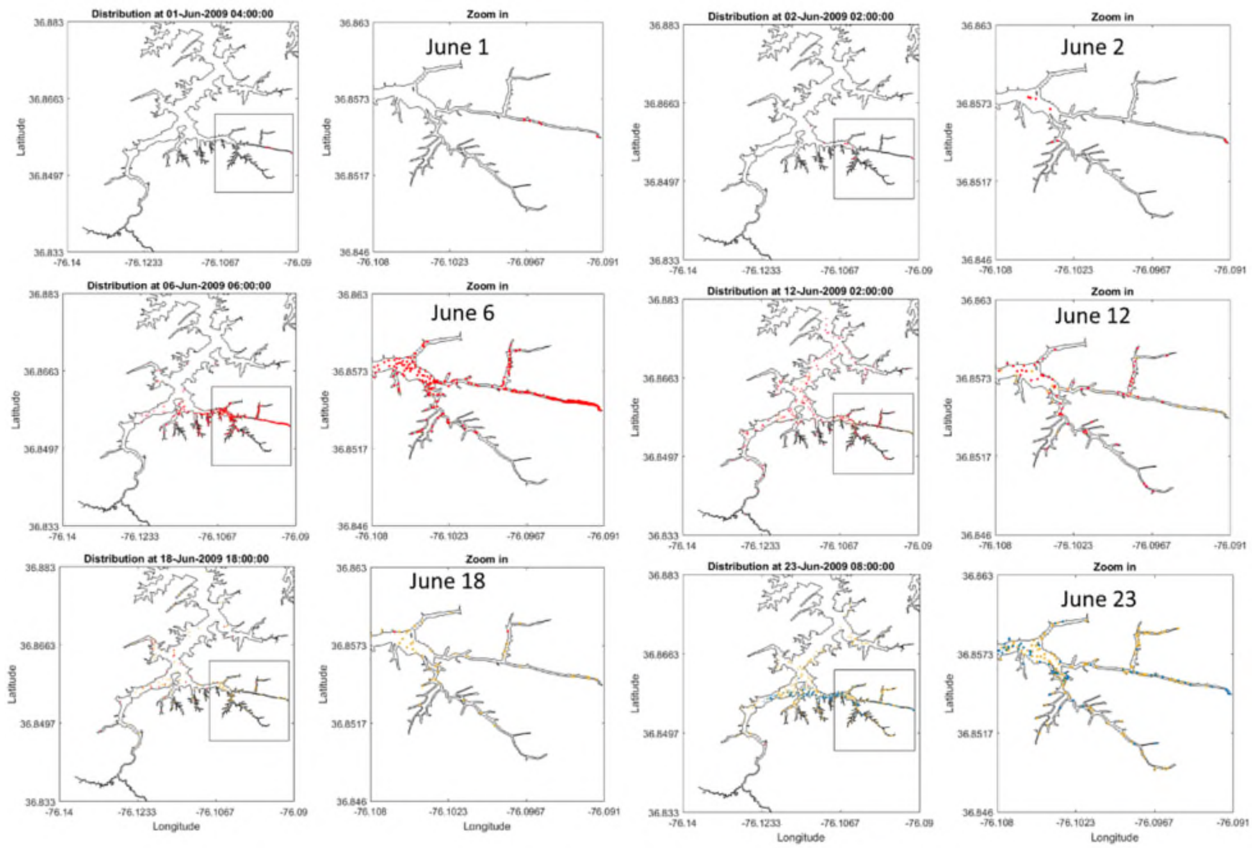


Figure 3.25. Distribution of freshwater discharged from Buchanan Creek near Little Neck Rd (red, yellow, and blue dots are particles representing water parcel, discharged in 1-10, 11-20, 20-30 days, respectively).

Figure 3.26 shows the transport of freshwater discharged from the upstream section of Thalia Creek. The water moves downstream in about 5 days. In 12 to 18 days, a portion of the water can be transported to Buchanan Creek and small creeks in the downstream Thalia Creek. As transport depends complexly on fresh water flow and tidal currents, movement of multiple water particles generally do not follow the same path, even in the creeks located very close to each other.

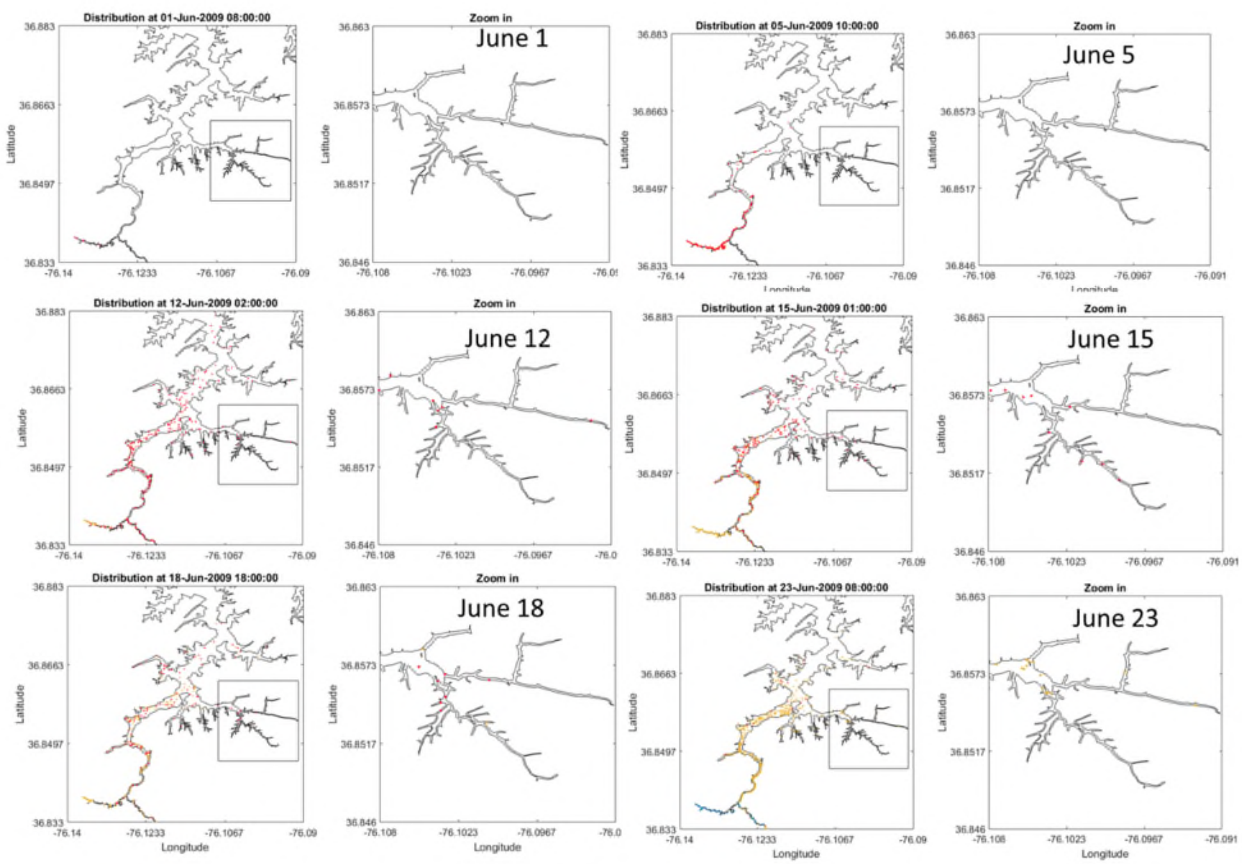


Figure 3.26. Distribution of freshwater discharged from upstream portion of Thalia Creek (red, yellow, and blue dots are particles representing water parcel, discharged in 1-10, 11-20, 20-30 days, respectively).

These experiments indicate that, pollutants discharged from the upstream sections of small creeks, either from Buchanan Creek or the upstream in Thalia Creek, can be transported to the Thalia-Buchanan system and to many small embayments and creeks (either downstream or upstream) due to tidally induced transport.

Statistical analysis was specifically conducted for the study area in Buchanan Creek (Fig. 3.26). Some particles can be permanently transported out of the domain quickly, while other particles can stay much longer. As shown in Fig. 3.27, when new particles are released into the creek, they may meet the previously released particles, and some particles can remain for up to about 10 days even in this small study area.

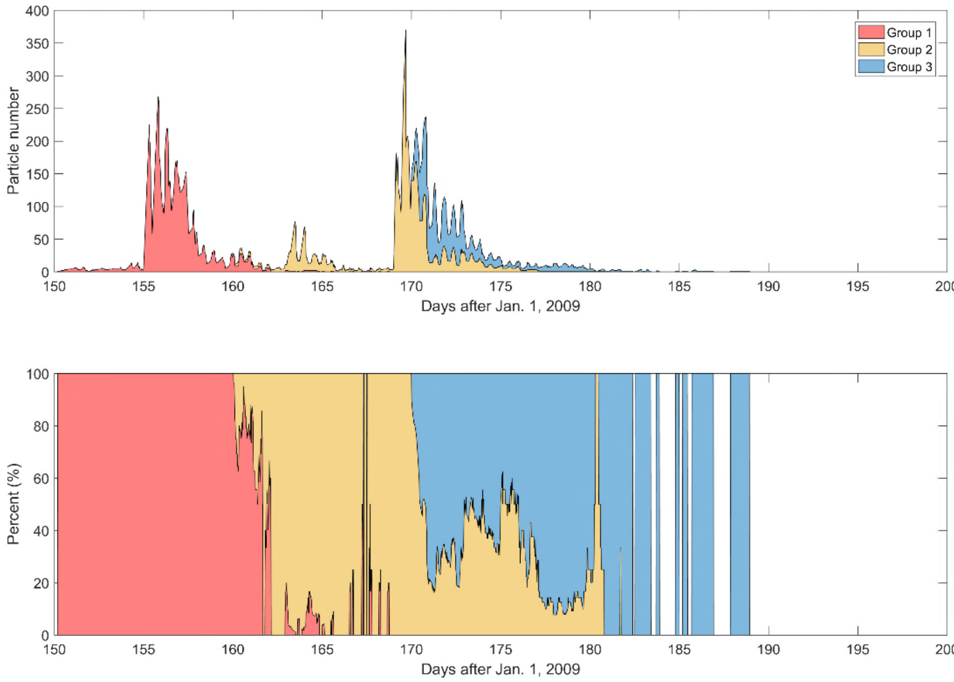


Figure 3.27. Particle numbers and percent of each group in the study area.

Water age

An alternative way to evaluate transport is to examine the transport time of freshwater or residence time (or water age). Water age can be used to measure the time required to transport freshwater and pollutants after they have been released from headwaters. A short water age indicates a high flushing capacity, while a long age indicates that a discharged pollutant will stay inside the domain for a longer time. The age is computed based on the continuous discharge at the headwater of Buchanan Creek near Royal Palm Arch for a simulation starting in March 2009. Because freshwater varies daily, the mean age for each day is examined. The change of water age due to channel deepening is also compared for scenarios I and II. Water ages are compared at five selected locations shown in Fig. 3.28.

Figure 3.28. Selected locations for water age comparison.

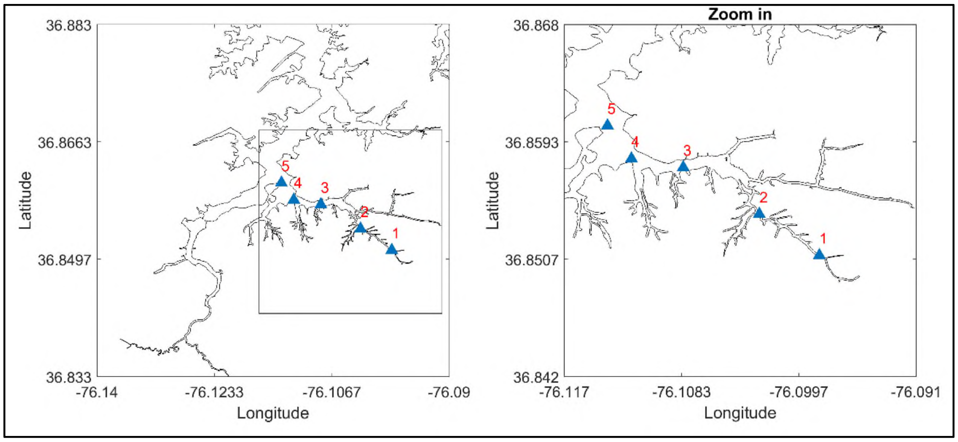


Figure 3.29 shows the water age at location 1, which shows the average time required to transport water from the discharge location (near Royal Palm Arch) out of this section of the creek. The water age varies with freshwater discharge. It ranges from less than 2 days to more than 25 days when discharge is low. The water age periodically decreases rapidly when freshwater discharge increases. Because of the tide, water will be transported back-and-forth in the upstream section. Flushing is sensitive to the freshwater discharge. The water age decreases very quickly in response to heavy rainfall induced discharge. Because the period of low flow is much longer than the high flow, it can cause sediment and particulate organic matter to settle to the bed and be recycled to water column for algae to growth. As water moves downstream along the creek (Fig. 3.30), increased tidal transport and freshwater discharge transport water out of the system more rapidly, resulting in less 'old water' (water discharged from headwater) remaining inside the creek. Thus, the average water age decreases at the downstream station, while 'old' water will stay upstream for a longer time due to less tidal flushing, resulting in a higher water age on average.

Figure 3.29. Change of water age at location 1 due to change of freshwater discharge

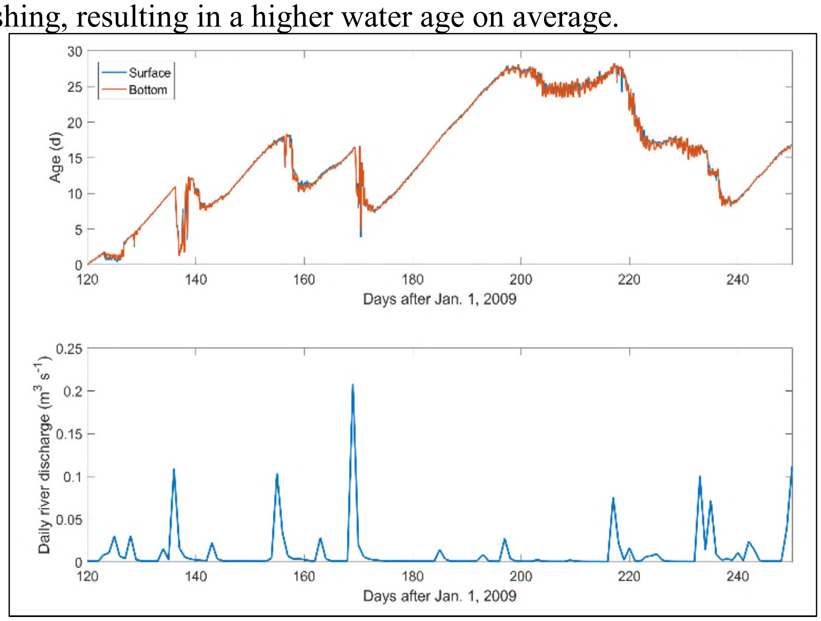
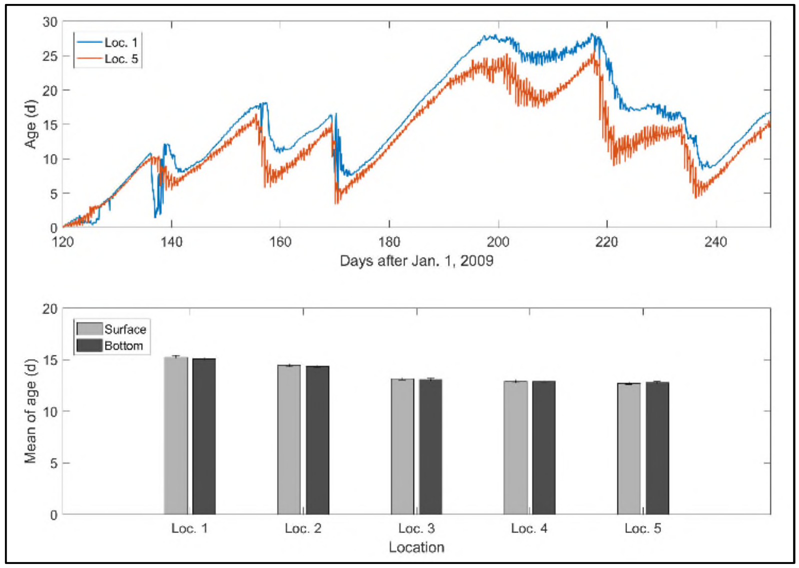


Figure 3.30. Change of water age at location 1 due to change of freshwater discharge

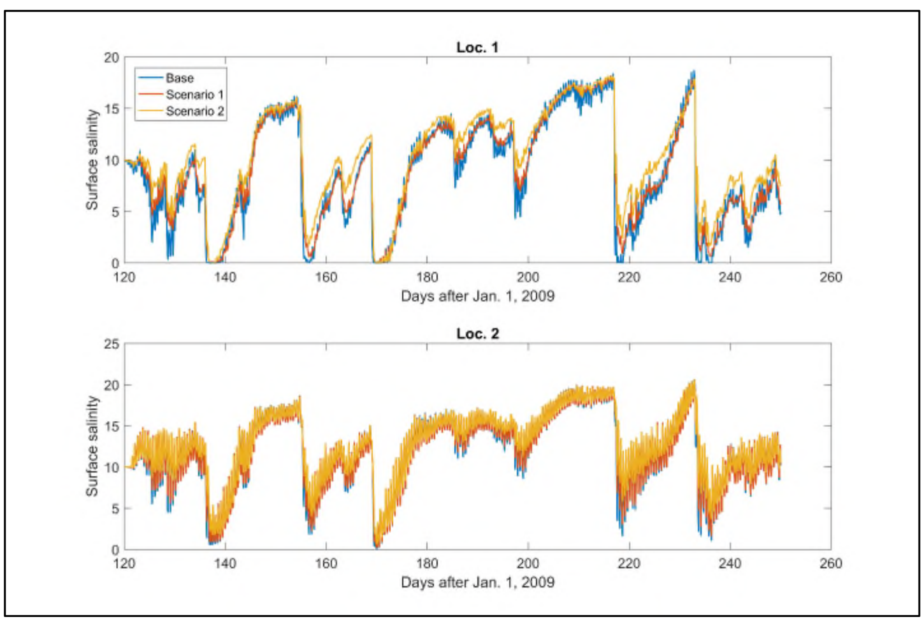


Impact of channel deepening on hydrodynamic conditions

The hydrodynamic conditions are affected by the interactions between physical forcings and geometry. Thus, changes in channel depth will cause changes in the hydrodynamic conditions.

As shown in Figs. 3.31 and 3.32, surface salinity at locations 1 and 2 increases significantly after dredging in both scenarios I and II, which indicates the deepened channel causes a stronger salt intrusion by the tide. This indicates the circulation also changes, which can be directly demonstrated by changes in the surface salinity (Fig. 3.32). Because the salinity intrusion results from interactions between the physical forcings and geometry, changes in the surface salinity after dredging are not linear with respect to the depth increase.

Figure 3.31. Comparison of time series of surface salinity for the dredging scenarios against baseline condition at Locations 1 (Upper Panel) and 2 (Lower Panel).



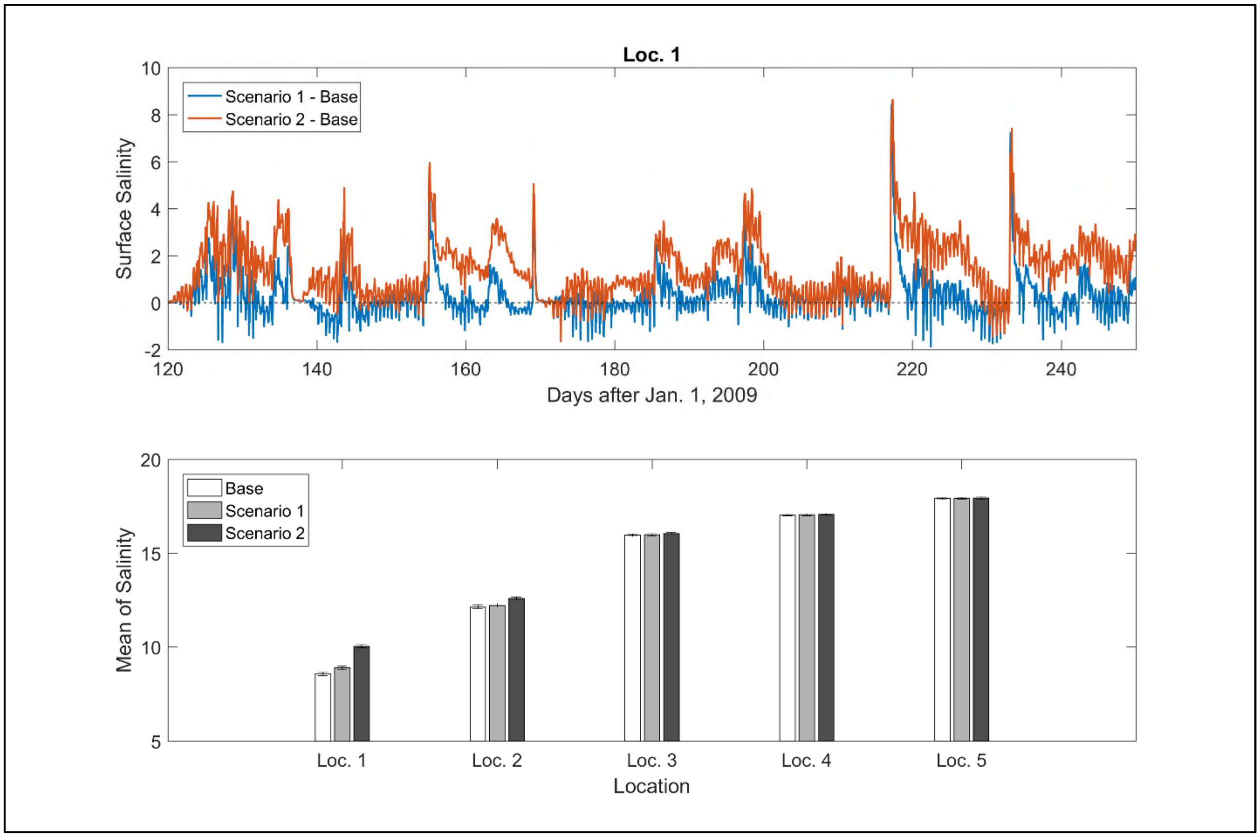


Figure 3.32. The difference in salinity at location 1 (Upper Panel) and the mean of salinity at five locations (Lower Panel) between two dredging scenarios and baseline condition, respectively. Note that the range of y-axis for the Lower Panel is set from 5-20 for clear demonstration.

The change in bathymetry will result in a change of velocity as well. Changes in the surface velocity can be either an increase or decrease, depending on the changes in circulation due to the tide. Since channel deepening increases the salt intrusion, it is expected that the velocity at the dredging area decreases during high flow periods. The statistics of daily freshwater discharge for the study period are shown in Fig. 3.33, and comparisons between the base scenario and dredging scenarios are conducted for the entire study period and also for daily discharge larger than 0.005 and 0.1 $m^3\ s^{-1}$, respectively (Fig. 3.34 and 3.35). During higher discharge periods, the velocity tends to be lower in the dredged segment relative to the baseline condition (Location 1 for scenario I, and locations 1 and 2 for scenario II).

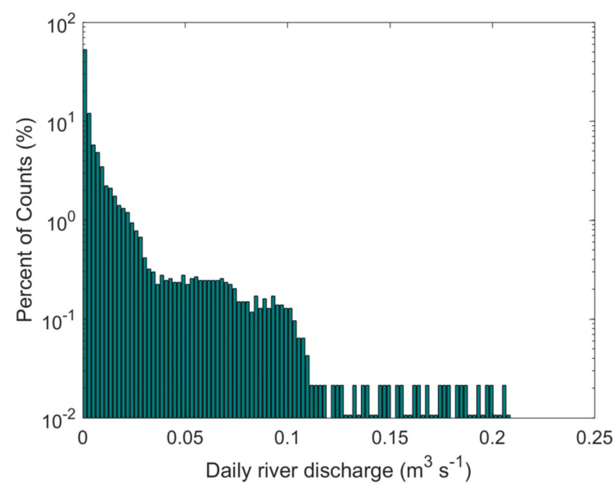


Figure 3.33. Histogram of the daily river discharge during the study period (May 1-Sep. 8, 2009).

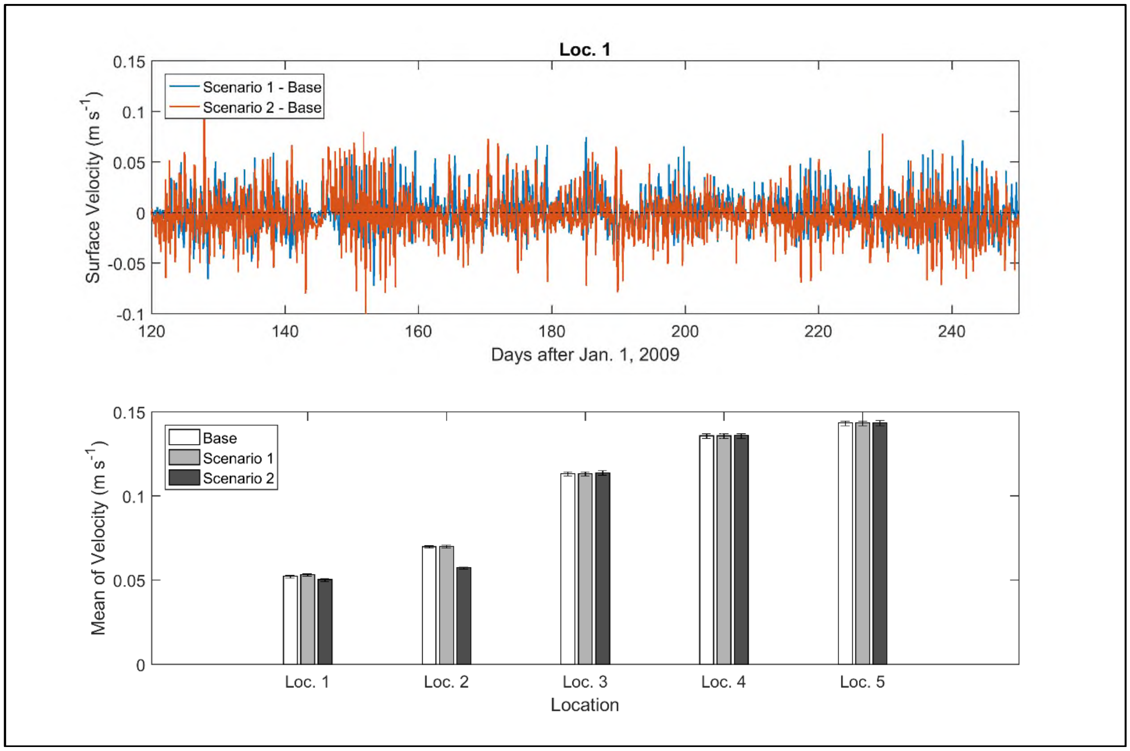


Figure 3.34. The difference in surface velocity at location 1 (Upper Panel) and the mean of surface velocity at five locations (Lower Panel) between two dredging scenarios and baseline condition, respectively.

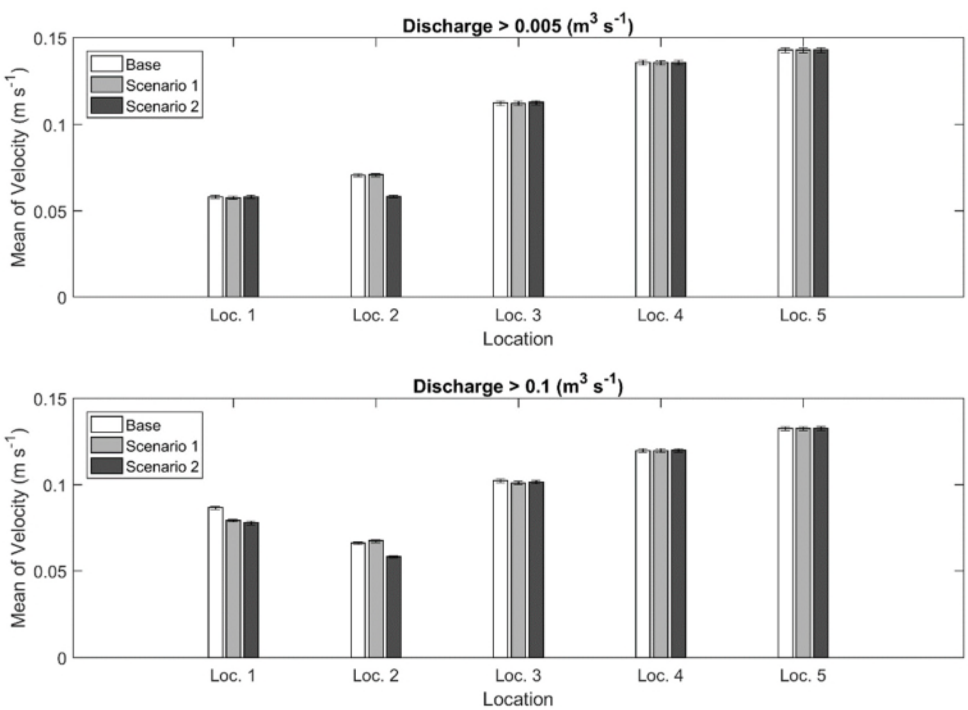


Figure 3.35. The mean of surface velocity at five locations between two dredging scenarios and baseline condition, respectively, for days with daily discharge larger than 0.005 $m^3 s^{-1}$ (Upper Panel) and 0.1 $m^3 s^{-1}$ (Lower Panel).

Changes in velocity, however, only reflect the instantaneous effect of channel deepening on hydrodynamic conditions, which are not sufficient to study how the accumulation and transport of pollutants will change after dredging. To examine the accumulative effect on hydrodynamic conditions and the resulting changes in the transport of pollutants, changes in water age are computed for the two scenarios (scenarios I and II).

The impact of channel deepening of 2 ft (0.6 m) for both two scenarios results in a minor increase of water age, suggesting that it only takes little longer time to move pollutants out of upstream segments of Buchanan Creek (Fig. 3.36 and 3.35). The average water age increase is less than one day at upstream region, and no observed change of water age is seen in the downstream region outside the dredged segment of the creek. However, during high flow periods, water age increases about 5 days, indicating pollutants will not be removed from the creek as rapidly after channel deepening.

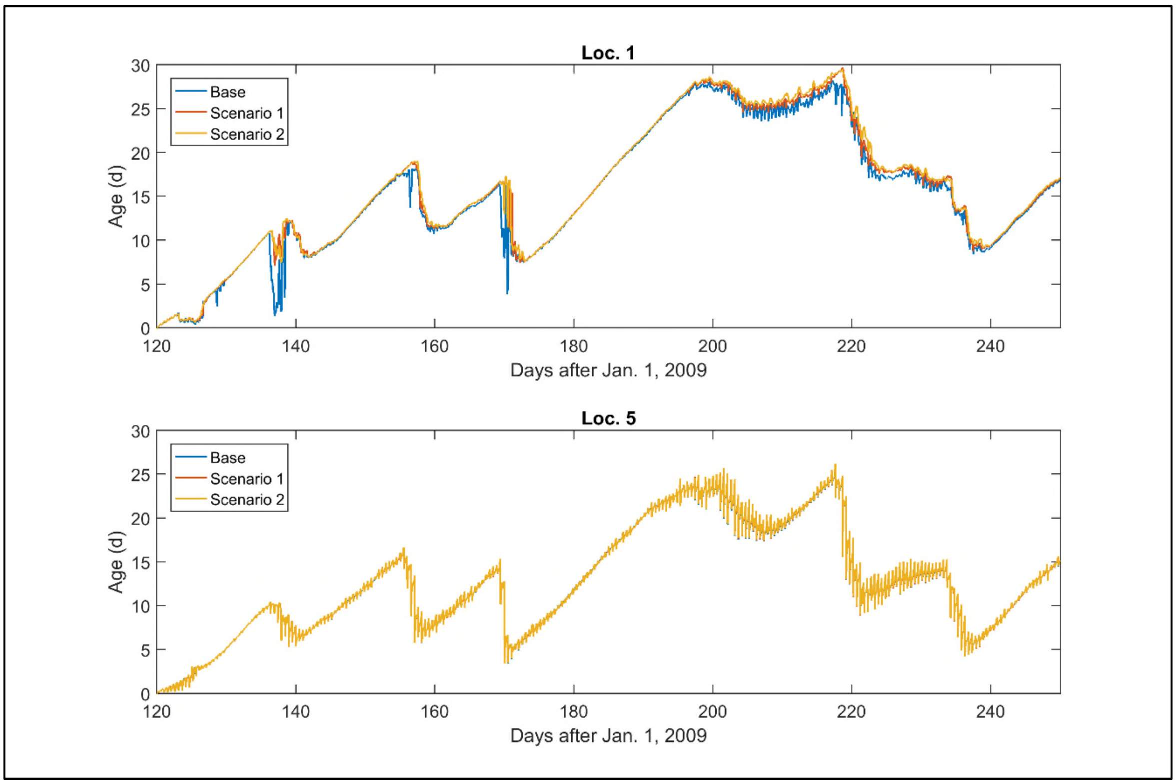


Figure 3.36. Comparison of time series of surface ages for the dredging scenarios against baseline condition at Locations 1 (Upper Panel) and 5 (Lower Panel).

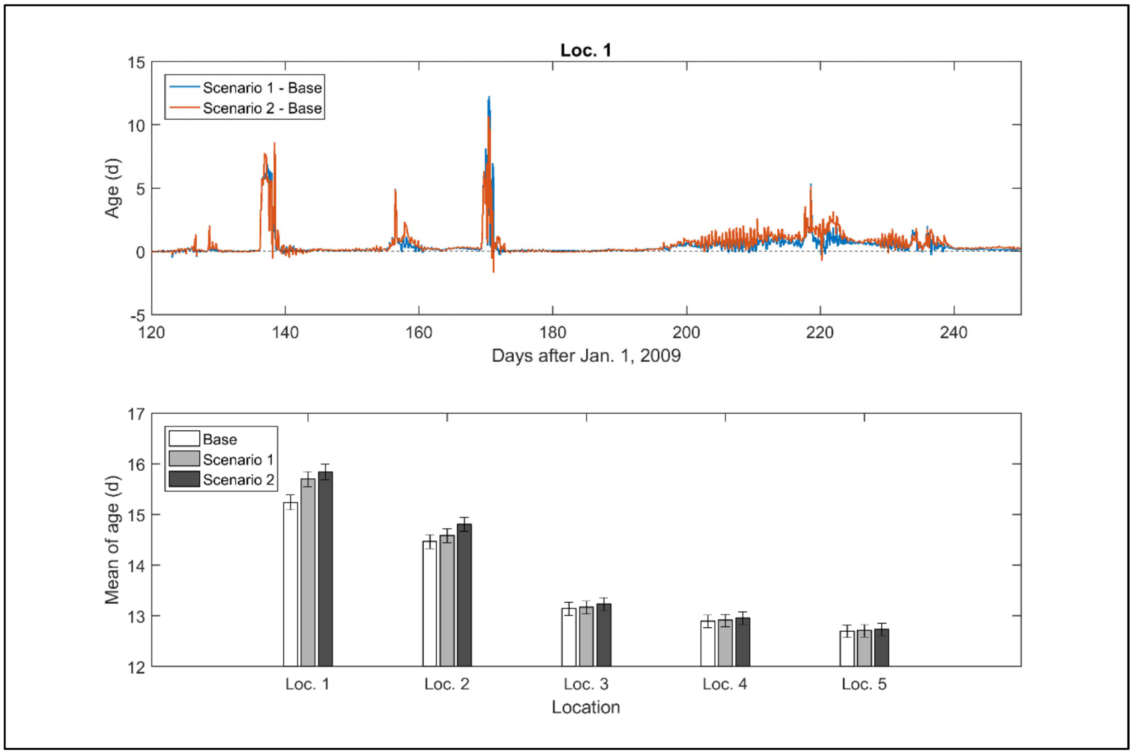


Figure 3.37. The difference in age (Upper Panel) and the mean ages at five locations (Lower Panel) between two dredging scenarios and baseline condition, respectively. Note that the range of y-axis for the Lower Panel is set from 12-17 days for clear demonstration.

While the water age represents the mean time fluvial substances spend traveling to the location, the one-time particle release experiments provide information on the accumulation of pollutants in the water that are not discharged from the watershed. Such experiments are conducted for the study area in Buchanan Creek (Fig. 3.38). A total of 1000 particles are released at once from the surface of study area. The tidal effect is evident, as particles move back and forth toward the mouth. A portion of the particles that have left the study area are returned on the following flood tide, which is reflected by changes in the remaining portion of particles inside the study area. After dredging, the remaining portion increases for both scenarios, indicating that pollutant movement becomes slow.

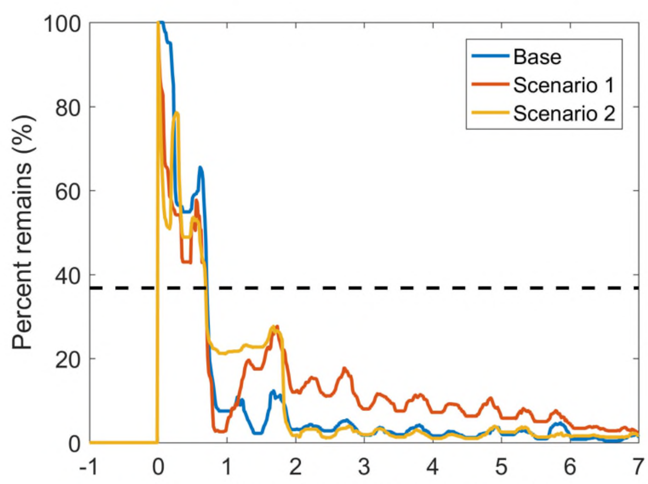


Figure 3.38. The time series of percent of remained particles in the study area after the one-time initial release, for the scenario with current bathymetry (Base) and the two dredging scenarios.

Decreased flushing capacity also suggests more sedimentation will occur after dredging. Based on a sediment core collected in the stream, the sediments in the surface layer are much coarser than the sediments 20 cm below the surface, which suggests that the Creek is presently under a near-equilibrium condition. If the top layer is removed by dredging, finer sediments will be deposited again due to the decreased velocity.

Impact on water quality due to channel deepening

The water quality model simulations with respect to changes of water depth were conducted to investigate the impact of dredging on water quality. The simulation results for 2018 water quality between two dredged scenarios and presents condition are shown in Figs. 3.39 and 3.40, respectively. For scenario I, the impact of dredging on both Chl-a and DO only occurred locally at Buchanan Creek Station 3. The daily averaged Chl-a concentration decreased slightly. DO had a very minor change. Either a DO increase or decrease can occur, and the DO differences vary with time. Downstream of the dredged segment, both Chl-a and DO have only minor changes. For an increase of channel deepening region (scenario II) in the downstream region, very minor changes can be seen in both segments at Stations Buch. 2 and Buch. 3. In general, Chl-a decreases slightly and DO increases slightly, but a decrease of DO can also be observed for some days. DO concentrations below 4 mg/L persisted for most of the summer. Changes in Chl-a and DO concentrations during this period were mainly due to changes in water volume and the associated change in dynamic conditions. As shown in both particle tracking and water age simulations, the dynamic change is very minor due to local channel deepening, which is consistent with the very small change in water quality condition. Overall, there are no obvious changes in terms of DO and Chl-a, and water quality condition is expected to remain very similar.

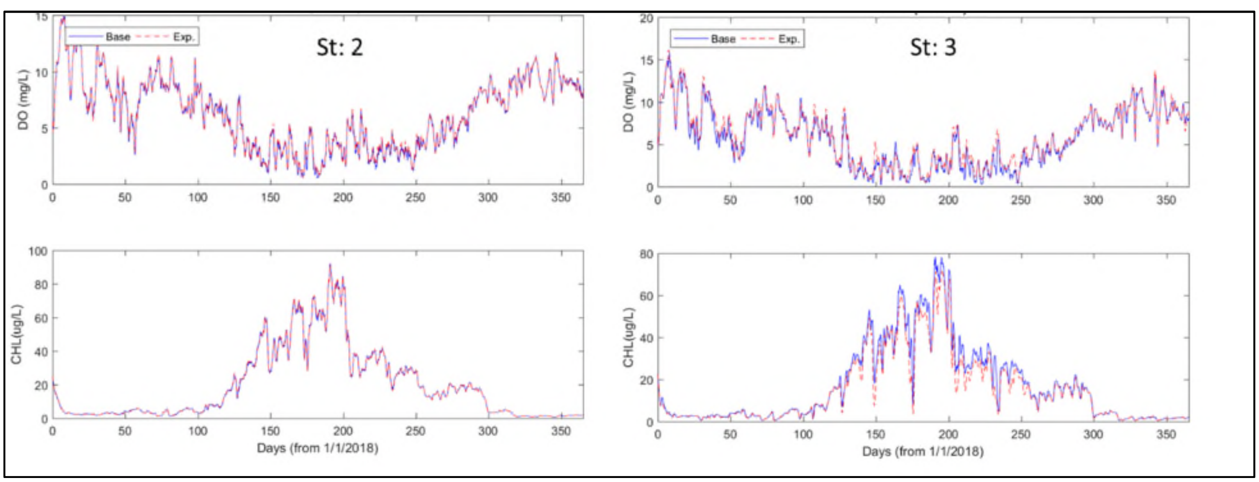


Figure 3.39. Comparison of DO and algae of channel deepening against the existing conditions at Stations 2 and 3 (scenario 1).

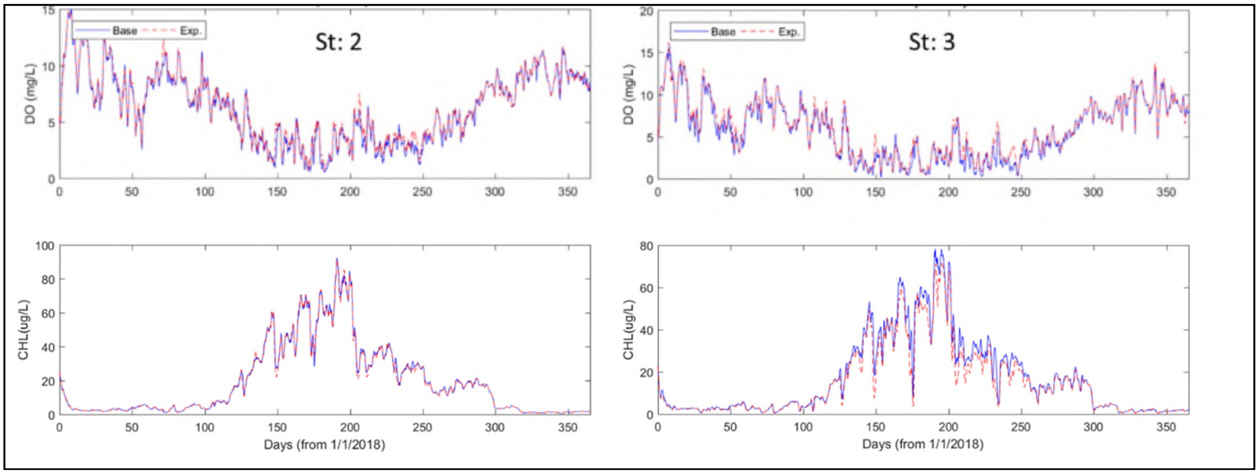


Figure 3.40. Comparison of DO and algae of channel deepening against the existing conditions at Stations 2 and 3 (scenario 2).

For small creeks, particulate organic matter can quickly settle to the bottom and be deposited, where benthic respiration will result in release of nutrients, followed by benthic uptake. As a result of the dredging, recently deposited organic matter will be removed. However, new organic matter will be quickly deposited once more to the bottom in this system (Sisson et al., 2010). To examine short- and long-term changes due to the removal of sediment organic matter by dredging process, a model simulation with initially clean sediment (containing no nutrients or OC) is conducted. The model results for bottom deposition of organics in two sediment layers (top layer and bottom layer) show that both organic carbon and nutrients will quickly increase in the bottom again due to low flushing. Flux of ammonium (NH4) (a limiting nutrient) is almost the same as the un-dredged condition after 100 days (Fig. 3.41). This suggests that removing sediment organic matter by dredging does not help change water quality condition for long, because renewed bottom deposition occurs annually and depends highly on runoff. The nutrients entering during spring runoff are likewise quickly utilized by primary producers, and then quickly recycled via remineralization. In fact, coring indicates that the sediments in the surficial layer are much coarser than the sediments 20 cm below the surface, and the organic content of the surficial layer may actually be lower than layers below. This also suggests that deposited nutrients are presently used up quickly due to quick remineralization.

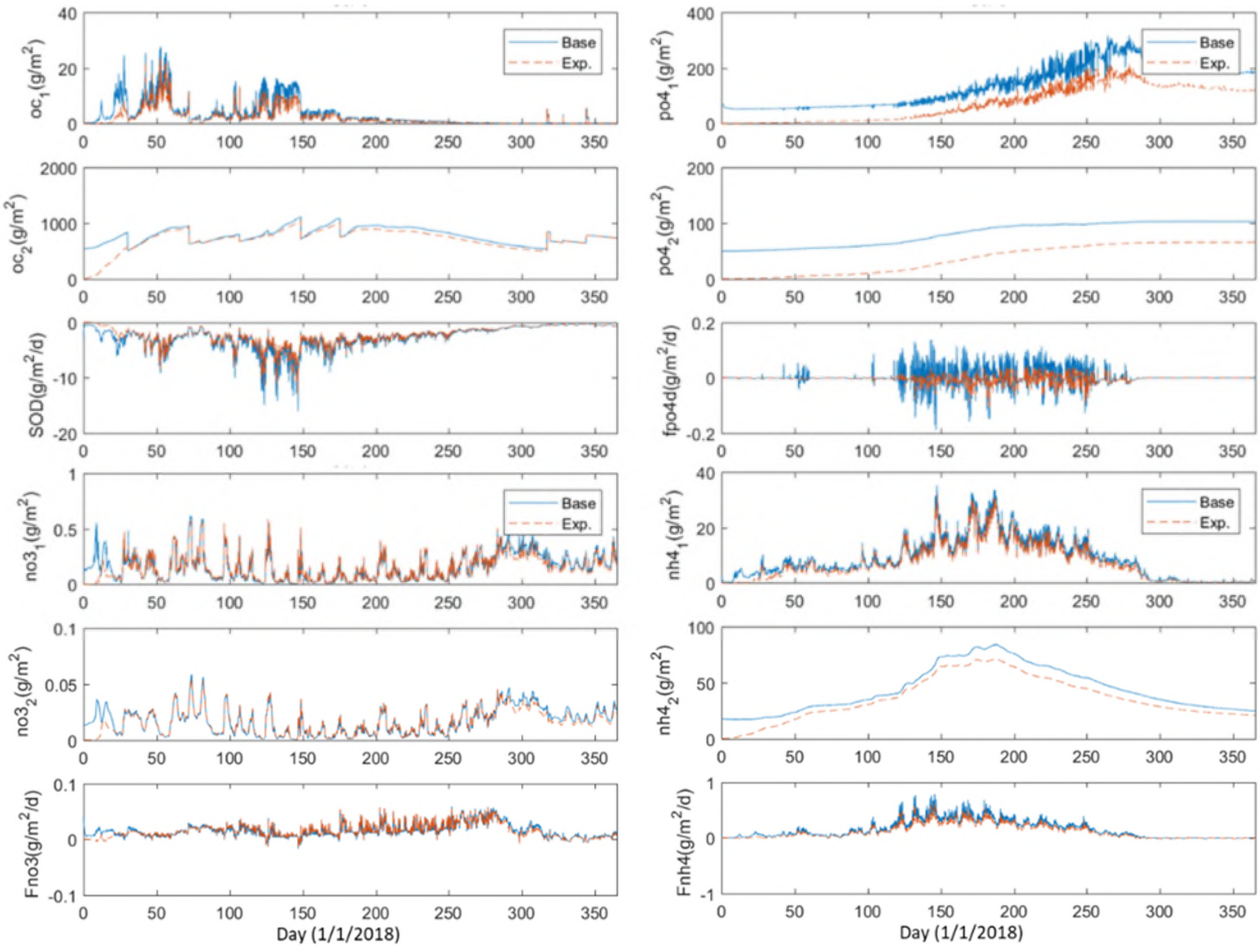


Figure 3.41. Comparison of bottom accumulation and sediment fluxes at Station Buch. 3 (subscripts 1 and denote sediment layer 1 and 2, respectively).

Conclusions

The numerical models of the Buchanan Creek watershed, hydrodynamics, and water quality have been developed for this work were calibrated using 2009 and 2018 observations in Buchanan Creek and Thalia Creek. The models were used to assess the impact of changes in channel geometry, specifically channel deepening, on hydrodynamics (flushing) and water quality conditions. Two scenarios were evaluated:

> Scenario I: Deepening the channel by 2 ft (0.6 m) in the region between headwater of Buchanan Creek (near Royal Palm Arch) to 400 m (440 yd) downstream of the creek; and
>
> Scenario II: Deepening channel by 2 ft (0.6 m) in the region between headwater of Buchanan Creek (near Royal Palm Arch) to 740 m (810 yd) downstream of the Creek.

We used particle tracking and water age as indicators of water movement to evaluate overall water movement and freshwater and pollutant transport in the creeks. Model experiments using both particle tracking and water age are conducted for the present hydrodynamic condition and for conditions after channel deepening, and results suggest that channel deepening will result in a reduction of transport of water and pollutants out of the creek due to decreased flushing capacity for the creek. Consequently, more pollutants and sediments will be deposited inside the channel.

Water quality model simulations under the present condition and under channel deepening conditions were also conducted. The model results show that there will be no obvious changes in DO and Chl-a concentrations after channel deepening. Removals of bottom organic matter in Buchanan Creek due to dredging will quickly be reversed due to annual runoff and a decrease in flushing capacity.

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Appendix A
History of VIMS Modeling and Lynnhaven Research

The Virginia Institute of Marine Science (VIMS) was requested by the Virginia Department of Environmental Quality's (DEQ) Tidewater Regional Office (TRO) to assess specific characteristics of Buchanan Creek, a waterbody in the Lynnhaven River watershed, regarding concerns of water quality. The Virginia General Assembly provided funds to assess the adequacy of Buchanan Creek's channel, shoreline deterioration along the headwaters, and contributions from the site of a former sewage treatment plant adjacent to Buchanan Creek (Birchwood Gardens). This study constitutes a continuation of issue-specific studies conducted by local and state agencies over the past few years. VIMS investigators included faculty and staff from the Departments of Physical Sciences and Aquatic Animal Health, the National Estuarine Research Reserve System (NERRS) Program, and the Office of Research and Advisory Services. Offered for context to this project, VIMS has a rich and distinguished research history in tidal hydrodynamic modeling and water quality assessment.

Research projects requiring hydrodynamic modeling, many incorporating water quality dynamics, have resulted in over 360 peer reviewed publications, Total Maximum Daily Loads (TMDLs), contract reports, and special scientific reports. The marine hydrodynamic models of which VIMS has experience and expertise include Environmental Fluid Dynamics Computer Code (EFDC, Hamrick 1992), Three-Dimensional Hydrodynamic-Eutrophication Model (HEM-3D, a submodel of EFDC; Park *et al*. 1995), Tidal Prim Water Quality Model (Kuo and Park. 1994), the Chesapeake Bay Program modeling suite, Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM)(Zhang et al 2016), Semi-implicit Eulerian- Lagrangian Finite Element (SELFE), Eulerian-Langrangian Circulation (ELCIRC), Hydrologic Simulation Program FORTRAN (HSPF), Loading Simulation Program C++ (LSPC), Storm Water Management Model (SWMM), Regional Ocean Modeling System (ROMS), and other smaller scale models. VIMS has created unique models to serve specific issues (such as the MARINA model used by the Virginia Department of Health's Division of Shellfish Sanitation), and open source models have been modified to address specific geophysical situations.

EFDC and HEM-3D were developed by VIMS faculty. Since their initial development each have been refined and increased in accuracy of simulation; and have been used in countless projects worldwide. It has been used for all Virginal coastal embayment TMDLs and various of water quality issues for Virginal tributaries. The EFDC model provides real-time simulations of density; topographically-induced circulation; tidal flows; wind driven flows; and spatial distribution of salinity, temperature, and sediment concentration. Further EFDC model capabilities include advective and diffusive physical transport processes, intertidal movement, friction resistance from marsh vegetation, hydraulic control structures (structures occupying the water column such as pilings), and Lagrangian particle tracking. Simulations of passive particle transport and non-conservative water quality parameters have high accuracy.

HEM-3D is a 21-state variable water quality model integrated with EFDC, and incorporates a sediment process model also developed by VIMS. Spatial and temporal distribution are simulated for water quality parameters including but not limited to fecal coliform bacteria; dissolved oxygen;

floating and attached algae; and various components of carbon, nitrogen, phosphorous, and silica cycles. The sediment process model component simulates remineralization of settled particulate organic matter; sediment oxygen demand; and fluxes of ammonium, nitrate, phosphate, and silica back to the water column. Direct coupling of water quality model and hydrodynamic model enhances the accuracy of parameter prediction and also the ability to simulate long-term water quality changes in response to changes in nutrient loadings.

The LSPC model is a stand-alone, personal computer-based watershed modeling program developed initially by EPA (Shen et al., 2005) and modified at VIMS for Virginal watersheds. LSPC includes algorithms for simulating hydrology, sediment, and general water quality on land, as well as a simplified stream transport model.

Water quality issues specific to the Lynnhaven River watershed constitute a significant portion of VIMS' historical research efforts. VIMS' involvement with technical water quality issues within the Lynnhaven River began 42 years ago with a similar study of Buchanan Creek (Ho *et al.* 1977a). Since that time VIMS has conducted at least 14 additional efforts to assess and address the aquatic conditions within the Lynnhaven watershed. These past studies have relevance today to the issues surrounding Buchanan Creek and adjacent waterways, and also demonstrate the level of knowledge within VIMS of the focus of this latest study. A summary of our historical efforts follows; however, it should be understood that the level of expertise available at VIMS specific to watershed and waterway health, water quality, and hydrodynamic modeling began shortly after the Virginia General Assembly established the Virginia Fisheries Laboratory (the precursor agency to VIMS) in 1940. The very early studies on the Lynnhaven River presented below were but part of a larger VIMS initiative around that same time (the *Hydrography and Hydrodynamics of Virginia Estuaries*) for the development and evolution of hydrodynamic water quality modeling. Modeling and model development by VIMS also continued throughout Virginia's portion of Chesapeake Bay beyond this particular program, and applications to the effects to estuarine waters from sewage outfalls were the focus of many of these early modeling and assessment efforts, including Buchanan Creek.

In the mid-1970s VIMS was approached by the Tidewater Regional Office of the State Water Control Board (SWCB) to investigate water quality concerns in Buchanan Creek, with emphasis on the potential contributions of pollutants resulting from the then-active Birchwood Gardens Sewage Treatment Plant located near the headwaters of Buchanan Creek. This study was dually funded by the SWCB and VIMS through the Cooperative State Agencies program. The study included water quality sampling and a dye study. The dye study was used to model local tidal exchanges and currents to determine the extent of pollutant distributions from the plant discharge. Model results were compared with the results of water quality sampling to assess the relative contribution of pollutants from the treatment plant and nonpoint sources. This study concluded that although plant discharges exceeded the nutrient criteria suggested by the Environmental Protection Agency (EPA) nonpoint source pollutants were also large (Ho *et al.* 1977a).

A parallel modeling effort by VIMS and funded by the EPA developed a mathematical tidal flushing model of the Lynnhaven Bay system (Ho *et al.* 1977b), using the data from an earlier study that conducted intensive and slack water sampling (Neilson 1976; also funded by the EPA). This effort produced a one-dimensional model able to reasonably simulate estuarine hydrology, and chemical and biological processes; however, the tidal averaging inherent to the developed model resulted in appreciable deviations between observed and modeled levels of fecal coliforms. Later model development corrected this anomaly.

Two years later VIMS was contracted to conduct two studies designed to increase the understanding of water quality in the Lynnhaven watershed (Kuo and Hyer 1979a,b; funded by the U.S. Army Corps of Engineers Norfolk District and a private consulting firm). The model used to address these issues was the VIMS tidal prism model, which simulates the mixing and dilution of freshwater inflow to estuaries. The impetus for these studies was proposed by the Norfolk District Corps to address flooding by increasing freshwater discharge in the Eastern Branch of the Lynnhaven, achieved by widening and deepening an existing headwater canal and dredging a new canal (London Bridge Creek). Slack water sampling and a dye release experiment were used to support the modeling that addressed the Norfolk District Corps' objective of assessing changes in water quality conditions post-dredging. A tidal prism model was able to demonstrate that the modifications proposed for the existing canal would have little impact on dissolved oxygen levels after large rain events even though slight increases in the amounts of nonpoint pollutants (including coliform bacteria and nitrogen) would be delivered to the larger Lynnhaven system, but the construction of the new canal would mitigate these increases and result in levels similar to existing conditions. Slight but ecologically benign increases in salinity were also expected during normal conditions.

Next, a comprehensive synthesis of Lynnhaven Bay water quality trends that was jointly funded by the Hampton Roads Water Quality Agency and EPA presented information on point and nonpoint pollution sources along with recommended control strategies and management practices (Neilson 1982). Neilson's synthesis was based in large part on stormwater impact field studies and refinement of the earlier water quality model of Lynnhaven Bay conducted by Kuo et al. (1982; funded by EPA), and a VIMS evaluation of urban area management practices for protection of tidal water quality (Anderson *et al*. 1982). Urban runoff data were collected and the refined model used these data to test the effectiveness of various management practices. Some example recommendations forwarded by Neilson (1982) to reduce nonpoint source runoff included application of erosion and sediment control ordinances to the rapidly urbanizing Lynnhaven watershed, fertilizer management, pervious concrete grid pavement options, and greater use of large onsite detention ponds such as Lake Wolfsnare.

The VIMS tidal prism water quality model developed and refined through those studies described above was subsequently used by the Virginia Water Control Board for point source waste load allocations and by local planning district commissions for assessment of management efforts to address nonpoint source pollution. Further water quality assessment and modeling specific to the Lynnhaven watershed by VIMS was discontinued until the mid-1990s when this tidal basin was used to demonstrate the need to incorporate small coastal basins into the larger EPA Chesapeake Bay three-dimensional water quality model, and refinement of the tidal prism model for these purposes (all funded by the DEQ Coastal Resources Management Program). Specifically, the tidal prism model was modified to include simulations of smaller secondary branches rather than only the main channel and primary branches of small coastal basins. The tidal prism model was also modified to incorporate sediment processes that provided predictive capability (Kuo and Park 1994). Field studies in the Lynnhaven River were subsequently conducted specifically to support the calibration of the modified tidal prism water quality model (Park *et al*. 1995a). This study used intensive water quality sampling and analyses protocols, DEQ monitoring data (1975-1994), and VIMS water quality data from previous studies. The calibration and verification of the modified tidal prism model proved successful (Park *et al.* 1995b); reproductions of algal stoichiometry (ratios of nitrogen-to-carbon and phosphorus-to-carbon in algae), sorption coefficient for phosphorus, and light extinction coefficients were simulated with minimal error. A noticeable error occurred in model results for organic matter in the extreme upriver portions of the Lynnhaven watershed, which could be attributed to the level of accuracy of nonpoint source load data.

The next focus on the Lynnhaven watershed by VIMS was an intensive field survey and high-resolution hydrodynamic and water quality modeling exercise. High nutrient and fecal coliform levels in Mill Dam Creek and Dey Cove were the underlying concerns that led the Norfolk District Corps and City of Virginia Beach to jointly fund VIMS to address these problems, but providing accurate results at the scale of concern required development of a model more sophisticated than the VIMS tidal prism model. The resultant model developed and applied to this project provided accurate simulation and predictions of 23 water quality state variables (Sisson *et al*. 2009).

Parallel with the previous study an additional yet similar model development was conducted for the entire Lynnhaven River to support basin-wide environmental restoration goals established by the Norfolk District Corps and City of Virginia Beach (both of whom also provided the funding). VIMS developed and applied the same model architecture as for Mill Dam Creek and Dey Cove, but on a much larger scale (Sisson *et al*. 2010a). Historical data and new field data (onsite tidal elevations and salinities; sediment flux measurements of dissolved oxygen, ammonia, nitrate-nitrite, and phosphate; chlorophyll A; turbidity; and organic matter), along with controlled laboratory-based flux measurements, were used to calibrate and validate the model. The model was successfully able to simulate sediment transport and all targeted water quality parameters. Model runs showed degraded water clarity and dissolved oxygen in headland areas, and all model output for selected environmental scenarios ultimately informed restoration planning, as described below.

The newly-developed, calibrated, and validated VIMS high-resolution three-dimensional hydrodynamic water quality model was applied to the first Lynnhaven sub-watershed targeted for water quality restoration—Thalia Creek and Thurston Branch (Sisson *et al*. 2010b). The VIMS model provided robust results and guidance on nutrient load reduction strategies that were used by the Norfolk District Corps and City of Virginia Beach (whom once again funded this and the partner project discussed below). The prevailing hypothesis for Thalia-Thurston was that the buildup of legacy nutrients in bottom sediments and their subsequent resuspension to the water column was a primary cause of local observed dissolved oxygen problems. The VIMS model (80-day simulations) showed this not to be the case, and that removal of sediments would not provide the desired improvements without additional controls of nonpoint source runoff. The levels of reduction shown necessary by the VIMS model to achieve restored water quality was an approximate 70% reduction of nitrogen and carbon, and 40% reduction of phosphorus based on the water quality open water DO standard of 5 mg/l. Results of model runs for fecal coliform exceedances for shellfish criteria showed a “land effect” borne from high ratios of shoreline to water volume in the upper tidal reaches. This led to VIMS' development of a fecal coliform model that showed swimming criteria could be achieved only under a 90-95% reduction, and criteria attainment for shellfish harvesting could occur only under a 99% reduction.

The next application of the VIMS model involved assessment of the beneficial effects of proposed oyster, scallop, and submerged aquatic vegetation (SAV) restoration on water column levels of suspended solids and chlorophyll (Sisson *et al*. 2010c). This required further enhancement of the VIMS model by adding "sink terms" based on resource locations and constituent removal rates. The enhanced VIMS model was able to show that various restoration scenarios resulted in reduction percentages of suspended solids from 2.5% - 74%, and chlorophyll reductions from 10% - 30%.

Further related research in the Lynnhaven River by VIMS to assess restoration plans involved the utility of oyster reefs as a tool for achieving Total Maximum Daily Load (TMDL) reductions (Sisson *et al*. 2011). This exhaustive study of oyster reef-water quality dynamics found that oysters can contribute to water quality improvements for nitrogen and suspended solids, but are ineffective for reductions of phosphorus levels. VIMS offered to modify the model to incorporate elements of the oyster reef dynamics demonstrated through this project, which could then be used for more broad scale simulations within the Lynnhaven watershed, but continuation was not funded.

A comprehensive shoreline management plan for the Lynnhaven River, funded by the Virginia Coastal Zone Management Program, was completed in 2013 (Hardaway *et al*. 2013). This study analyzed existing shoreline conditions, tidal marsh structure, fetch, and bathymetry to produce guidance on environmental best management practices to address erosion control for 174 miles of Lynnhaven shoreline.

It is also worth noting that our current involvement in a water quality study of Thalia Creek managed by the Hampton Roads Sanitation District provided added value to the understanding of Buchanan Creek within the context of those study objectives.

Because of our rich historical research and water quality modeling involvement VIMS possesses the most comprehensive technical and environmental understanding available for this complex watershed.

Several relevant independent studies by groups other than VIMS in Buchanan Creek conducted between 2015 and 2017 are listed below.

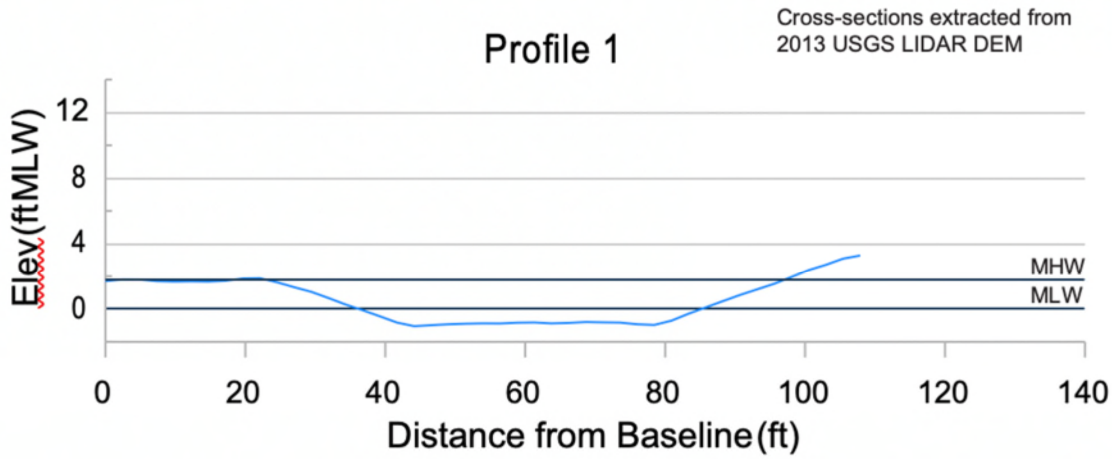
- August 2015 – Citizen collected water sample analyzed through the Virginia Aquarium Water Quality Lab Citizen Water Quality Monitoring Program. Fecal Indicator Bacteria (FIB) levels for 26 samples ranged from 2.0 to 10,950 colonies/100 ml. (September 12, 2016 inter-office memorandum from Mr. Leahy to Mr. Hansen, both City of Virginia Beach officials)

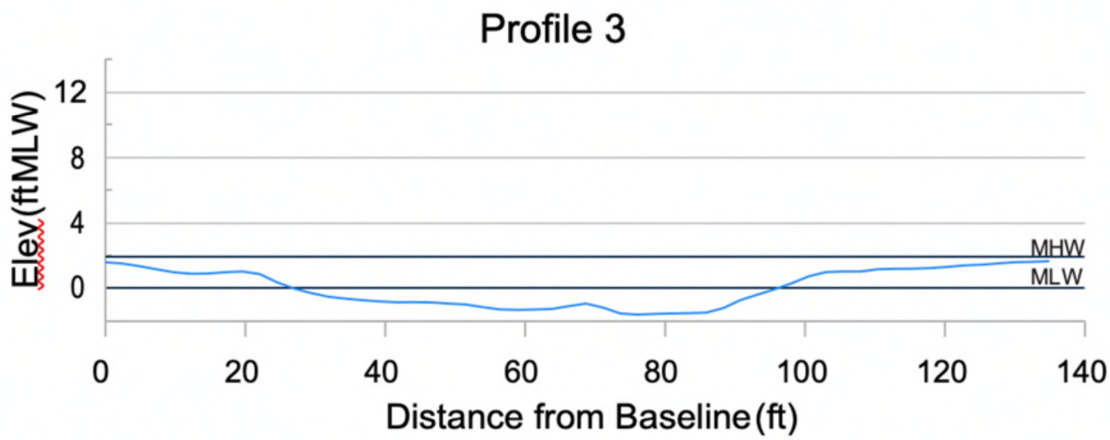
- July 2016 – Household Water Quality Program (designed for well water sampling and not open water). E. coli levels were 2,419 Most Probable Number (MPN)/100 ml.

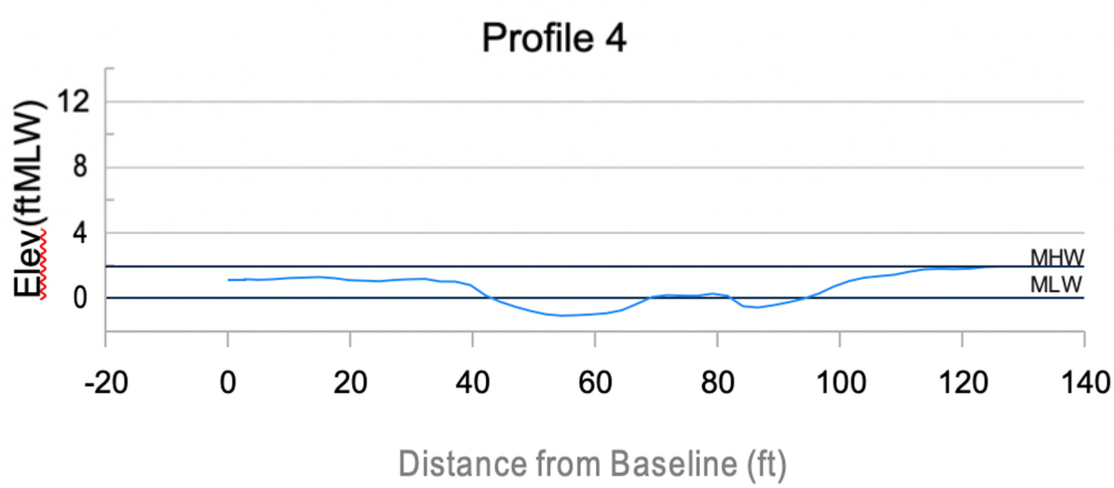
- August 2016 – DEQ sampling of Buchanan Creek from Birchwood Malibu Park (October 4, 2016 communique from Roger Everton (DEQ) to Ms. Impervento). Found low dissolved oxygen (DO) levels of 0.94 mg/l and 1.74 mg/l at two sampling stations, and elevated bacteria (Enterococcus levels of 300 Colony Forming Units (CFU)/100 ml and 230 CFU/100 ml) and nutrients (Total Kjeldahl Nitrogen (TKN) levels of 2.2 mg/l and 2.7 mg/l) and Total Phosphorus (TP) levels of 0.39 mg/l and 0.46 mg/l.).

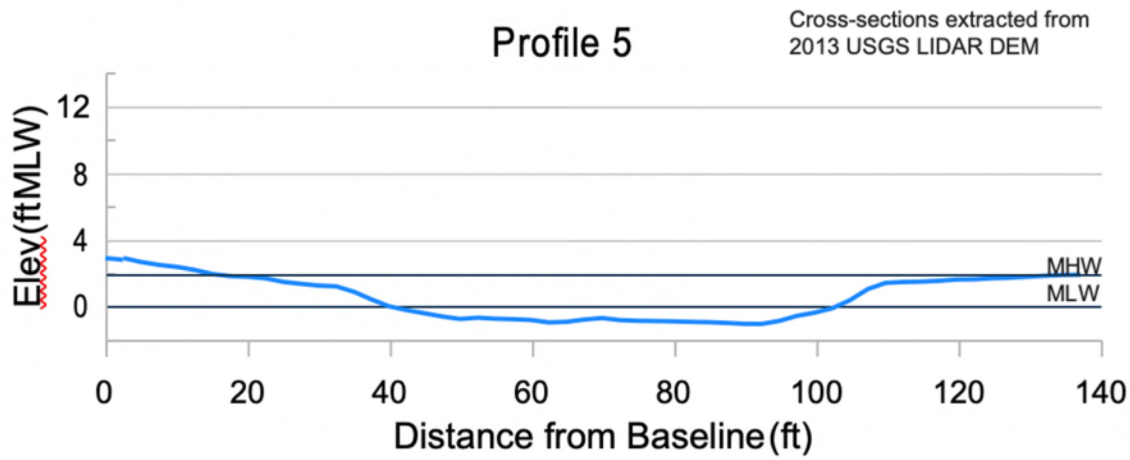
- January 2017 – Birchwood Malibu Park surface water runoff sampled for heavy metals, pesticides, volatile organics, and fecal bacteria (Feb 20, 2017 communique from Dr. Peter Pommerenk to City of Va Beach and DEQ officials). Found only trace levels of arsenic, cadmium, chromium, copper, lead, nickel, and zinc; also elevated but reasonably expected bacterial levels for estuarine urban headwaters (E. coli (318 CFU/100 ml) and Enterococcus (187 CFU/100 ml)).

Appendix B
Bathymetric Profile from Upper Buchannan Creek





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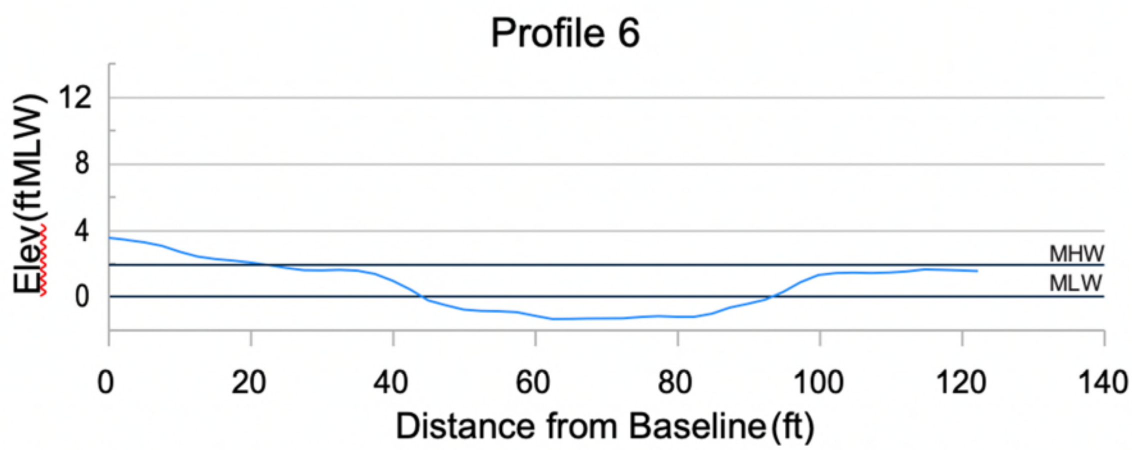
Distance from Baseline (ft)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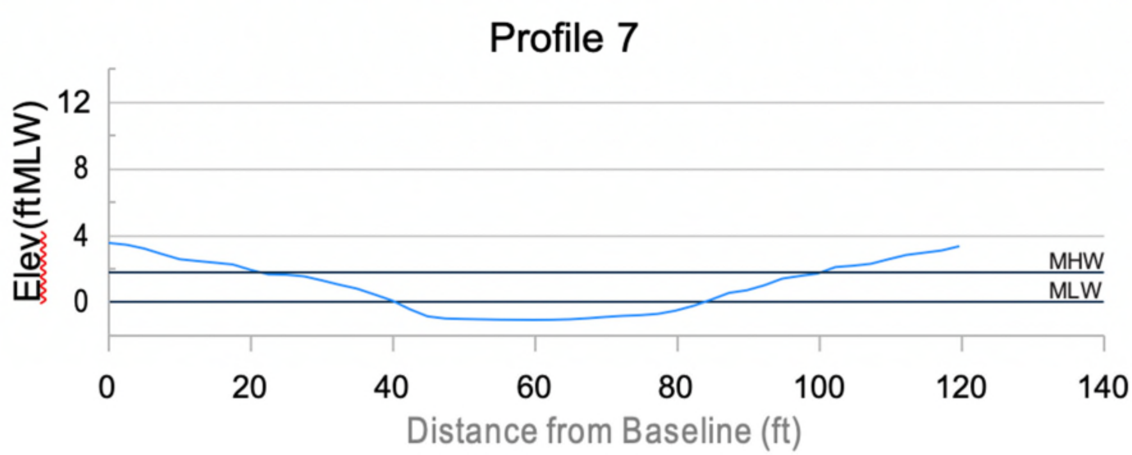
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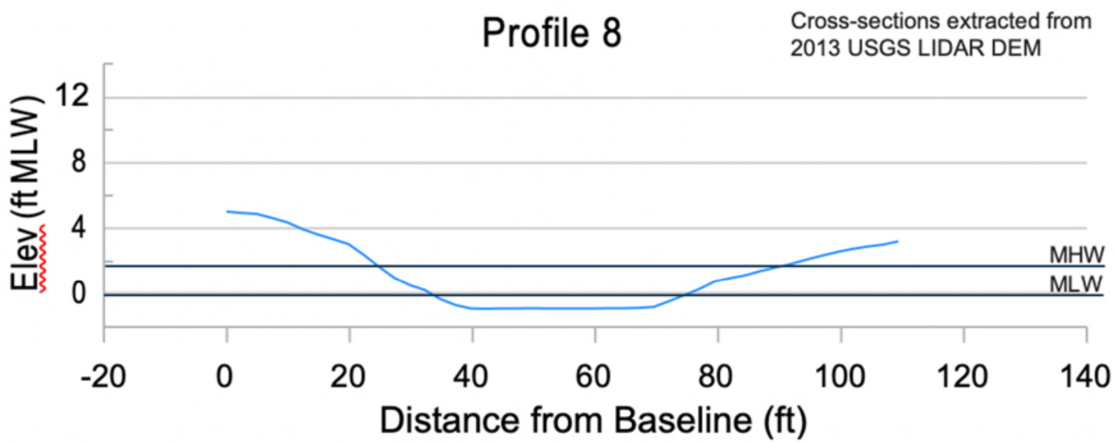
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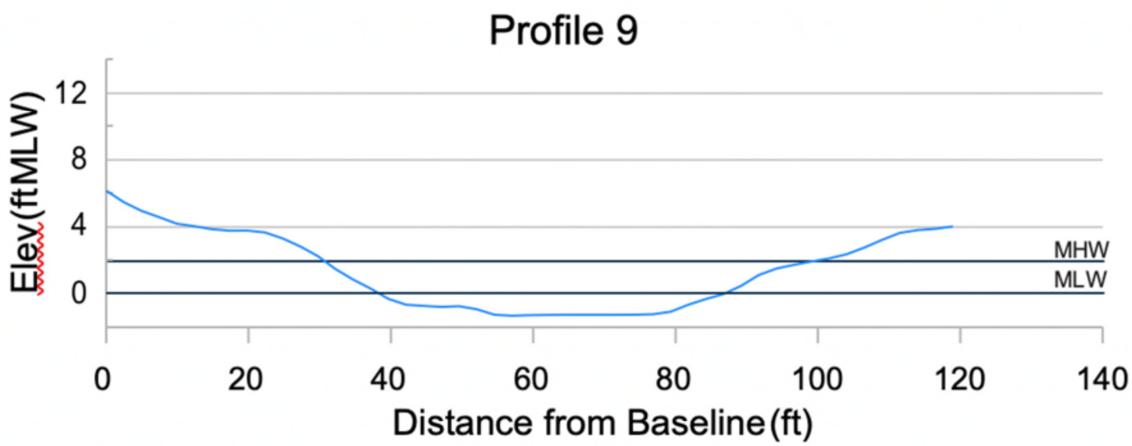
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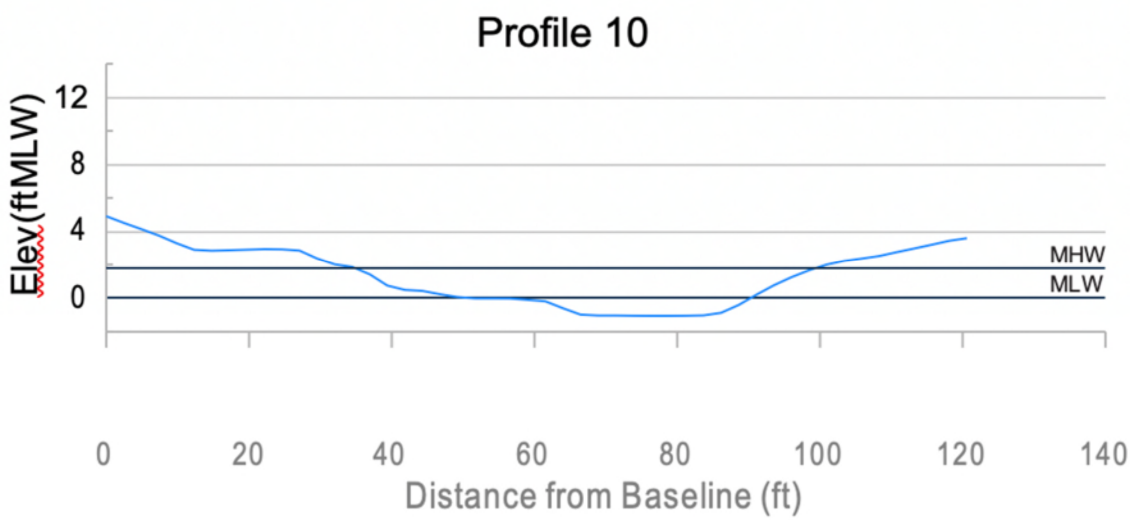
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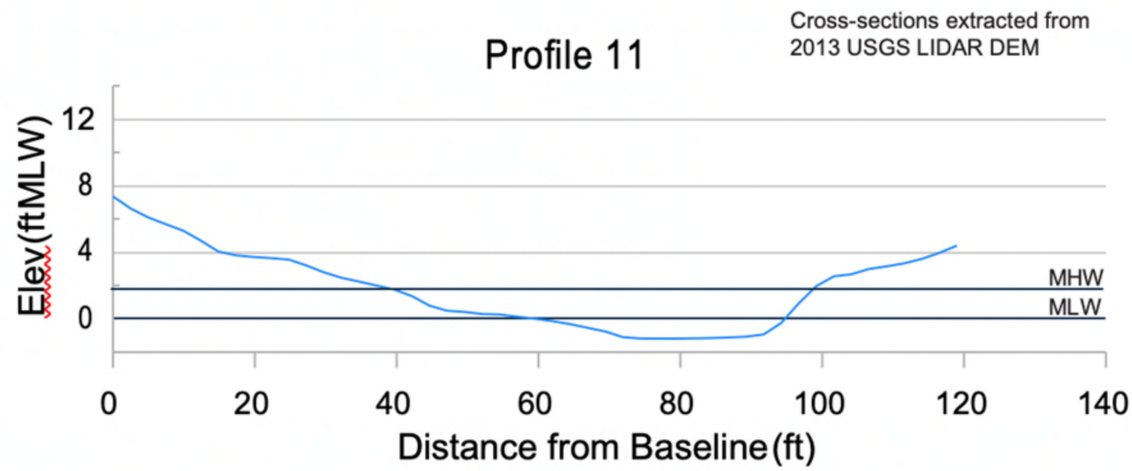
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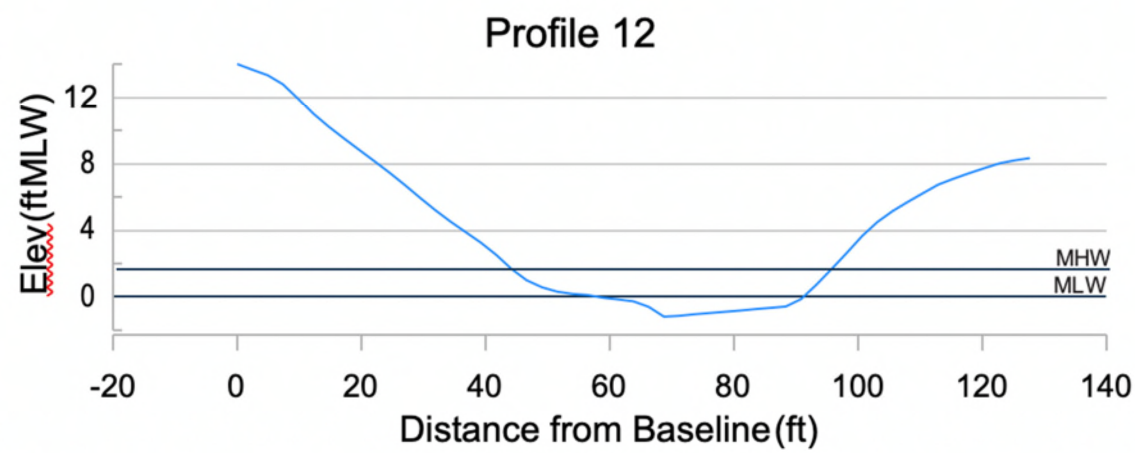
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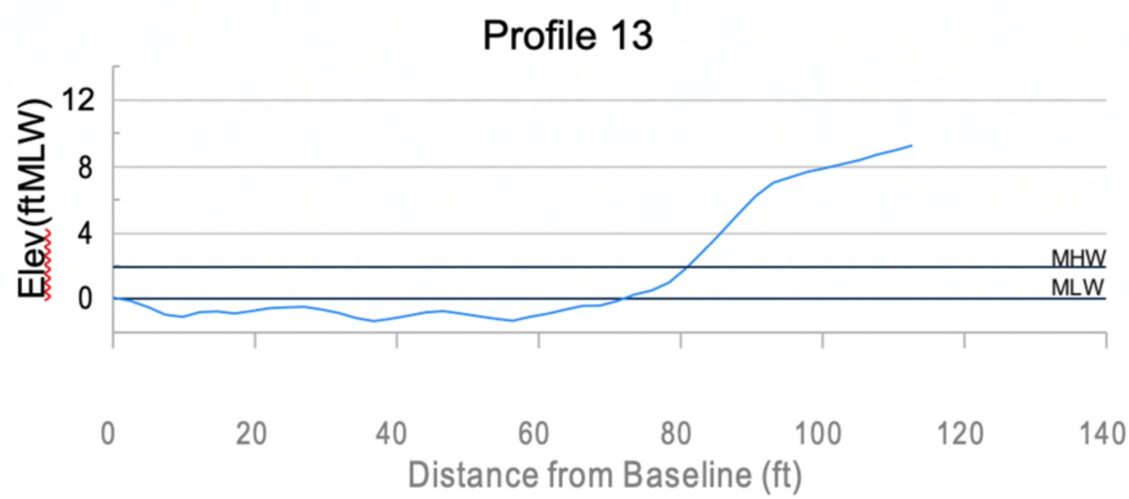
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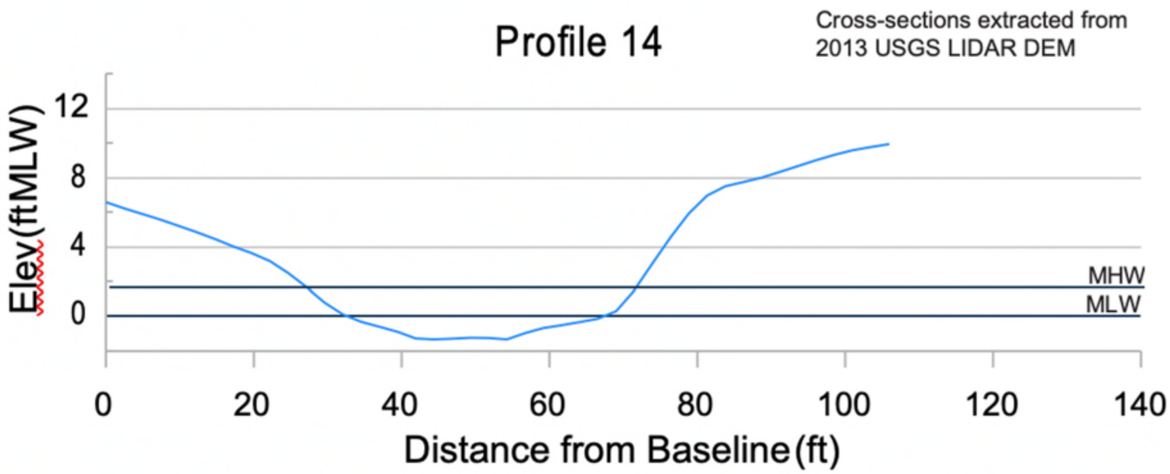
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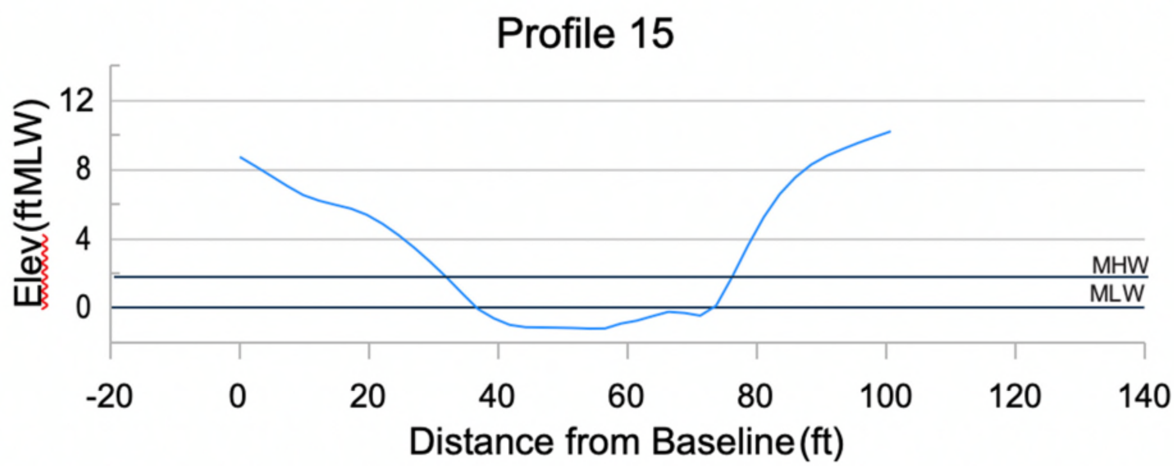
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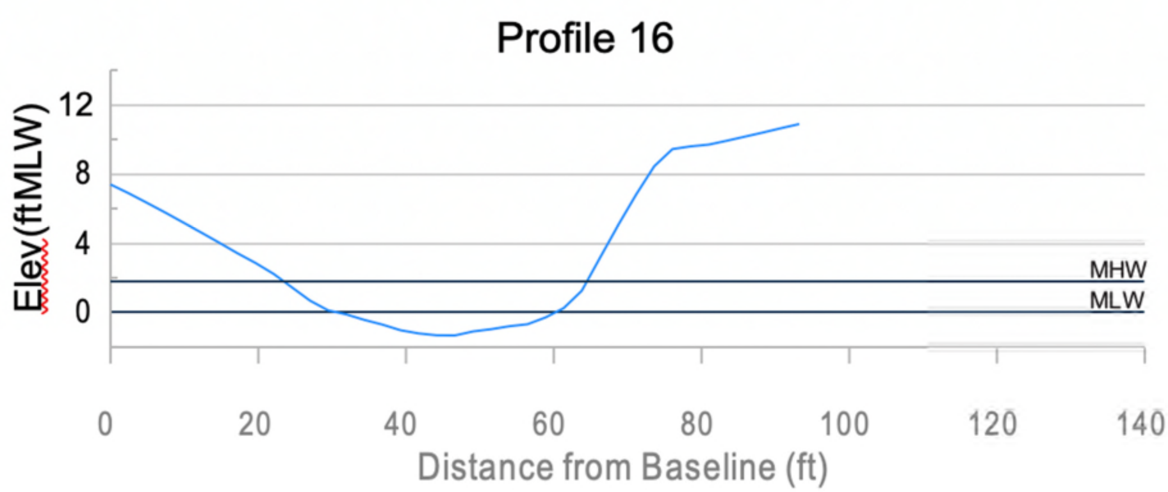
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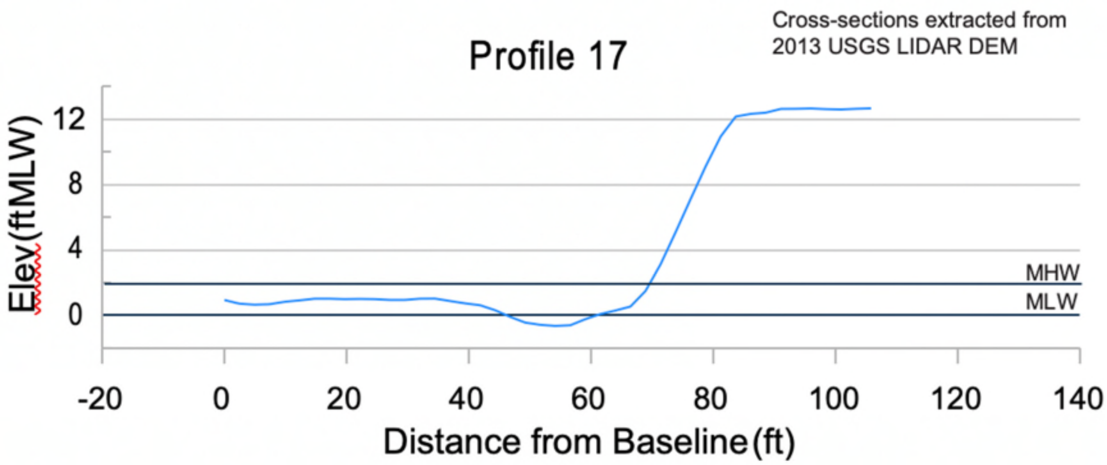
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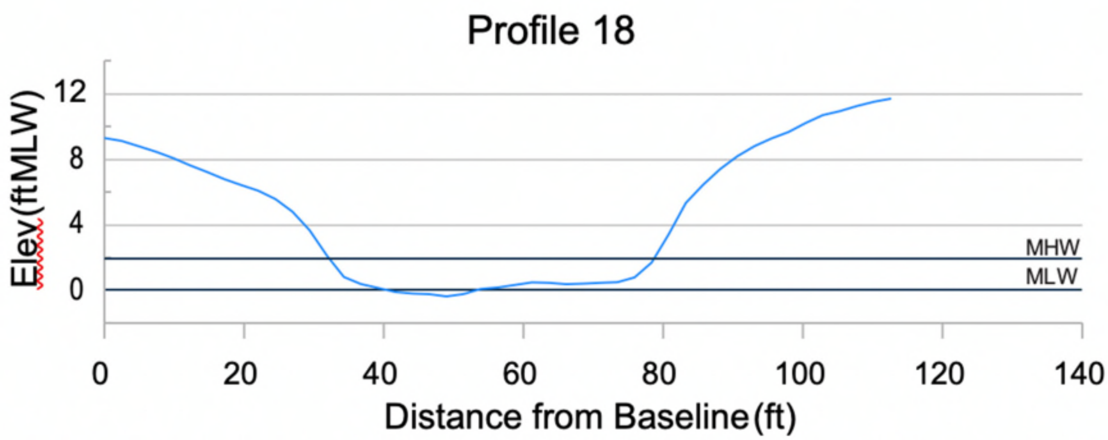
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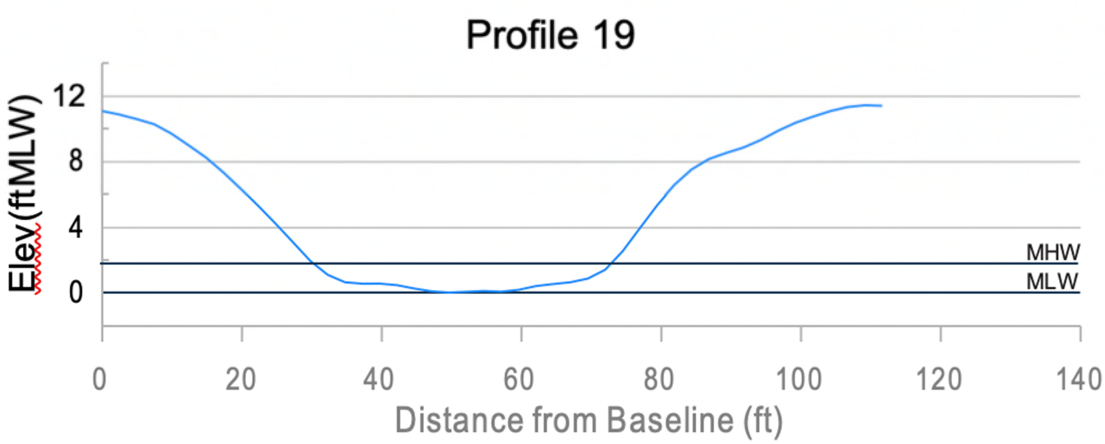
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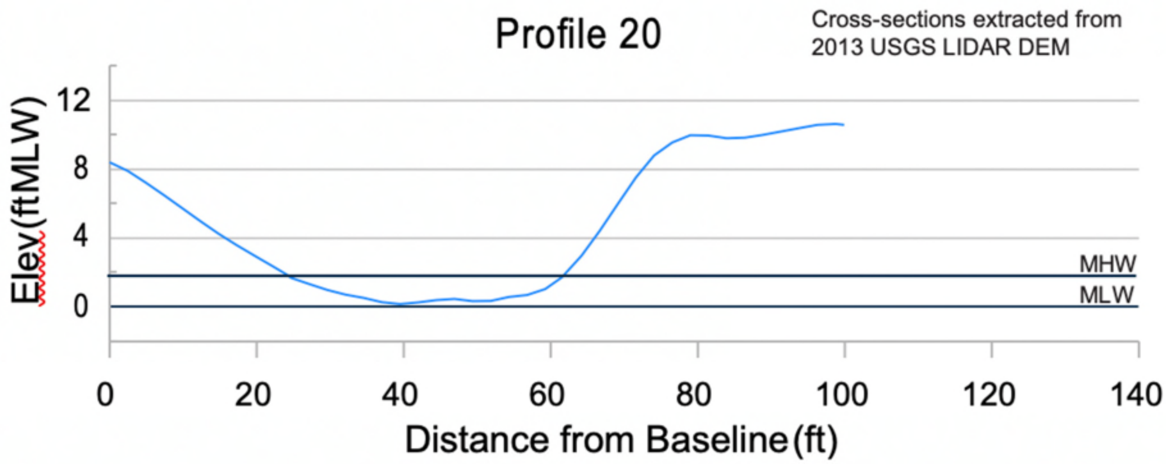
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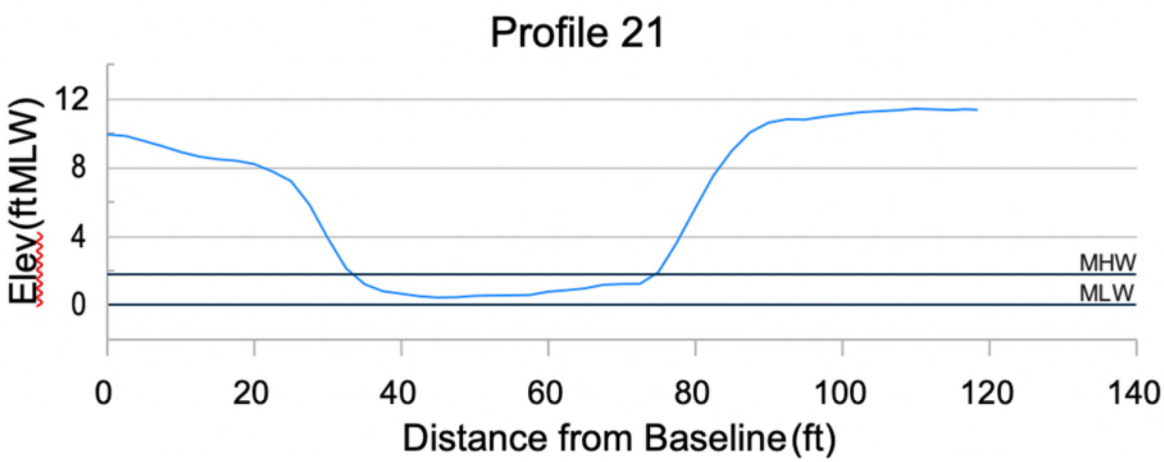
Distance from Baseline (ft)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Distance from Baseline (ft)

Appendix C
Tolerant Plants

NC Cooperative Exension

Plants appropriate to Buchanan Creek highlighted.

Key to Plant Lists

Highly Salt Tolerant
Plants tolerant of the direct salt spray such as that received along dunes and immediately adjacent to the oceanfront.

Moderately Salt Tolerant
Plants tolerant of moderate levels of salt spray, such as that received in landscapes adjacent to the beach front, but which are sheltered by other plants, structures or natural dunes.

Slightly Salt Tolerant
Plants with the lowest level of tolerance to salt spray. These plants should be used only in areas receiving some protection from direct salt spray, either from a building or other vegetation. In areas that are completely sheltered, plants with no known salt tolerance can be grown.

Underlined Plants
Plants that are extremely tolerant of growing in sandy, poor soils and display extreme drought tolerance once established.

*** Native**
Plants that are native to the coastal plains of the southeast USA, ranging from New Jersey south along the Atlantic Seaboard through Florida and along the Gulf Coast to East Texas.

'Cultivar Names'
Cultivar names are written in single quotes. Cultivars, or varieties, are plants that have been selected because they display desirable characteristics such as larger flowers, different color foliage, more compact growth, etc. Cultivars are propagated vegetatively (cuttings, division, tissue culture) so they are genetically identical to each other.

Evergreen/Deciduous
E or D refers to whether a plant is evergreen (retains its foliage all year) or deciduous (sheds its foliage each fall and grows new leaves in spring).

Exposure
Refers to the amount of sunlight a site receives as follows:

- **Full sun** indicates a site that receives at least 8hrs of direct sun each day.
- **Light Shade** indicates a site that is shaded less than half of the day by a light high shade such as that cast by pines.
- **Part Shade** indicates a site that is shaded for half the day by a dense shade like that cast by buildings or shade trees.
- **Full Shade** indicates a site that is in shade all day.

Soil
Refers to soil condition at the site as follows:

- **Wet** indicates a site that stays moist most of the time and receives periodic flooding.
- **Moist** indicates a site that is moist most of the time with brief (less than 12hrs) periods of standing water.
- **Well Drained** indicates a site where water drains from the surface and rarely stands.
- **Xeric** indicates a site that is extremely dry and sandy with very little ability to hold water.

ORNAMENTAL GRASSES

Ornamental Grasses—*Highly Salt Tolerant*

Common Name	Botanical Name	Height x Spread	Soil Conditions	Exposure
Pampas Grass	*Cortaderia selloeana*	8' x 6'	Moist to Well Drained	Full Sun
Lyme Grass	*Leymus arenarius*	2' x 4'	Well Drained to Xeric	Full Sun
Maiden Grass	*Miscanthus sinensis*	4'-8' x 3'-6'	Moist to Well Drained	Full Sun
Muhly Grass*	*Muhlenbergia capillaris*	3' x 3'	Well Drained to Xeric	Full Sun
Bitter Panicum*	*Panicum amarum*	3' x 2'	Well Drained to Xeric	Full Sun
Sand Cordgrass*	*Spartina bakeri*	3' x 3'	Well Drained	Full Sun

Ornamental Grass—*Slightly Salt Tolerant*

Common Name	Botanical Name	Height x Spread	Soil Conditions	Exposure
Panic Grass*	*Panicum virgatum*	4'-8' x 2'-4'	Moist to Well Drained	Full Sun
Fountain Grass	*Pennisetum alopecuriodes*	3' x 2'	Moist to Well Drained	Full Sun

PERENNIALS

Perennials—*Highly Salt Tolerant*

Common Name	Botanical Name	Height x Spread (ft.)	Exposure	Soil
Blanket Flower, Gaillardia*	*Gaillardia pulchella*	1-2 x 1-2	Sun	Well Drained to Xeric
Daylily	*Hemerocallis* species and hybrids	1-4 x 1-4	Sun/Partial Shade	Moist to Well Drained
Lantana	*Lantana camara* *Lantana montevidensis*	2-4 x 3-6	Sun	Well Drained to Xeric
Prickly Pear Cactus*	*Opuntia compressa*	1-2 x 2-3	Sun	Well Drained to Xeric
Lavender Cotton	*Santolina chamaecyparissus*	1-2 x 2	Sun	Well Drained
Seaside Goldenrod*	*Solidago sempervirens*	4-6 x 3-4	Sun	Well Drained to Xeric

Perennials—*Moderately Salt Tolerant*

Common Name	Botanical Name	Height x Spread (ft.)	Exposure	Soil
Fern Leaf Yarrow	*Achillea filipendulina*	3-4 x 2-3	Sun	Well Drained
Common Yarrow	*Achillea millefolium*	2-3 x 3	Sun	Well Drained to Xeric
Agapanthus	*Agapanthus africanus*	2-4 x 2	Sun to Part Shade	Well Drained

Perennials— ***Slightly Salt Tolerant***, continued

Common Name	Botanical Name	Height x Spread (ft.)	Exposure	Soil
Angel's Trumpets	*Brugmansia*	4-6 x 4-6	Sun to Part Shade	Well Drained
Canna Lily	*Canna* hybrids	4-8 x 2-6	Sun to Part Shade	Moist to Well Drained
Holly Fern	*Cyrtomium falcatum*	1-2 x 1-2	Part Shade to Shade	Moist to Well Drained
Golden Dewdrop	*Duranta erecta*	3-5 x 3-5	Sun to Part Shade	Well Drained
Purple Coneflower*	*Echinacea purpurea*	3-5 x 2-4	Sun to Part Shade	Well Drained
Hardy Hibiscus*	*Hibiscus moscheutos* *Hibiscus coccineus* *Hibiscus* hybrids	4-6 x 4-6	Sun to Light Shade	Moist to Well Drained
Hosta	*Hosta* species and hybrids	1-3 x 1-3	Part to Full Shade	Well Drained
Red Hot Poker	*Kniphofia* species and hybrids	2-4 x 1-3	Sun	Well Drained
Daffodil	*Narcissus*	1 x 1	Sun to Part Shade	Well Drained
Leadwort, Blue jasmine	*Plumbago auriculata*	3-4 x 3-4	Sun	Well Drained
Dwarf Mexican Petunia	*Ruellia brittoniana 'Katie'*	6" x 1	Sun to Light Shade	Well Drained
Autumn Sage*	*Salvia greggii* *Salvia microphylla*	2-4 x 2-4	Sun to Light Shade	Well Drained
Princess Flower	*Tibouchina urvilleana*	3-5 x 3-5	Sun to Light Shade	Well Drained
Common Thyme	*Thymus vulgaris*	1 x 1	Sun	Well Drained
Verbena*	*Verbena canadensis*	1 x 2-3	Sun to Light Shade	Moist to Well Drained

TURF GRASSES

Common Name	Salt Tolerance	Drought Tolerance	Shade Tolerance	Maintenance Level	Fertilizer Requirements	Wear Tolerance
Centipede	Slight – high soil pH often a problem for centipede in coastal sites	Moderate	Poor	Low	Very Low	Good
St. Augustine	Moderate	Low	Very Good	Low - Moderate	Moderate	Good
Zoysia	High	High	Good	Moderate	Moderate	Excellent
Common Bermuda	High	High	Very Poor	High	High	Excellent
Hybrid Bermuda	High	High	Very Poor	Very High	Very High	Excellent
Seashore Paspalum	Very High – tolerates irrigation w/ saline water	Moderate	Poor	Moderate	Moderate	Good

For more information about **Seashore Paspalum** see the following online factsheet:
Seashore Paspalum for Florida Lawns— http://edis.ifas.ufl.edu/EP059

Groundcovers—*Highly Salt Tolerant*

Common Name	Botanical Name	Height	Exposure	Soil Conditions
Winter Creeper	*Euonymous fortunei*	6"-2'	Full Sun to Full Shade	Well Drained
'Blue Pacific' Juniper	*Juniperus conferta* 'Blue Pacific'	12"-18"	Full Sun	Well Drained to Xeric
Spreading Liriope	*Liriope spicata*	12"	Full Sun to Full Shade	Moist to Well Drained
Mondograss	*Ophiopogon japonicus*	6"-10"	Part to Full Shade	Well Drained
Creeping Rosemary	*Rosmarinus officinalis* 'Prostratus'	12"-18"	Full Sun	Well Drained to Xeric
Golden Stonecrop	*Sedum acre*	4"- 6"	Full Sun to Light Shade	Well Drained

Groundcovers—*Moderately Salt Tolerant*

Common Name	Botanical Name	Height	Exposure	Soil Conditions
Beach Wormwood*	*Artemisia stelleriana*	6"- 12"	Full Sun	Well Drained to Xeric
Silver and Gold	*Chrysanthemum pacificum*	12"-18"	Full Sun	Well Drained
Algerian Ivy	*Hedera canariensis*	12"	Light to Full Shade	Well Drained
English Ivy	*Hedera helix*	6"-12"	Part to Full Shade	Well Drained
Creeping Juniper*	*Juniperus horizontalis*	10"-12"	Full Sun	Well Drained to Xeric
Liriope	*Liriope muscarii*	12"- 18"	Light to Full Shade	Moist to Well Drained
Star Jasmine	*Trachelospermum asiaticum*	6"-8"	Light to Part Shade	Well Drained

Groundcovers—*Slightly Salt Tolerant*

Common Name	Botanical Name	Height	Exposure	Soil Conditions
Cast Iron Plant	*Aspidistra elatior*	3'	Part to Full Shade	Well Drained
Beach St. John's Wort*	*Hypericum reductum*	12"	Full Sun	Well Drained to Xeric
Periwinkle, Vinca	*Vinca minor*	6"	Light to Full Shade	Moist to Well Drained

For More Information About Listed Plants

For more information about each plant, including recommended varieties for Pender County landscapes, visit the **Recommended Plants Lists** on the Pender County Cooperative Extension website, **http://pender.ces.ncsu.edu**. Click on the Lawn & Garden link to access the lists.

Or visit the **NCSU Urban Horticulture** website, **www.ncstate-plants.net** and click on the **Plant Fact Sheets** link to access hundreds of fact sheets with complete details about each plant, including images.

For complete **information** about turf grass care and selection, see the individual lawn maintenance calendars and other publications available from North Carolina Cooperative Extension at your local NC Cooperative Extension office or the **NCSU TurfFiles** website: **www.turffiles.ncsu.edu**

Drought Tolerant Perennials

The following drought tolerant perennials perform well in sandy, poor soils. Though they are not known to tolerate salt spray, they are recommended for coastal gardens when planted in sites sheltered from salt spray.

Common Name	Scientific Name
'Blue Fortune' Hyssop	*Agastache* x 'Blue Fortune'
Arkansas Blue Star*	*Amsonia hubrichtii*
Texas Firecracker*	*Anisacanthus wrightii*
'Powis Castle' Artemisia	Artimisia x 'Powis Castle'
False Wild Indigo*	*Baptisia* species and hybrids
Wine Cups*	*Callirhoe involucrata*
Threadleaf Coreopsis*	*Coreopsis verticillata*
Gaura*	*Gaura lindheimeri*
Russian Sage	*Perovskia* hybrids
Moss Pinks*	*Phlox subulata*
'Goldsturm' Rudbeckia*	*Rudbeckia fulgida* 'Goldsturm'
Mexican Bush Sage	*Salvia leucantha*
'Indigo Spires' Salvia	*Salvia* x 'Indigo Spires'
Stonecrops	*Sedum* species
Lamb's Ear	*Stachys byzantina*

Salt Tolerant Annuals

Most annuals do not tolerate salt spray but the following have proven to tolerant moderate levels. Most are perennials in warmer climates but are usually killed by the average winter temperatures in this area and so are best grown as annuals. In addition to those listed below, Allamanda, Bouganvilla and Mandevilla vines all tolerate moderate levels of salt spray, though are not hardy in this climate (USDA Hardiness zone 8a).

Common Name	Scientific Name
Baby Sun Rose	*Aptenia cordifolia*
Blue Daze	*Evolvulus glomeratus*
Joseph's Coat	*Alternanthera ficoidea*
Vinca, Periwinkle	*Catharanthus roseus*
Pentas	*Pentas lanceolata*
Moss Rose	*Portulaca grandiflora*
Coleus	*Solenostemon* hybrids

Drought Tolerant Annuals

The following annuals do not have any known salt spray tolerance but do grow well even in sandy, poor soils and are therefore recommended for planting in coastal gardens in sheltered sites.

Common Name	Scientific Name
Wheat Celosia	*Celosia spicata*
Globe Amaranth	*Gomphrena globosa*
Melampodium	*Melampodium padulosum*
Porterweed	*Stachytarpheta jamaicensis*
Mealycup Sage*	*Salvia farinacea*
Mexican Sunflower	*Tithonia rotundifolia*
Narrow Leaf Zinnia	*Zinnia angustifolia*

Appendix D
Numerical Model Descriptions

Numerical modeling is a widely used approach for water quality assessment, estimate of allowable loads for water quality attainment (VADEQ 2018), and impact of channel modification on environment (Shen, et al., 2017), and other water quality studies (e.g., Sisson et al., 2003). In this study, a system of numerical models was developed to simulate the loadings of organic matter and nutrients from the watershed, and the resulting response of in-stream water quality variables such as DO, algae, and nutrients. The modeling system consists of two individual model components: the watershed model and the hydrodynamic-water quality model. The watershed model Loading Simulation Program C++ (LSPC), developed by the USEPA (Shen et al., 2005), was selected to simulate the watershed hydrology and nutrient loads to the receiving waterbodies of the creeks. The EFDC/HEM3D model (Park *et al.*, 1995) was used to simulate the water quality of the receiving water. Figure C.1 shows a diagram of the modeling system. In order to accurately simulate water particle movement and transport time, the high-resolution unstructured grid model SCHISM (Zhang, et. al., 2016) was used to simulate complex interaction of geometry and hydrodynamics to assess modification of channels, such as channel deepening.

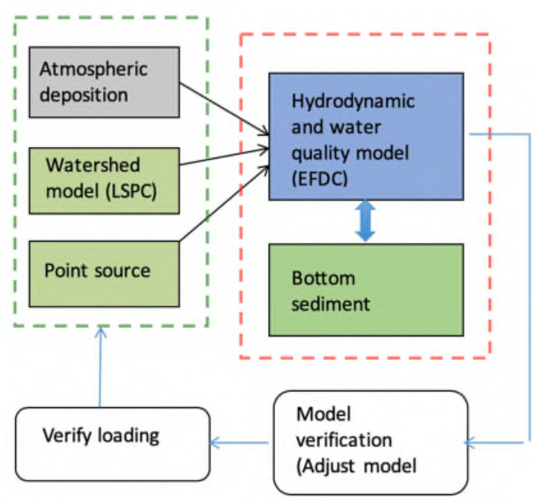

Figure C.1. Diagram of linked watershed and water quality modeling system

Watershed model

The LSPC model is a stand-alone, personal computer-based watershed modeling program developed in Microsoft C^{++} (Shen et al., 2005). It includes selected Hydrologic Simulation Program FORTRAN (HSPF) (Bicknell et al., 1996) algorithms for simulating hydrology, sediment, and general water quality on land, as well as a simplified stream transport model. Like other watershed models, LSPC is a precipitation-driven model and requires necessary meteorological data as model input.

The LSPC model was configured for Buchanan Creek and a portion of the Western Branch of the Lynnhaven River. The watershed was segmented into 230 sub-watersheds (Fig C.2). The sub-watersheds were used as modeling units for the simulation of flow, nutrient, and pathogen loads based on meteorology, land use, nutrient application, and pathogen deposition on the watershed. LSPC was used to simulate the freshwater flow and its associated nonpoint-source pollutants (nitrogen, phosphorus, organic carbon, etc.). The simulated freshwater flow and pollutant loadings for each sub-watershed were fed into the adjacent water quality model segments. In simulating nonpoint-source pollutants from the watershed, LSPC uses a traditional buildup and washoff approach (Bicknell et al., 1996). Pollutants from various sources (fertilizers, atmospheric deposition, wildlife, septic systems, etc.) accumulate on the land surface and are available for runoff during rain events. Different land uses are associated with various anthropogenic and natural processes that determine the potential pollutant loads. The final loads were converted to model accumulation rates (ACQOP, units of lbs./acre/day for nutrients or counts/acre/day for pathogens). The ACQOP were calculated for each land use based on all sources contributing nutrients to the land surface. For example, croplands receive nutrients from fertilizer and manure application, atmospheric deposition, and feces from wildlife. Summarizing all these sources together can derive the accumulation rates for croplands. These loading parameters were adjusted accordingly during model calibration. The loads discharged to the stream were estimated based on model simulation results. The other two major parameters governing water quality simulation, the maximum storage limit (SQOLIM, unit in lbs/acre/day for nutrients or counts/acre/day) and the wash-off rate (WSQOP, units of inches/hour), were specified based on soil characteristics and land use practices, and were further adjusted during the model calibration. The WSQOP is defined as the rate of surface runoff that results in 90% removal of pollutants in one hour. The lower the value, the more easily wash-off occurs. Because there is not enough data for model calibration for bacteria, the watershed model only simulates loadings of nutrients and carbon. Municipal Separate Storm Sewer System (MS4) was not simulated separately, and it was combined with urban land use categories for this urban dominated area.

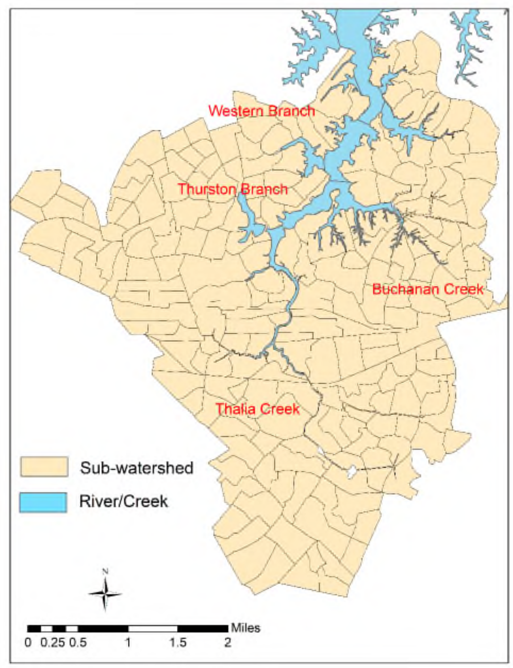

Figure C.2. Sub-watershed segmentation

USGS 2018 land use was used by the watershed model (https://archive.usgs.gov/archive/sites/landcover.usgs.gov/landcoverdata.html), which has better resolution of impervious and pervious land-use information. The dominant land use is urban impervious, which is about 45% followed by combined grassland and forest (50%). Urban pervious land is less than 2% (Fig. C.3). Nonpoint sources from the watershed are represented in the model as land-based runoff from the land use categories to account for their contribution.

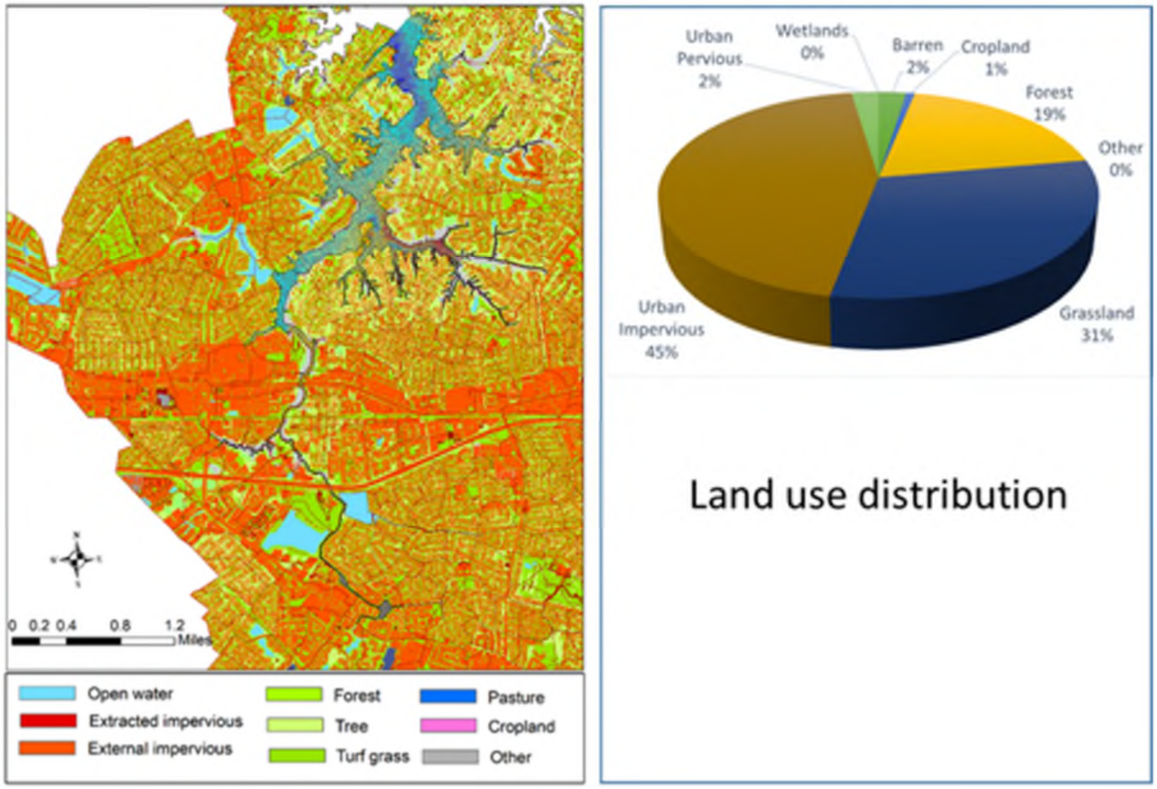

Figure C.3. Land use (USGS 2018) distribution in the Thalia and Buchanan creek area of the Lynnhaven.

The precipitation data were collected from the Norfolk airport and at a recent USGS station located in the middle of Thalia Creek. The simulation period is from 2009 to 2018. Because there is no USGS discharge data available, the hydrological parameters used in Rudee Inlet TMDL study (VADEQ, 2018) were applied. Because the dominant land use in the watershed is urban impervious that is similar to Rudee Inlet, the parameters applied to Buchanan watershed are suitable. The simulated flow was compared to previous URS watershed simulations at selected watersheds (Fig. C.4). Because different weather data were used for the watershed model, some discrepancy can be expected. As salinity distribution results from the interaction of tides and freshwater discharge, accurate simulation of salinity indicates accurate simulation of freshwater discharge. Based on hydrodynamic model simulations of salinity (see next sections), the freshwater simulations are reliable.

There are three relative long-term observations from 1996-2001 located in the Lynnhaven River but outside of the modeling domain. One is located in a residential area near Five Forks Road (Site V-1), and one is located in the upstream Thalia Creek (Site V-3). The third one is located near the Eastern Branch. The variation in TN and TP concentrations are within the same range (Tables C.1 & C.2). Comparison of model simulations of TN and TP at a station near the upstream portion of Thalia Creek is shown in Fig. C.5. The model simulation is within the same range as the observations.

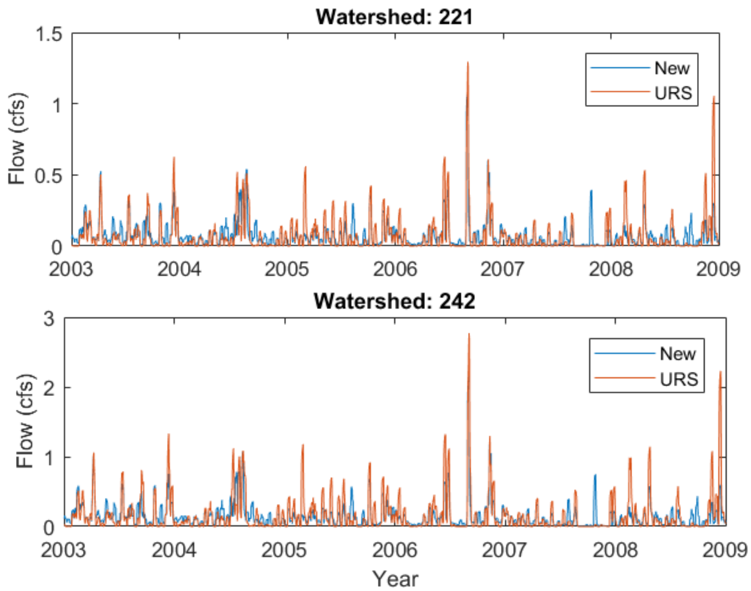

Figure C.4. Comparison of watershed model simulation of flow against URS model

Table C.1. Site V-1 Sampling Date and Pollutant Concentration (mg/L) (Residential)

Date	BOD	TSS	TDS	COD	NOX	TKN	HN3	TP	DP	TN	NH3/TN	NO3/TN	DP/TP
2/14/1997	5	191	59	93	0.38	2.38		0.56	0.16	2.76	0.00	0.14	0.29
3/14/1997	7	183	73	114	0.41	1.9	0.71	0.51	0.18	2.31	0.37	0.18	0.35
4/28/1997	17	62	132	65	0.82	2.07	0.19	0.36	0.15	2.89	0.09	0.28	0.42
6/14/1997	14	191	108	116	0.93	1.81	0.78	0.53	0.17	2.74	0.43	0.34	0.32
7/16/1997	21	337	91	348	0.98	2.78	1.35	0.99	0.37	3.76	0.49	0.26	0.37
8/14/1997	17	52	62	83	1.08	2.99	0.81	0.83	0.65	4.07	0.27	0.27	0.78
9/11/1997	8	7	126	61	0.42	1.2	0.16	0.2	0.12	1.62	0.13	0.26	0.60
11/1/1997	5	36	53	40	0.41	0.98	0.13	0.34	0.22	1.39	0.13	0.29	0.65
12/1/1997	15	86	50	93	0.24	1.29	0.25	0.51	0.3	1.53	0.19	0.16	0.59
1/28/1998	4	50	61	34	0.41	1.03	0.31	0.27	0.18	1.44	0.30	0.28	0.67
2/12/1998	9	65	180	54	0.32	1.29	0.34	0.24	0.06	1.61	0.26	0.20	0.25
7/5/1998	11	51	62	77	0.72	1.99	0.62	0.42	0.21	2.71	0.31	0.27	0.50
7/5/1998	10	68	54	81	0.75	1.57	0.62	0.39	0.22	2.32	0.39	0.32	0.56
7/23/1998	22	118	70	91	0.93	2.07	0.57	0.5	0.3	3	0.28	0.31	0.60
8/11/1998	26	46	154	166	0.83	3.1	0.8	0.7	0.52	3.93	0.26	0.21	0.74
2/12/1999	11	85	88	80	0.87	1.77	0.64	0.46	0.08	2.64	0.36	0.33	0.17
2/28/1999	8	49	69	57	0.65	1.88	0.52	0.34	0.18	2.53	0.28	0.26	0.53
7/24/1999	7	32	153	69	0.72	1.25	0.59	0.35	0.24	1.97	0.47	0.37	0.69
8/25/1999	6	12	65	37	0.57	1	0.22	0.32	0.22	1.57	0.22	0.36	0.69
2/12/2000	9	26	109	51	1.12	1.39	0.53	0.21	0.06	2.51	0.38	0.45	0.29
2/12/2000	8	23	108	47	1.1	1.38	0.52	0.21	0.07	2.48	0.38	0.44	0.33
3/21/2000	6	12	114	50	0.4	1.31	0.33	0.19	0.07	1.71	0.25	0.23	0.37
7/15/2000	19	22	92	66	1.1	3.16	0.89	0.9	0.74	4.26	0.28	0.26	0.82
Ave	11.52	78.43	92.74	85.78	0.70	1.81	0.54	0.45	0.24	2.51	0.30	0.29	0.51
Std	6.18	78.75	36.95	64.63	0.28	0.68	0.29	0.23	0.18	0.87	0.12	0.08	0.19

Table C.2. Site V-3 Sampling Date and Pollutant Concentration (mg/L)

Date	BOD	TSS	TDS	COD	NOX	TKN	HN3	TP	DP	TN	NH3/TN	NO3/TN	DP/TP
1/18/1996	8	72	28	60	0.47	1.15	0.57	0.27	0.13	1.62	0.50	0.29	0.48
1/19/1996	25	43	79	180	2.48	13.01	4.09	0.58	0.39	15.49	0.31	0.16	0.67
6/18/1996	8	72	82	60	0.47	1.15	0.57	0.27	0.13	1.62	0.50	0.29	0.48
8/13/1996	8	12	30	60	0.43	0.38	0.2	0.21	0.15	0.81	0.53	0.53	0.71
9/6/1996	6	19	58	49	0.3	0.91	0.37	0.22	0.16	1.21	0.41	0.25	0.73
12/6/1996	7	42	36	45	0.61	1.53	0.24	0.37	0.15	2.14	0.16	0.29	0.41
1/9/1997	7	13	26	38	0.4	0.71	0.2	0.15	0.13	1.11	0.28	0.36	0.87
1/9/1997	6	15	24	43	0.37	0.88	0.2	0.14	0.11	1.25	0.23	0.30	0.79
7/10/1997	17	40	77	82	1.28	3.06	1.2	0.51	0.36	4.34	0.39	0.29	0.71
7/30/1997	16	27	56	85	2.47	2	0.79	0.21	0.1	4.47	0.40	0.55	0.48
12/10/1997	19	18	20	62	0.38	0.98	0.57	0.15	0.31	1.36	0.58	0.28	2.07
1/13/1998	18	41	62	69	1.14	1.9	0.97	0.36	0.27	3.04	0.51	0.38	0.75
7/16/1998	15	33	36	77	0.72	1.84	0.83	0.33	0.2	2.56	0.45	0.28	0.61
8/16/1998	8	8	36	57	0.77	1.04	0.29	0.23	0.39	1.81	0.28	0.43	1.70
2/12/1999	24	34	86	100	1.48	2.59	1.41	0.51	0.36	4.07	0.54	0.36	0.71
2/13/1999	8	8	24	43	0.55	1.06	0.61	0.22	0.16	1.61	0.58	0.34	0.73
2/28/1999	7	12	16	38	0.44	1.11	0.61	0.22	0.16	1.55	0.55	0.28	0.73
8/20/1999	25	12	114	117	2.58	2.44	1.69	0.71	0.01	5.02	0.69	0.51	0.01
9/15/1999	31	10	84	88	1.31	2.44	0.95	0.64	0.55	3.75	0.39	0.35	0.86
12/6/1999	27	17	25	72	0.35	1.27	0.48	0.33	0.26	1.62	0.38	0.22	0.79
2/12/2000	24	34	86	108	1.4	2.59	1.41	0.51	0.39	3.99	0.54	0.35	0.76
7/15/2000	13	11	40	65	0.77	1.54	0.59	0.34	0.29	2.31	0.38	0.33	0.85
6/30/2001	18	90	68	89	1.08	2.38	1	0.44	0.23	3.46	0.42	0.31	0.52
Ave	15.00	29.70	51.87	73.35	0.97	2.09	0.86	0.34	0.23	3.05	0.43	0.34	0.76
Std	7.99	22.72	27.88	32.07	0.71	2.49	0.82	0.16	0.13	2.99	0.13	0.10	0.41

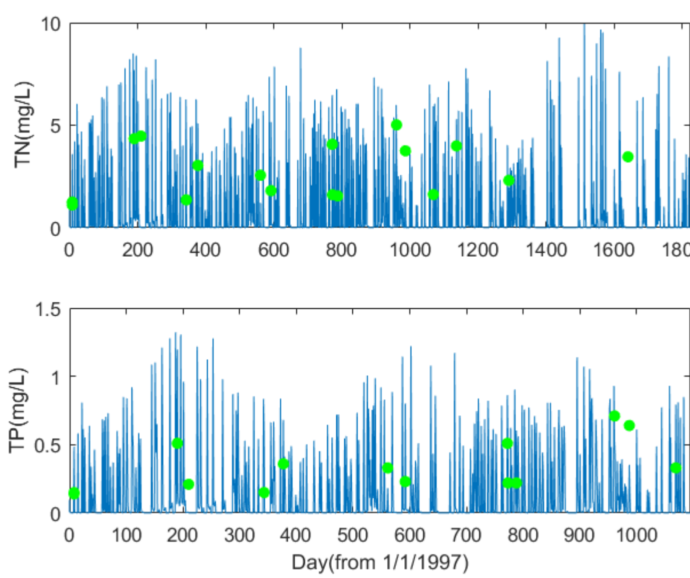

Figure C.5. Comparison of TN and TP with observations near the upstream of Thalia Creek

EFDC/HEM3D hydrodynamic and water quality models

Hydrodynamic transport is essential for driving the movement of dissolved and particulate substances in aquatic waters. Hydrodynamic models are used to represent transport patterns in complex aquatic systems. For this study, the EFDC/HEM3D model was selected to simulate hydrodynamics. The model is a general-purpose modeling package for simulating 1-, 2-, and 3-dimensional flow and transport in surface water systems including: rivers, lakes, estuaries, reservoirs, wetlands, and oceanic coastal regions. It was originally developed at the Virginia Institute of Marine Science for estuarine and coastal applications and is considered public domain software (Hamrick, 1992; Park et al., 1996). The model code has been extensively tested and documented. The EFDC model has been integrated into the EPA's TMDL Modeling Toolbox for supporting TMDL development (https://www.epa.gov/exposure-assessment-models/efdc).

The EFDC model coupled with a water quality model solves the continuity and momentum equations for surface elevation and horizontal and vertical velocities. The model simulates density and gravitationally induced circulation as well as tidal and wind-driven flows, spatial and temporal distributions of salinity, temperature, and suspended sediment concentration, and eutrophication processes in estuaries. The model has been applied to a wide range of environmental studies in the Chesapeake Bay system and other systems (Shen and Lin, 2006, Shen, et al., 2016).

Inputs to the EFDC hydrodynamic model for this study include:

- Bathymetry
- Freshwater inputs (lateral and up-stream) from watersheds
- Surface meteorological parameters (wind, atmospheric pressure, solar radiation, dry and wet temperature, humidity, and cloud cover)

The water quality processes simulated include

- Particulate and dissolved organic carbon (POC, DOC)
- Particulate and dissolved organic nitrogen (PON, DON)
- Inorganic nitrogen (NH4, NO3)
- Particulate and dissolved organic phosphorus and inorganic phosphorus (POP, PO4)
- Dissolved oxygen (DO)
- Phytoplankton (Chl-a)

The model uses a grid comprised of cells connected through the modeling process to represent the area. The scale of the grid (cell size) determines the level of resolution in the model and the model efficiency from an operational perspective. The smaller the cell size, the higher the resolution and the lower the computational efficiency. Because Buchanan Creek connects to the Thurston Branch and Thalia Creek, and because the open boundary condition of tide and salinity are influenced by the Western Branch, the open boundary is located in the Western Branch. The model grid is shown in Fig. C.6a. There is a total of 934 cells in the horizontal, and three vertical layers were used in the model to simulate stratification for these shallow Creeks. The National Oceanic and Atmospheric Administration (NOAA) bathymetry data and NOAA chart, plus VIMS bathymetric survey data were combined to obtain water depths for the model.

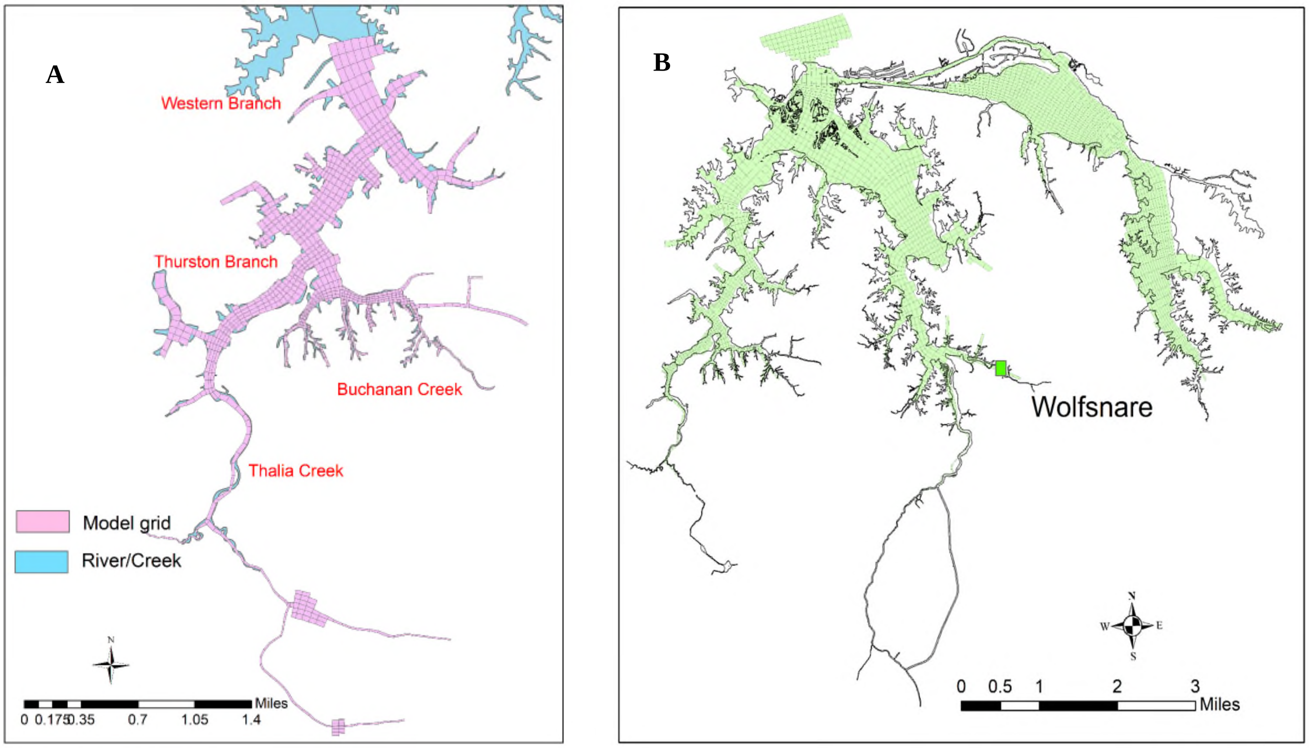

Figure C.6. EFDC/HEM3D water quality model grid

The calibration for the hydrodynamic model used data obtained from Thalia Creek and Thurston Branch during 2009 and observations from Buchanan Creek during 2018. The model calibration includes comparison of model predictions and high-frequency observed water surface elevation, salinity and temperature data for different deployment time series ranging from 10-40 days.

For the application of the EFDC hydrodynamic model to the system, it was necessary to specify the downstream boundary condition where the Thurston Branch enters into the portion of the downstream Western Branch. The downstream boundary conditions include specifications of time series of surface elevation and salinity along the exterior row of grid cells at the northern extent of the model grid, as shown in Fig. C.6 These data were derived from the water depth measurement as well as salinity measurements at the most downstream ConMon water quality stations and DEQ monthly data.

For water quality model simulation, a yearlong simulation is needed for simulating seasonal variation of water quality variables. As there is no long-term observation of tide at the open boundary, the NOAA observation of tide at Bay Bridge Tunnel was used for the open boundary condition. The data analysis showed that tide at Bay Tunnel has a high correlation with the tide at the Western Branch. With adjustment of tidal amplitude and phase based on statistical analysis, we can use it as open boundary condition for the 2018 simulation. There is a USGS station for tide in Thalia Creek located near our Station 4. A comparison of tides at the USGS station and the model simulation from Day 240-360 is shown in Fig. C.7. An empirical relationship for calculating salinity from river discharge and elevation at the boundary was derived using the observational data during the measurement periods, and the whole-year time series of salinity at the open boundary was then estimated using this relationship.

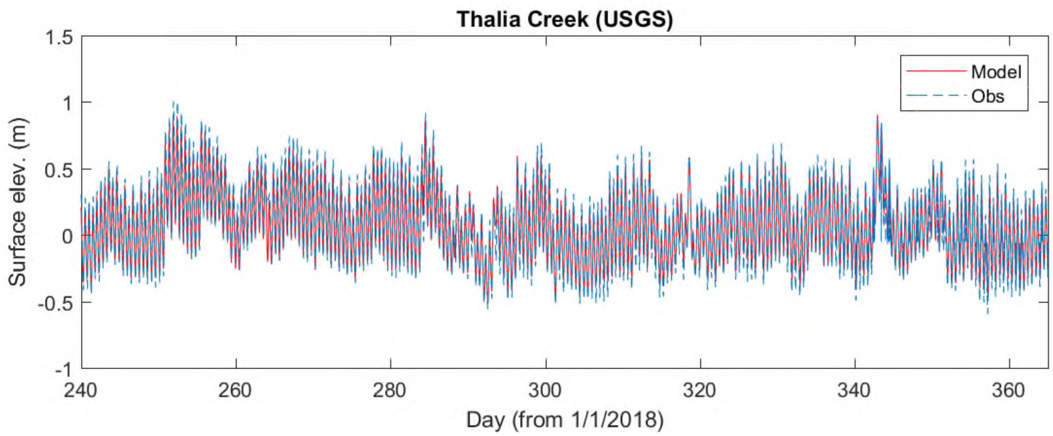

Figure C.7. Comparison of model simulated elevations and that observed at the USGS station.

Real-time comparisons of predicted vs. observed surface elevations in the Thurston Branch and Thalia Creek are shown in Fig. C.8a (June 30 to July 13, 2009), Fig. C.8b (July 27 to August 5, 2009), and Fig. C.8c (August 27 to September 6, 2009). It should be noted that some measurements only show water level variations during certain periods of one tidal cycle (most of the periods are near high tide). The surface elevation becomes smooth or very small during other periods of that tidal cycle (mostly near low tide), which is mainly caused by the instrument deployment when water depths become shallow during low tide. The model captures the tidal variations during flood tide well at Station 5, and the model simulations match the observations well at Stations 1-4 where water elevations are properly measured. Overall, the model captured the semi-diurnal peaks and troughs and the phases of the observations quite well.

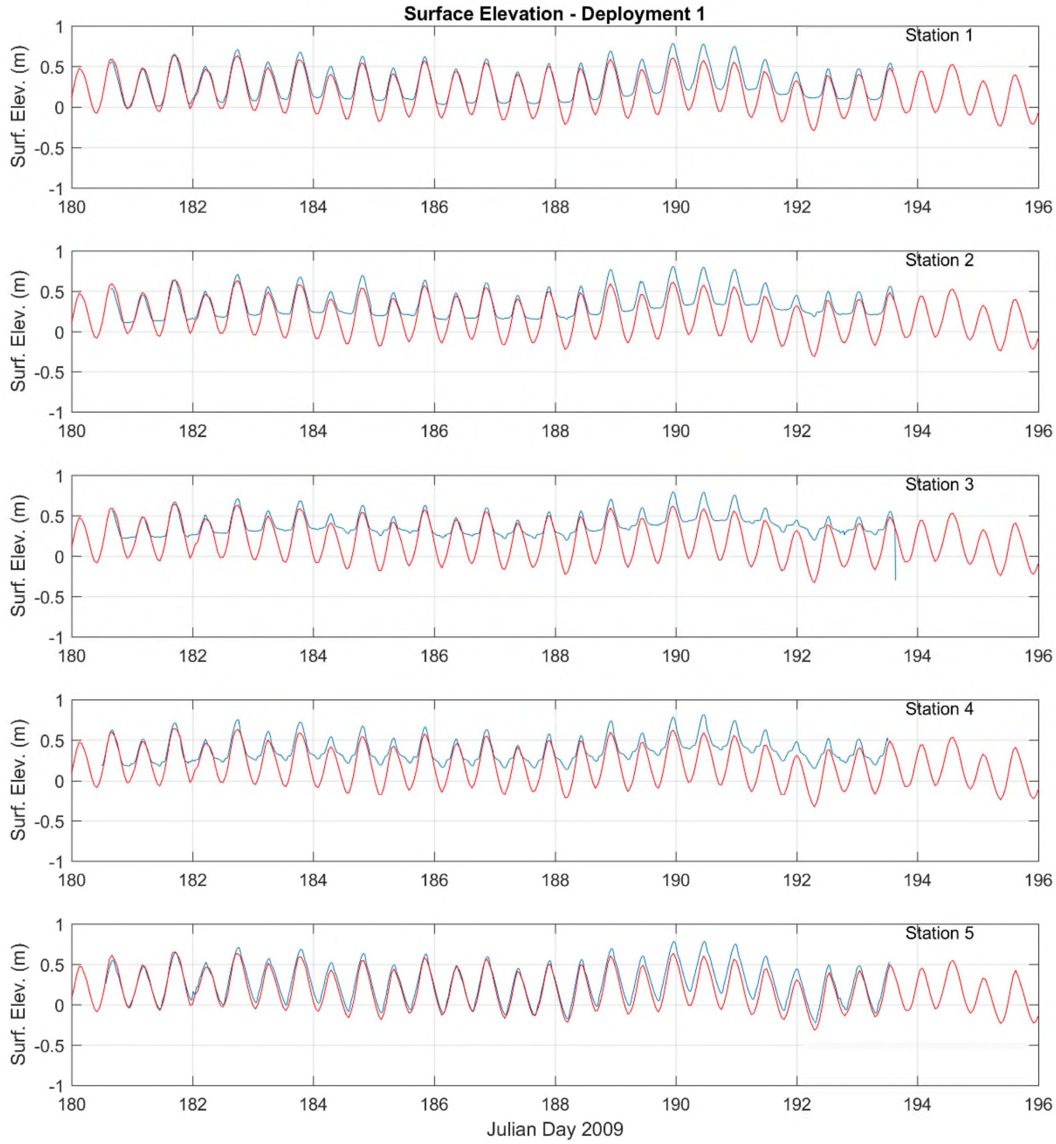

Figure C.8a. Real-time comparisons of predicted vs. observed surface elevations at five stations in the Thurston Branch and Thalia Creek during the deployment period 1.

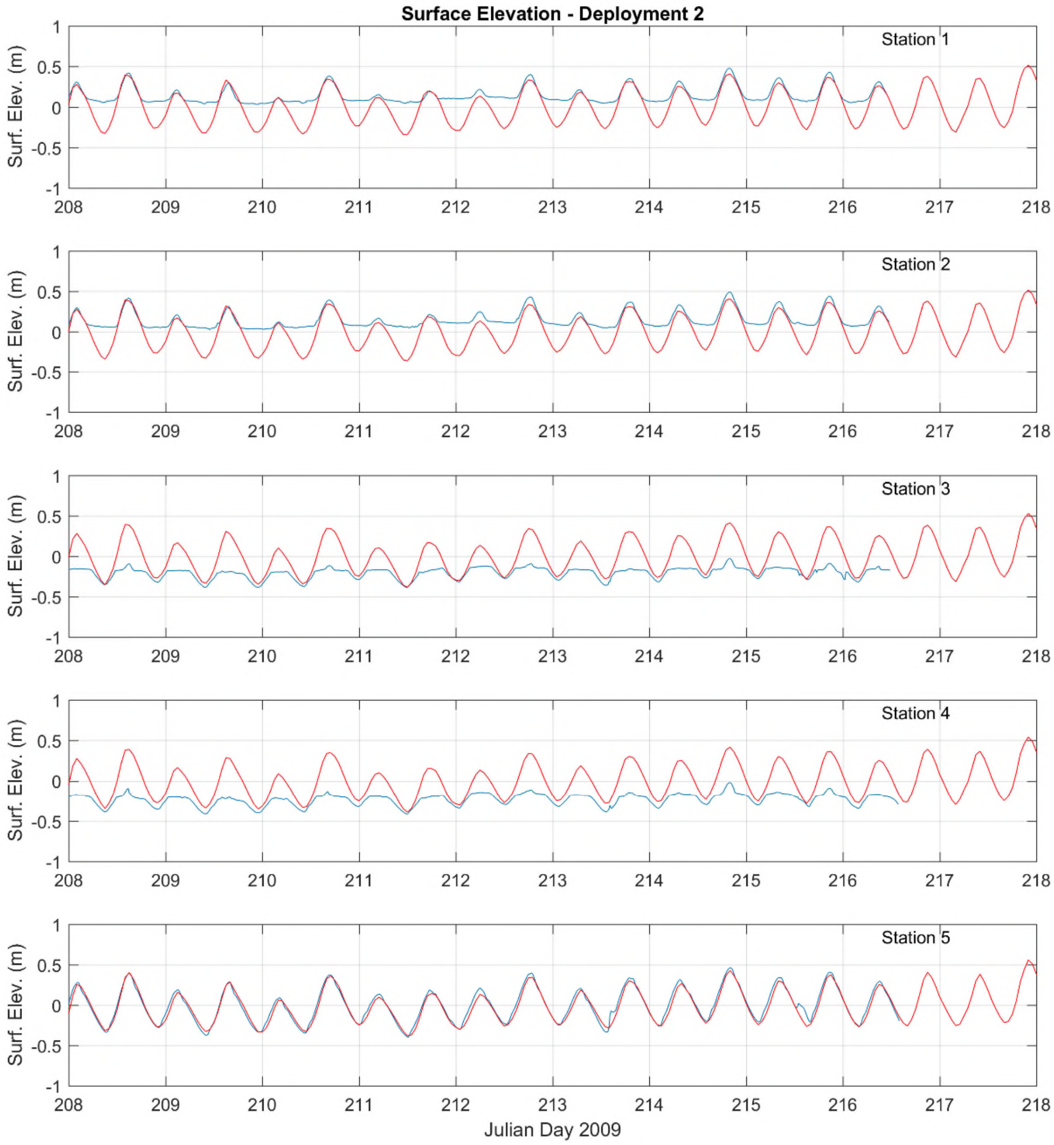

Figure C.8b. Real-time comparisons of predicted vs. observed surface elevations at five stations in the Thurston Branch and Thalia Creek during the deployment period 2.

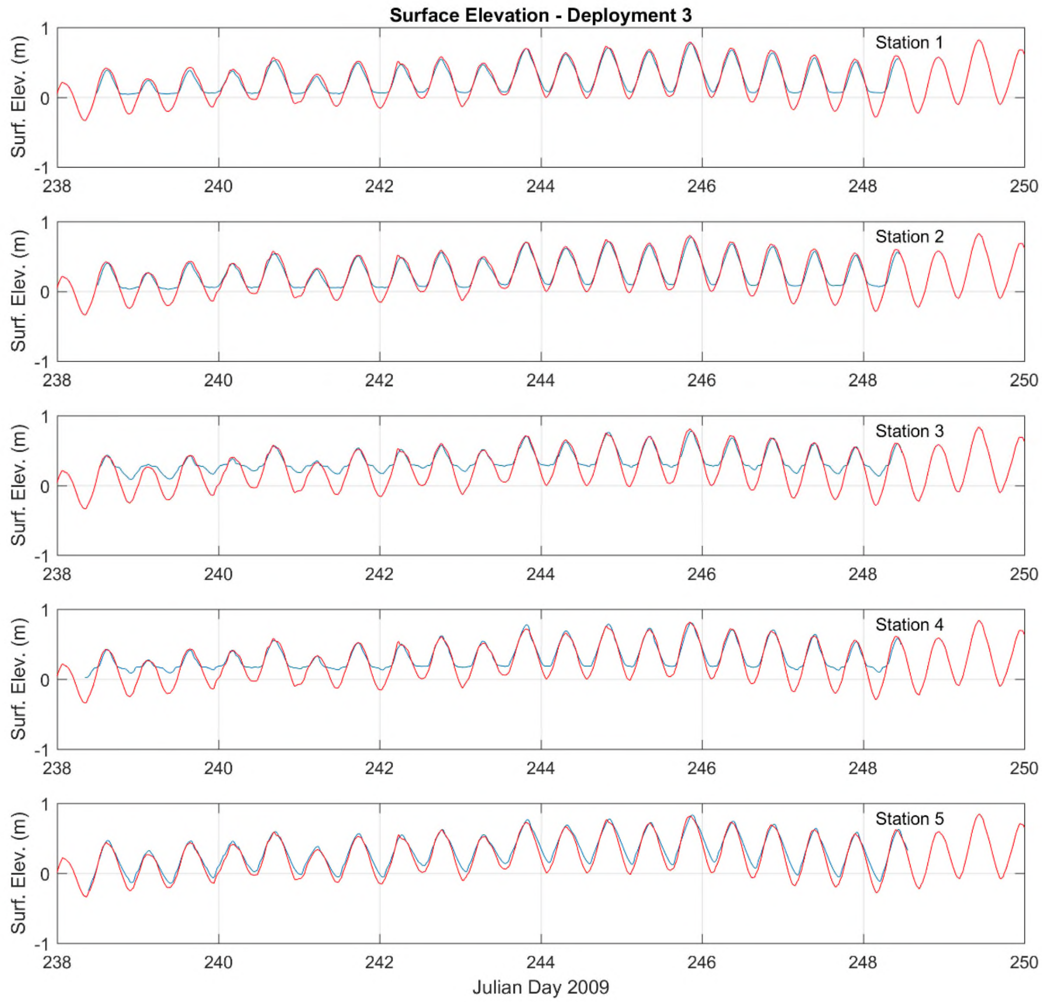

Figure C.8c. Real-time comparisons of predicted vs. observed surface elevations at five stations in the Thurston Branch and Thalia Creek during the deployment period 3.

The real-time comparisons for salinity (Figs. C.9a-c) and temperature (Figs.C.10a-c) in the Thurston Brach and Thalia Creek also show good agreement between the modeled and predicted values for the three deployment periods in 2009.

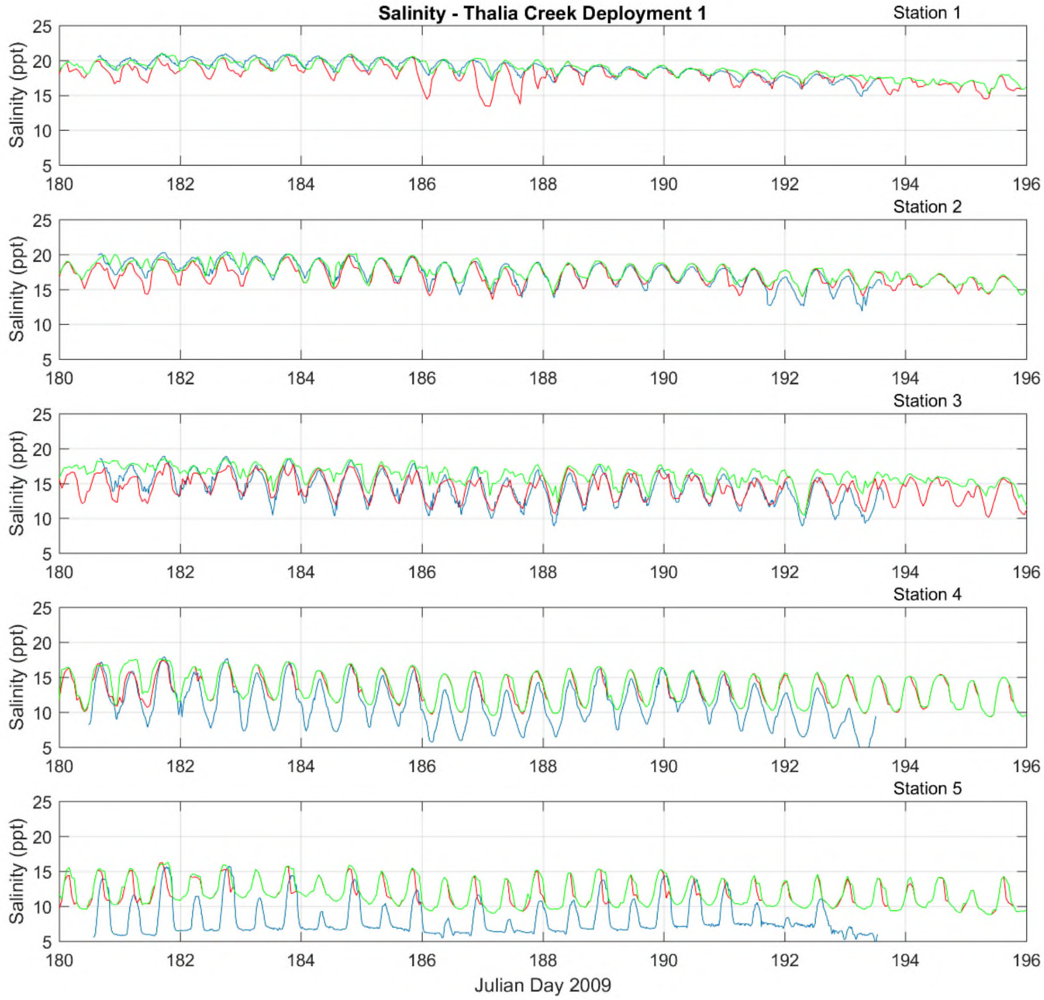

Figure C.9a. Real-time comparisons of predicted vs. observed salinity at five stations in the Thurston Branch and Thalia Creek during deployment period 1.

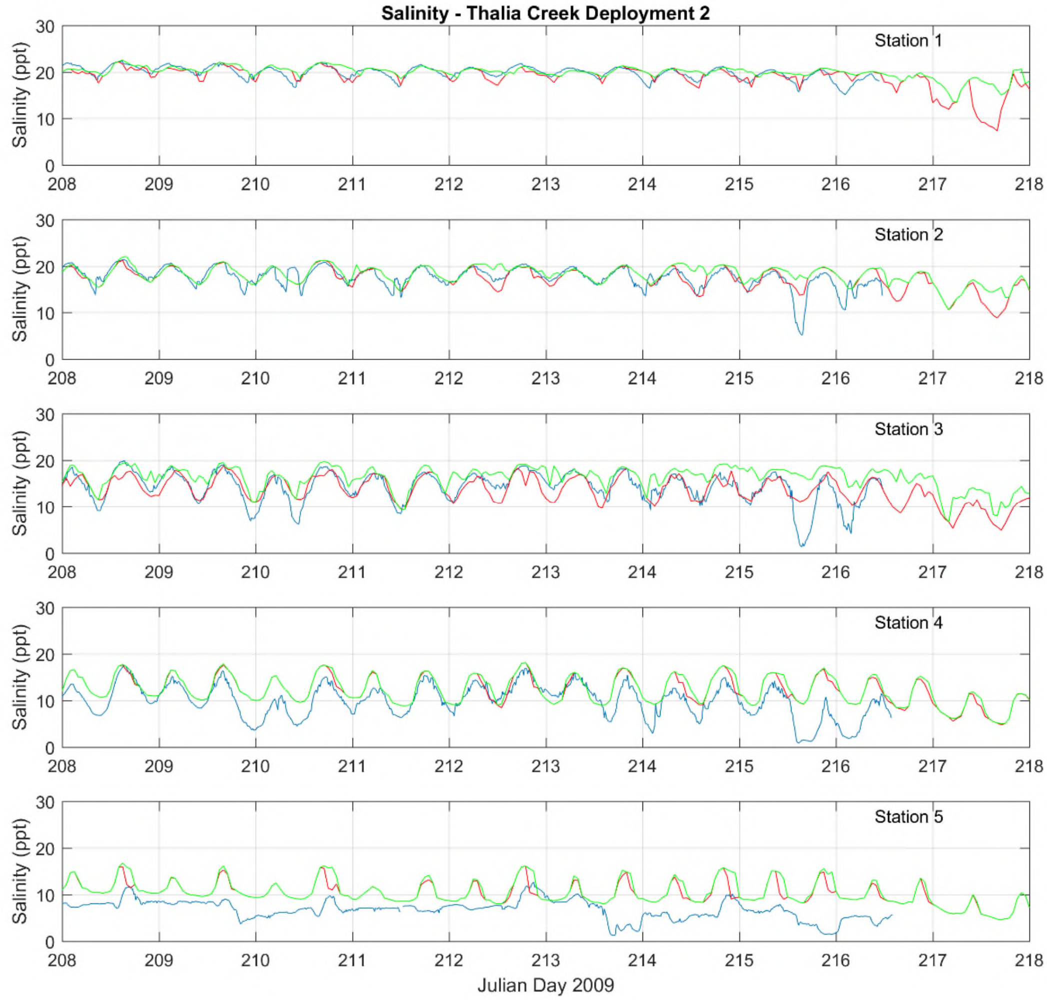

Figure C.9b. Real-time comparisons of predicted vs. observed salinity at five stations in the Thurston Branch and Thalia Creek during deployment period 2.

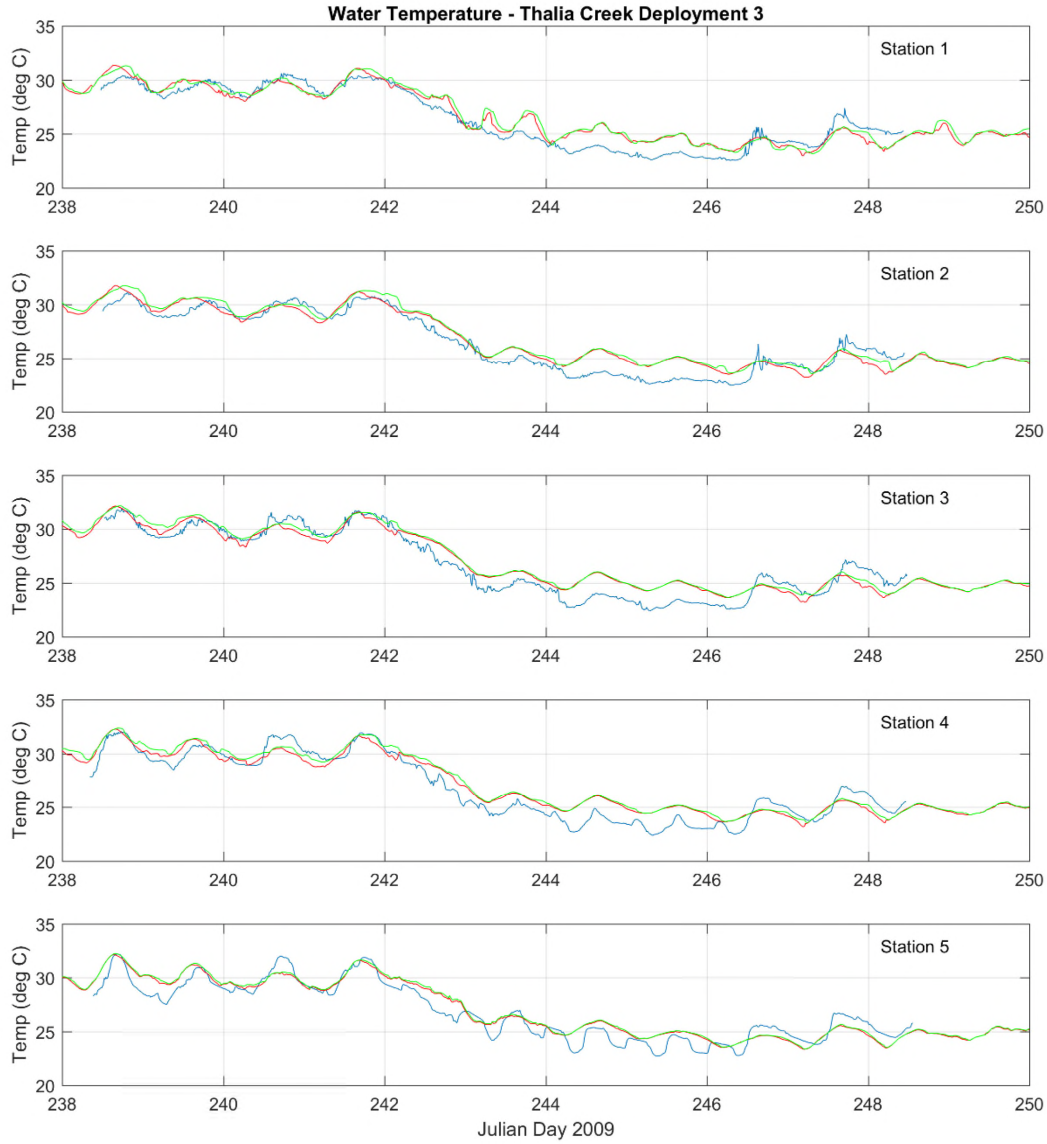

Figure C.9c. Real-time comparisons of predicted vs. observed salinity at five stations in the Thurston Branch and Thalia Creek during deployment period 3.

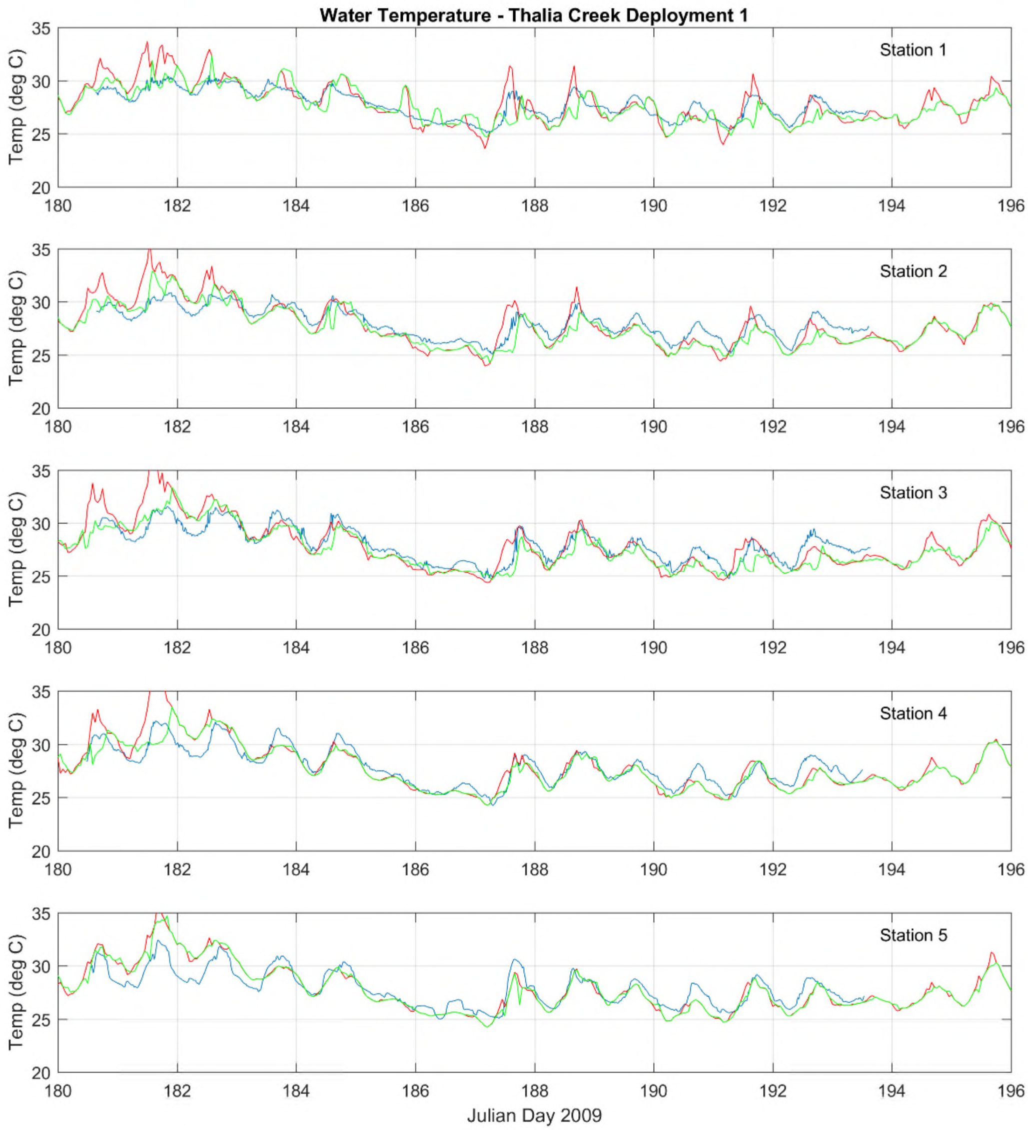

Figure C.10a. Real-time comparisons of predicted vs. observed temperature at five stations in the Thurston Branch and Thalia Creek during deployment period 1.

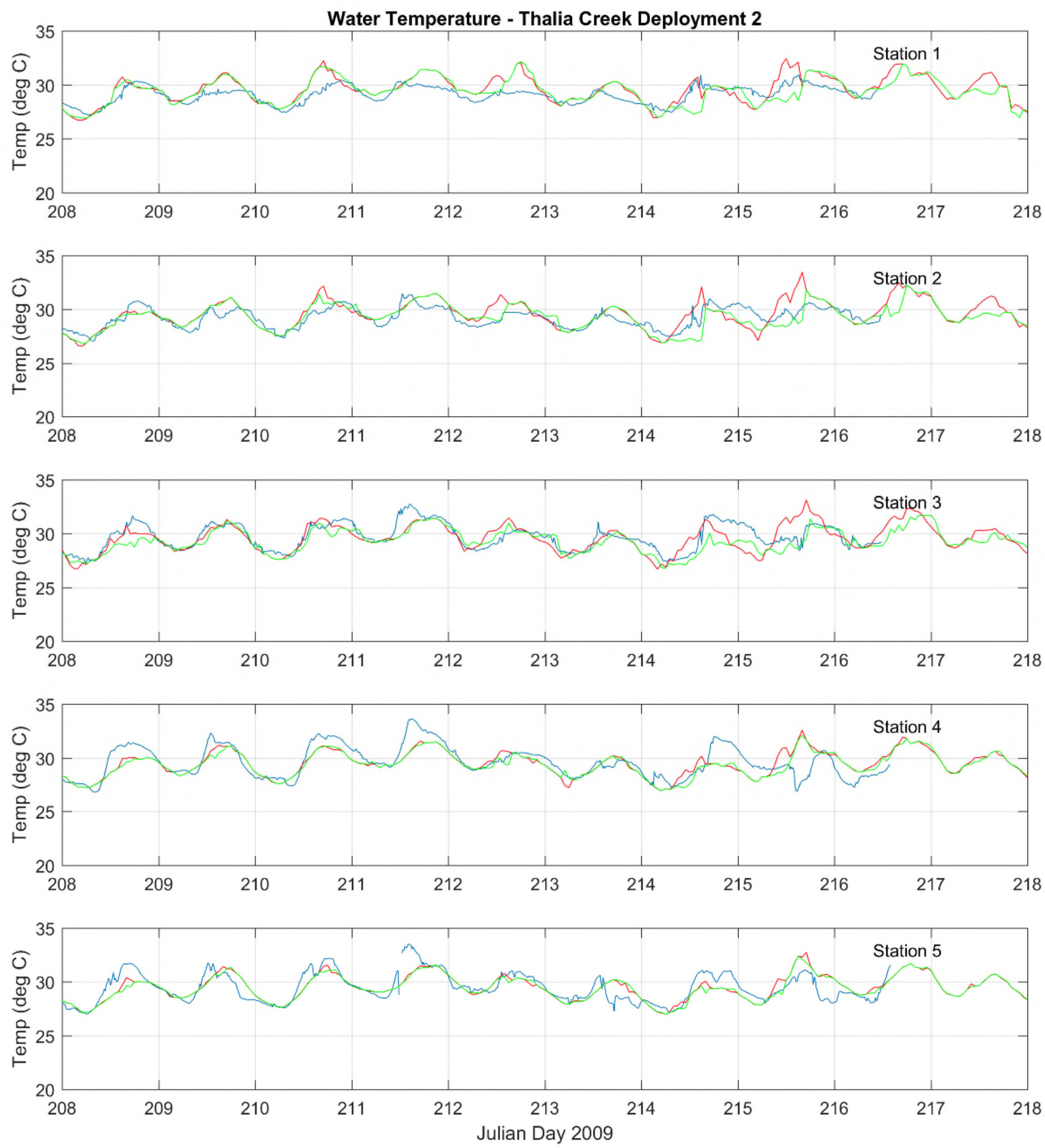

Figure C.10b. Real-time comparisons of predicted vs. observed temperature at five stations in the Thurston Branch and Thalia Creek during deployment period 2

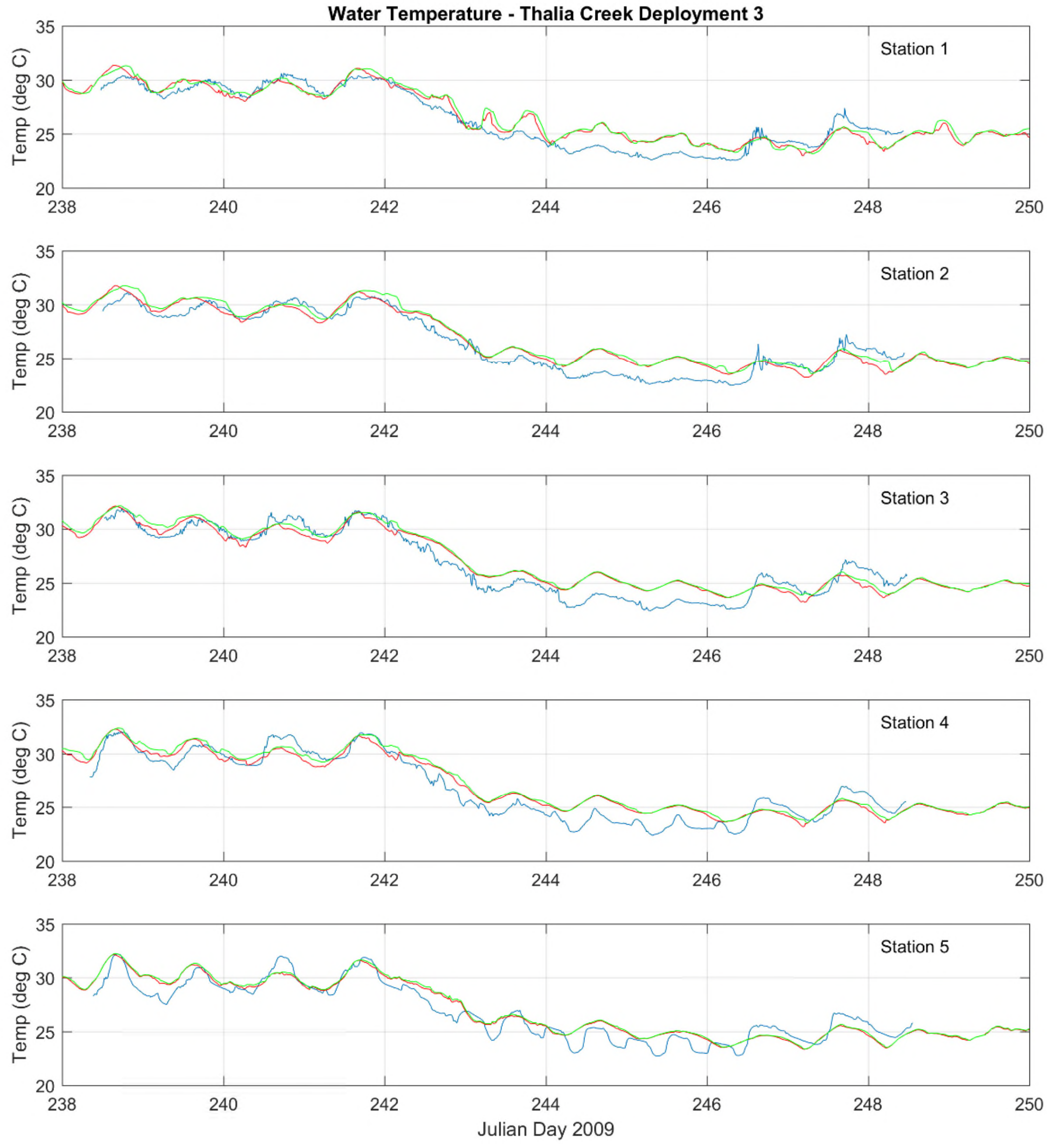

Figure C.10c. Real-time comparisons of predicted vs. observed temperature at five stations in the Thurston Branch and Thalia Creek during deployment period 3

The real-time comparisons for Chl-a (Figs.C.11a-b) and t and DO (Figs.C.12a-b) in the Thurston Brach and Thalia Creek also show good agreement between the modeled predictions and observed values.

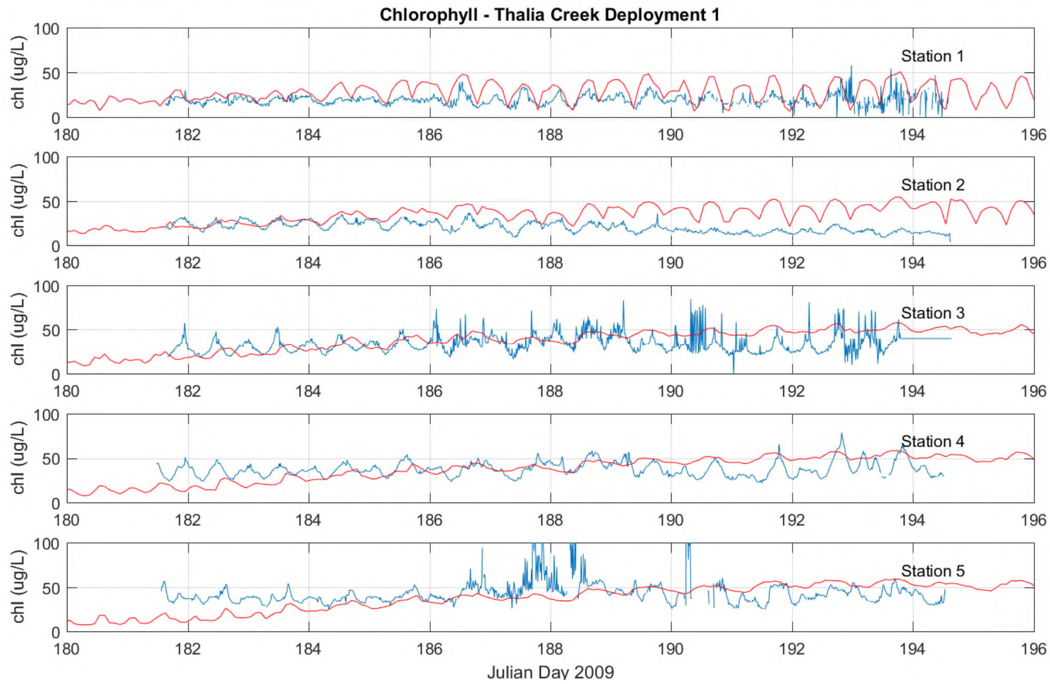

Figure C.11a. Real-time comparisons of predicted vs. observed Chl-a at five stations in the Thurston Branch and Thalia Creek during deployment period 1

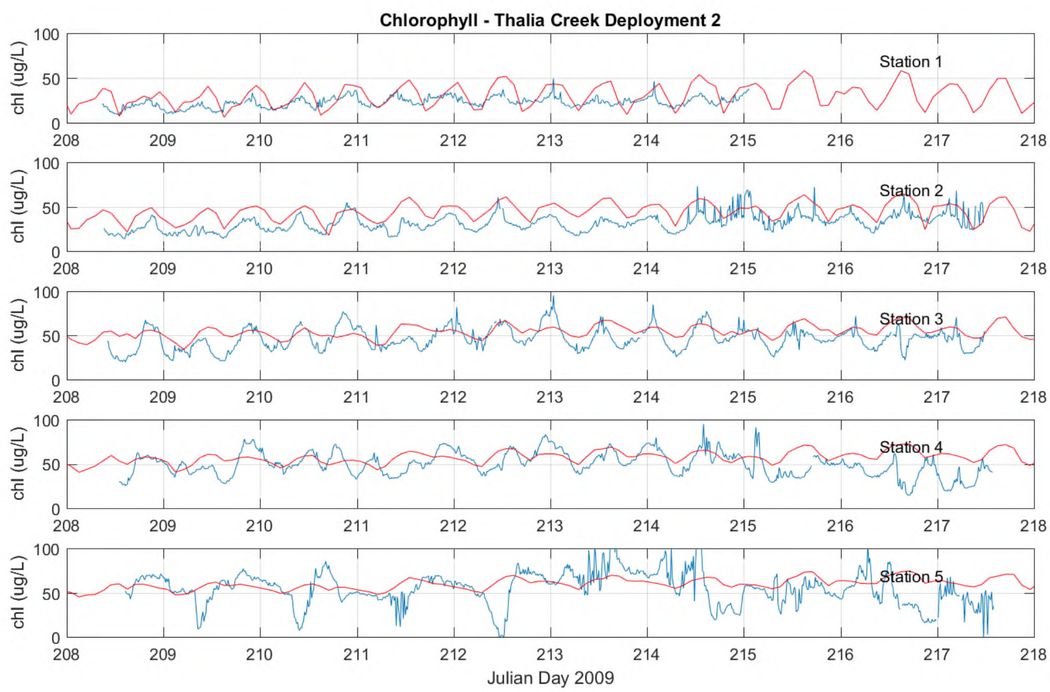

Figure C.11b. Real-time comparisons of predicted vs. observed Chl-a at five stations in the Thurston Branch and Thalia Creek during deployment period 2

Figure C.12a. Real-time comparisons of predicted vs. observed DO at five stations in the Thurston Branch and Thalia Creek during deployment period 1

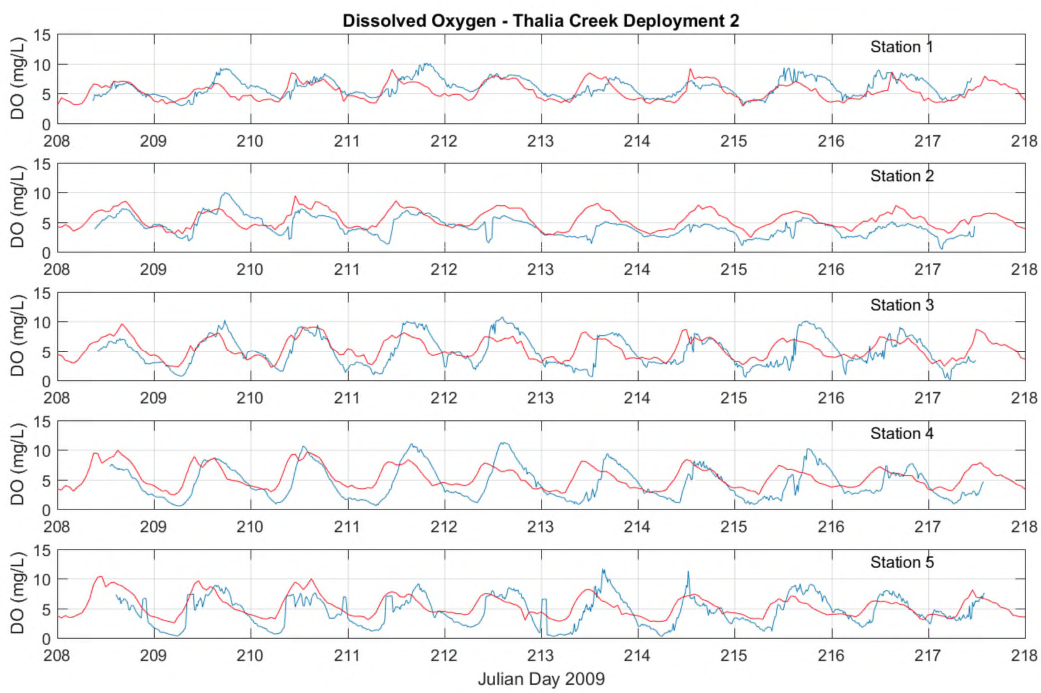

Figure C.12b. Real-time comparisons of predicted vs. observed DO at five stations in the Thurston Branch and Thalia Creek during deployment period 2.

Model calibration for the year 2018 was also conducted. Figs. C.13 and C.14 show the comparisons between model simulations and observational data for salinity and temperature and for DO and Chl-a, respectively. Overall, the model performs well in simulating the magnitudes and variations in both hydrodynamic and water quality parameters.

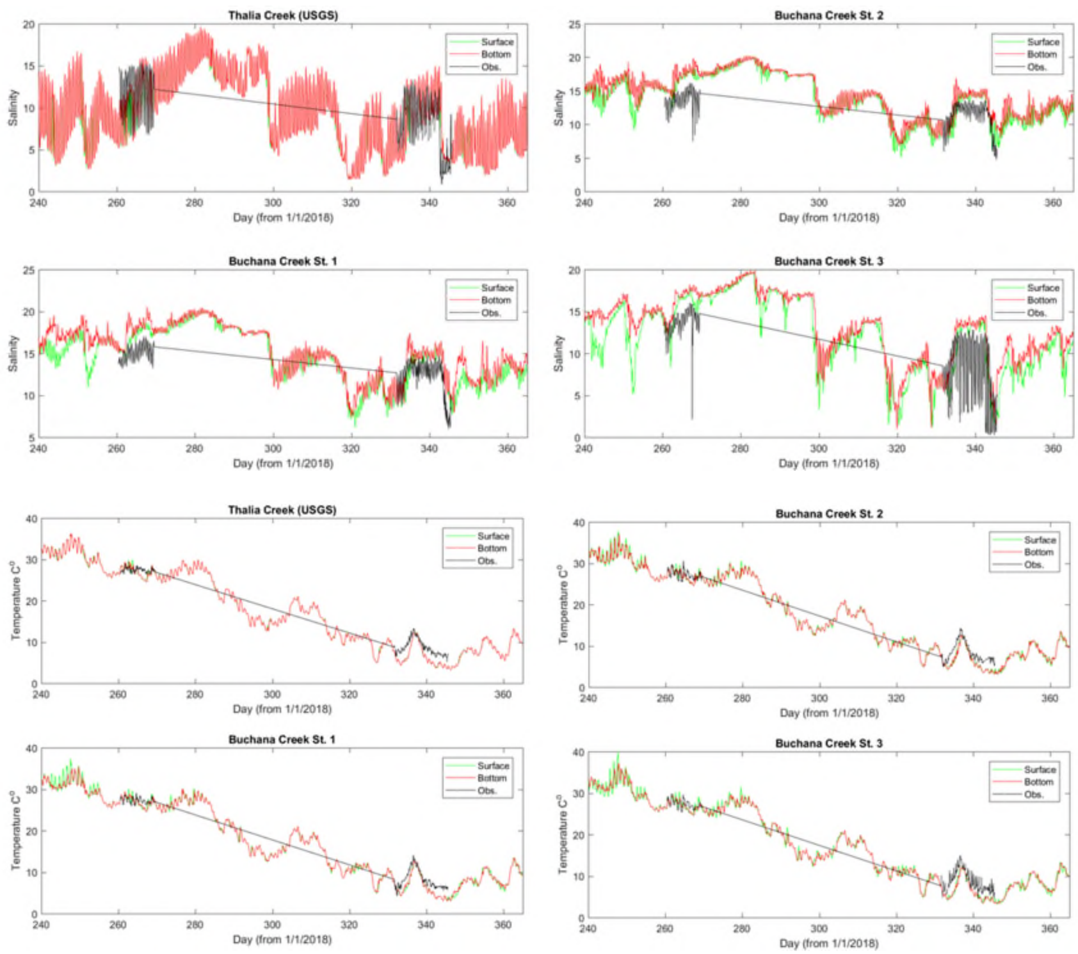

Figure C.13. EFDC model calibration of salinity and temperature for 2018. Green lines: model simulations at the surface; Red lines: model simulations at the bottom; Black lines: observational data.

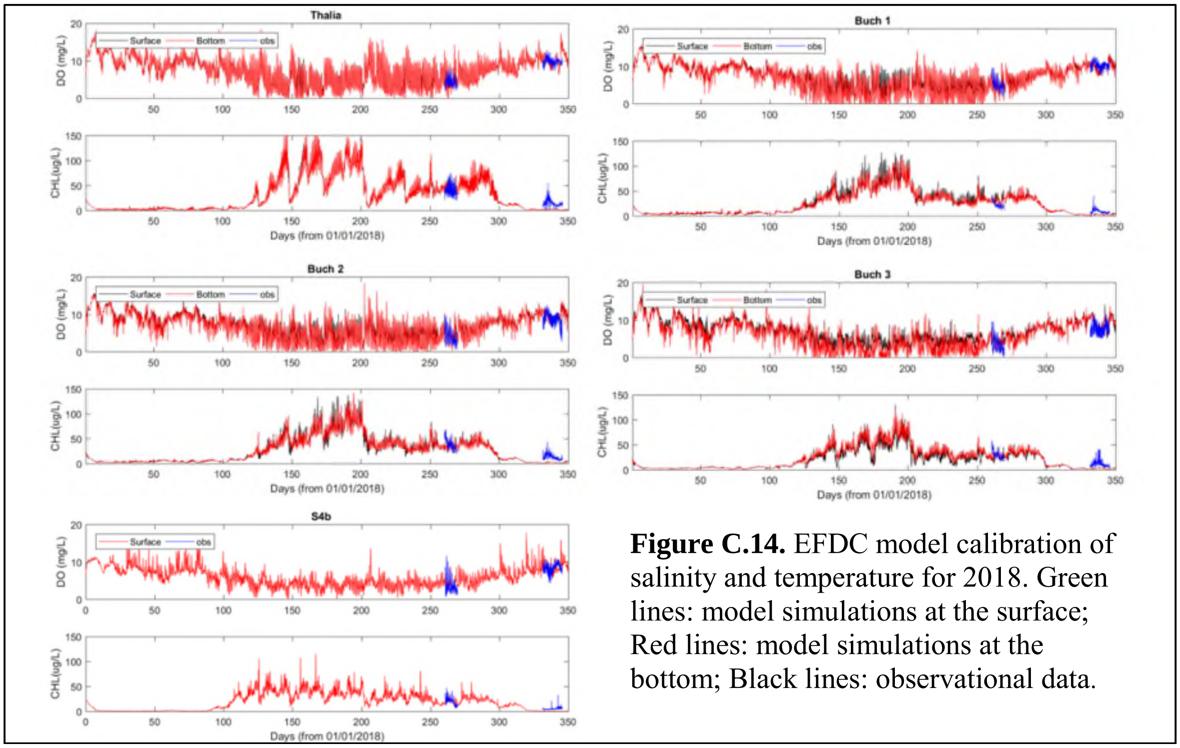

Figure C.14. EFDC model calibration of salinity and temperature for 2018. Green lines: model simulations at the surface; Red lines: model simulations at the bottom; Black lines: observational data.

SCHSIM model

For this study, we applied a 3D unstructured-grid hydrodynamic model (SCHISM, Zhang et al., 2016) to the study of impact of channel dredging on hydrodynamics in the project area. The model is an open-source community supported modeling system, based on mixed triangular-quadrangular unstructured grids in the horizontal and a very flexible coordinate system in the vertical direction (Zhang et al., 2015; Ye et al., 2018). The model employs a semi-implicit finite-element/finite-volume method, together with an Eulerian-Lagrangian method (ELM; Baptista, 1987) for momentum advection, to solve the Navier-Stokes equations in its hydrostatic form. The model was adopted due to its flexible gridding systems and computation efficiency. High resolution of up to 15 m (50 ft) is used to faithfully resolve the channels. The model simulates surface elevation, salinity, current, and temperature. The model can also conduct particle tracking study to simulate flushing time and transport time such as water age (Shen and Lin, 2006). The model grid including the Western Branch, the Thurston Branch, Thalia Creek, and Buchanan Creek is shown in Fig. C.15.

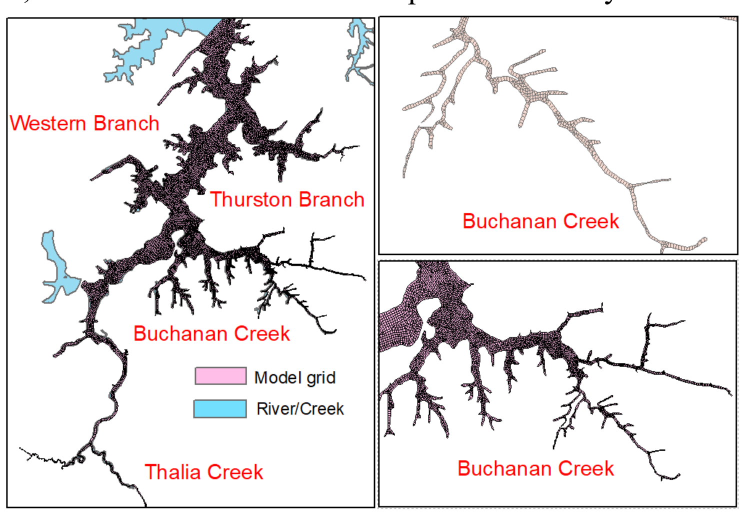

Figure C.15. SCHISM unstructured model grid

The calibration for the SCHISM hydrodynamic model used the same data set as the EFDC hydrodynamic model: data obtained from Thalia Creek and Thurston Branch during 2009, including high-frequency observed water surface elevation, salinity, and temperature data for different deployment time series ranging from 10-40 days.

Real-time comparisons of predicted vs. observed surface elevations for the Thurston Branch and Thalia Creek are shown in Figs. C.8a-c for deployments periods 1 – 3, June 30 to July 13, 2009, July 27 to August 5, 2009, and August 27 to September 6, 2009, respectively. Overall, the SCHISM model captured the semi-diurnal peaks and troughs and the phases of the observations quite well.

Real-time comparisons of predicted vs. observed salinity and temperature are shown in Figs. C.9a-c and C.10a-c, respectively, for deployments periods 1 – 3. The predicted salinity and temperature agree well with the observations.

Similarly, SCHISM model predictions and observed values for chlorophyll *a* and DO were in good agreement (Figs. 10a-b and 11a-b, respectively).