doi:10.25923/t5pn-xc77

A Decade of Water Level Changes along the New River Estuary in North Carolina, USA

National Centers for Coastal Ocean Science

NOAA National Ocean Service

NOAA Technical Memorandum NOS NCCOS #258

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November 2021

NOAA Technical Memorandum NOS NCCOS #258

United States Department of Commerce	National Oceanic and Atmospheric Administration	National Ocean Service
Gina Raimondo Secretary	Richard Spinrad Under Secretary of Commerce for Oceans and Atmosphere and NOAA Administrator	Nicole LeBoeuf Assistant Administrator

Acknowledgements

The New River Estuary water level monitoring program was conducted under Defense Coastal/Estuarine Research Program (DCERP1, RC-1413 and DCERP2, RC-2245), funded by the US Department of Defense's Strategic Environmental Research and Development Program. The National Oceanic and Atmospheric Administration's (NOAA) National Centers for Coastal Ocean Science (NCCOS) provided additional funding. Dr. Susan Cohen provided operational assistance within Marine Corps Base Camp Lejeune, including facilitation of station installation and site access. The monitoring program benefited from consultation with staff at NOAA's Center for Operational Oceanographic Products and Services and National Geodetic Survey. Data collection, instrument calibration, and station maintenance was conducted with the technical assistance of NOAA contract staff: Lisa Cowart, Priscilla Delano, Luke Snedaker, and John Wernly (JHT, Inc.); and Quentin Walker (CSS, Inc.). Alan Bol (University Corporation for Atmospheric Research); Tomma Barnes, Gregory Dusek, Artara Johnson, Ryan Lange, Michael Michalski, Greg Piniak, Paula Whitfield and David Wolcott (NOAA); and Scott Lerberg and Megan Tyrell (National Estuarine Research Reserve System) provided helpful comments on drafts of this material. Kevin McMahon (NOAA) improved editorial content.

Citation

Hilting, A.K., M. D. Greene, and C.A. Currin. 2021. A Decade of Water Level Changes along the New River Estuary in North Carolina, USA. NOAA Technical Memorandum NOS NCCOS 258. Silver Spring, MD. 76 p. doi:10.25923/t5pn-xc77

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Executive Summary

From 2008-2018, our program evaluated coastal marsh resilience to changes in inundation along the New River Estuary in Marine Corps Base Camp Lejeune (MCBCL) near Jacksonville, NC. To properly contextualize marsh parameters and processes across a range of tidal influence, we required site-specific information on water levels, temperature, and salinity. This was a challenge in that the study area was in a known coverage gap in the National Water Level Observation Network (NWLON), whose closest station was ~60 km away in Beaufort, NC. We established secondary water level stations in two different tidal regimes, supplemented by tertiary stations at our marsh monitoring sites. This technical memorandum summarizes ~ 10 years of water level, temperature, and salinity changes at MCBCL and provides our lessons learned regarding requirements for site-specific applications of water level data.

The overall patterns at the Beaufort NWLON station and our secondary water level stations in MCBCL were qualitatively similar but different in range or magnitude, with additional spatial variation within MCBCL. Tidal range decreased with distance from an ocean inlet (0.95 m at the Beaufort NWLON, located within an inlet; 0.44 m at Mile Hammock Bay (MHB), located ~ 2 km from an inlet; and 0.18 m at Gottschalk Marina Wallace Creek (GMWC), ~26 km up the estuary. Distance from an ocean inlet and proximity to riverine input also drove differences in salinity and marsh inundation patterns. GMWC had an average salinity of 14 and exceeded minor flood thresholds on nine days, whereas MHB's average salinity was 30 and the station experienced 19 minor floods. A sensitivity analysis demonstrated that the scale and variability of annual inundation duration depends on site-specific water levels and marsh elevation. For marshes at 0 m NAVD 88, average inundation duration near GMWC was found to be longer and more variable than near MHB. Though the tidal range at the NWLON station in Beaufort was about twice (0.95 m) that observed at MHB, their rates of relative sea level rise over the duration of the record were comparable (9.7 ± 5.1 mm y^{-1} at MHB and 9.6 ± 3.8 mm y^{-1} in Beaufort; GMWC's rate was 12.6 ± 7.2 mm y^{-1}). These rates are about three times greater than the regional long-term rates (1953-2020) observed at the Beaufort NWLON.

We learned several lessons about water level monitoring networks over the course of the project. We found the need for localized data was site-specific and application-specific. For example, we learned from our sensitivity analyses that data from the NWLON station 60km distant was sufficient for inundation calculations at one of the MCBCL marshes, while for another MCBCL marsh site in a tidal creek, a secondary water level station only 2 km away was insufficient for tidal datum or inundation calculations. An error budget and inundation sensitivity analysis also indicated that marshes with lower tidal ranges require greater water level (and marsh surface elevation) accuracy to reduce uncertainty in inundation duration analyses. We also archived our 6-minute water level, salinity, and temperature data, at the National Centers for Environmental Information, to fill a known gap in the National Water Level Observation Network and serve as a benchmark from which to assess influences of climate change and sea level rise on the New River Estuary. If done properly in advance, incorporating preliminary water level data collections, determining an acceptable error budget, and establishing a data stewardship plan can all improve the robustness and utility of a water level monitoring program.

Contents

List of Tables

List of Figures

List of Abbreviations and Symbols

%	Percent
°C	Degrees Celsius
AIWW	Atlantic Intracoastal Waterway
BM	Bench Mark
CI	Confidence Interval
cm	Centimeter
CO-OPS	Center for Operational Oceanographic Products and Services
DCERP	Defense Coastal/Estuarine Research Program
EC Gap	East Coast Gap
FC	Freeman Creek
FN	French Creek
GPS	Global Positioning System
GMSL	Global Mean Sea Level
GMSLR	Global Mean Sea Level Rise
GMWC	Gottschalk Marina Wallace Creek
GT	Great Diurnal Range (MHHW - MLLW)
km	Kilometer
LCM	Local Control Mark
m	Meter
MCBCL	Marine Corps Base Camp Lejeune
MHB	Mile Hammock Bay
MHHW	Mean Higher High Water
MHW	Mean High Water
MLLW	Mean Lower Low Water
MLW	Mean Low Water
mm	Millimeter
MN	Mean Range of Tide (MHW - MLW)
mS	MilliSiemans
MSL	Mean Sea Level
NAVD 88	North America Vertical Datum of 1988
NCCOS	National Centers for Coastal Ocean Science
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NSRS	National Spatial Reference System
NTDE	National Tidal Datum Epoch
NWLON	National Water Level Observation Network
OBB	Onslow Beach Backbarrier
PDSI	Palmer Drought Severity Index

PP	Pollocks Point
RSL	Relative Sea Level
RSLR	Relative Sea Level Rise
SD	Standard Deviation
SE	Standard Error
SLP	Survey Leveling Point
SZP	Sensor Zero Point
SLP	Survey Leveling Point
TIP	Top of the Interior Pipe
WL	Water Level
TIP	Top of the Interior Pipe
WL	Water Level
y	Year
YSI	Yellow Springs Instruments

1. Introduction

Long-term monitoring of water level, temperature, and salinity is valuable for addressing whether and how fast sea level rise and climate change may be altering the physical, chemical, and biological properties of coastal ecosystems (Paerl and Huisman, 2009; Osland et al., 2015; Lauchlan and Nagelkerken, 2020). In estuaries, with a gradient of tidal and nontidal influences, localized data are important for evaluating coastal wetland resilience to changes in inundation, salinity, and temperature.

One of the goals of the Defense Coastal/Estuarine Research Program (DCERP1, RC-1413 and DCERP2, RC-2245; funded by the US Department of Defense's Strategic Environmental Research and Development Program) was evaluating the resilience of salt marshes to sea level rise along the New River Estuary in Marine Corps Base Camp Lejeune (MCBCL) near Jacksonville, NC (Christenson et al., 2020; Davis et al., 2017; Cunningham, 2013a; 2013b; 2018). An understanding of the relationship between salt marsh primary production, surface elevation, and inundation across the MCBCL landscape was needed to model the coastal wetland response to local changes in inundation associated with the predicted 21st century increase in GMSL of 0.3 m to 1.3 m (Morris et al., 2002; Sweet et al., 2017a).

Sea level relative to land (relative sea level; RSL) can differ from GMSL by a wide range of regional conditions (Rovere et al., 2016). The National Oceanographic and Atmospheric Administration's (NOAA) Center for Oceanographic Operational Products and Services (CO-OPS) computed changes in RSL at 142 National Water Level Observation Network (NWLON) stations with minimum span of 30 years of observations at each location (NOAA, 2021). The reported rates are based on the entire duration of observations, which differs among stations. For East Coast stations with observations through 2019, RSL rise (RSLR) rates range from 1.89 ± 0.14 millimeters per year (mm y^{-1} ± 95 percent [%] confidence interval [CI]) (1912-2019; Portland, ME) to 5.97 + 0.80 mm y^{-1} (1975-2019; Ocean City, MD). The closest NWLON station to MCBCL is in Beaufort, NC (#8656483), where the RSLR rate is 3.22 ± 0.35 mm y^{-1} (1953–2019).

Building on the work of Hall et al. (2016), Sweet et al. (2017b) developed projections of RSLR based on 0.5 meter (m) incremental scenarios between the scientifically plausible lower and upper bounds of 21st century GMSLR. Based on the intermediate scenario (1.0 m of rise from 2000-2100), decadal RSLR rates near MCBCL are projected to increase from 8 mm y^{-1} (2000 to 2010) to 13 mm y^{-1} (2040 to 2050) to 17 mm y^{-1} (2090 to 2100). Additionally, RSL is projected to be 0.47 m higher in 2050 and 1.22 m higher in 2100 than it was in 2000 (Sweet et al., 2017b). A related metric of sea level rise — of interest to coastal flood managers — is increased flooding frequency. At Beaufort, NC, flooding frequency is projected to increase from 0 days per year in 2000 to 138 in 2050 to 365 in 2100 (Sweet et al., 2018).

The impacts of RSLR on water levels can be obscured by shorter-term drivers of water level changes. Oceanographic and atmospheric oscillations, including the El Niño/Southern Oscillation, can drive interannual variability and anomalies in water level (Zervas, 2009; Zervas et al., 2009; Sweet and Zervas, 2011). Water levels also change with daily tides, storms, seasonal cycles, and over several astronomical cycles as long as 18.6 years (a tidal epoch). In an estuary, nontidal influences on water level such as precipitation, sustained winds, and river flow become more important further from the inlet. While the precision of the RSL trend increases with the length of the record (Zervas, 2009), shorter-term trends, along with their variability, may be more relevant for evaluating marsh resilience to a continued acceleration of RSLR.

NWLON stations are strategically located and supplemented by shorter-term stations to provide the greatest areal coverage of the coastline, but spatial gaps in the network, many in estuarine settings, remain (Gill, 2014). For most water level data applications, it is critical to establish a station's elevation relative to land (the process of vertical control) and this can be difficult to do in coastal wetlands. The NOAA National Geodetic Survey (NGS) defines vertical control as the process of establishing orthometric elevations of permanent reference points through differential leveling or Global Navigation Satellite System connections between local vertical control networks and the United States (US) National Spatial Reference System (NSRS) (Hensel et al., 2015). NWLON stations meet the highest standards (National Ocean Service [NOS], 2013a), which can require intensive resource investment. Researchers working with limited resources and short time frames and in less than ideal conditions (e.g., marshes) must adapt CO-OPS and NGS standards and methods (Zilkoski et al., 1997, 2008; NOS, 2013a, 2013b; Hailegeberel et al., 2018) for the marsh environment (Hensel et al., 2015). Challenges of establishing vertical control in marshes include difficulty leveling on soft surfaces, lack of existing NSRS bench marks (BM), and lack of stable platforms for water level stations.

NWLON water level stations, with a planned operation of 19 years or longer, are considered primary stations for tidal datum calculation purposes. Stations with a planned operation of 1–19 years are called secondary stations and stations in operation for one month to one year are called tertiary stations (Gill and Schultz, 2001). Marsh research projects with water level data needs will typically require establishing secondary and/or tertiary stations, especially in locations with very different tidal characteristics from nearby NWLON or other long-term stations. Although the technical classification of primary, secondary, and tertiary stations is based on the duration of data collection, the quality of instrumentation and vertical stability of a water level station typically scales with length of deployment. For example, tertiary stations may be simple pressure transducer loggers attached to a pole or a piling deployed to evaluate differences in tidal range along an estuary. Their vertical position accuracy may not be sufficient to quantify the relationship between recorded water level and the marsh surface.

In recent years, CO-OPS has provided technical assistance to help researchers collect and analyze their own data. The most comprehensive and current guidance document for secondary water level stations in marsh environments, co-developed by the NGS, CO-OPS, and the National Estuarine Research Reserve System (Hensel et al., 2015), was unavailable when our project started. There remains a need for guidance for coastal wetland water level monitoring program design (e.g., station siting and deployment duration) and data analysis for application-specific requirements (e.g., inundation, tidal datums, and RSLR) in estuaries where localized conditions can vary within short distances.

To provide support for the DCERP marsh resilience studies (2008–2016) and a related National Centers for Coastal Ocean Science (NCCOS) project (2016–2018), NCCOS collected water level, salinity and temperature data in the New River Estuary from 2008-2018. The monitoring effort included maintaining vertical control, assessing error, analyzing temporal and spatial trends, and conducting sensitivity analyses. This memorandum presents a baseline climatology of water level, temperature, and salinity data in an NWLON gap, describes collection and analytical methods, and provides recommendations to inform similar efforts in estuarine data collection and analysis. Analytical results include spatial and temporal trends in water level, temperature, salinity, and tidal datums. Error budgets and sensitivity analyses are provided to illustrate the impact of uncertainty in water level on inundation and tidal datum results. We also highlight the importance of assessing requirements (e.g., duration of collection and localized data) for specific applications of water level data prior to commencement of a monitoring program.

2. Methods

2.1 Monitoring Design and Data Collection

MCBCL is located within Onslow County, NC near the City of Jacksonville. It borders the Atlantic Ocean and is intersected by the New River Estuary and the Atlantic Intracoastal Waterway (AIWW). The estuarine waters surrounding the DCERP research sites at MCBCL are about 63 kilometers (km) away from the closest NWLON station in Beaufort, NC (henceforth, the Beaufort station) and lie within NWLON East Coast (EC) Gaps #12 and #13 (Figure 1).

NCCOS monitored water level, marsh vegetation, and marsh surface elevation along the AIWW and New River Estuary salinity and tidal gradients (Figure 2). In 2008, six marsh research sites were established. At each site, two to six deep-rod Surface Elevation Tables (Cahoon et al., 2002; Lynch et al., 2015) were installed to monitor marsh surface elevation changes and provide reference marks for calculating inundation of the marsh surface. Two sites adjacent to the AIWW were situated approximately 2.0 and 3.5 km from Browns Inlet and four sites were located 2.5, 3.9, 8.5, and 19.5 km from the New River Inlet within the New River Estuary (Figure 2). Ideally, a secondary water level station would be co-located with each marsh research site to collect contemporaneous records of marsh elevation change and local sea level change (Cahoon, 2015). Challenges of working in the marsh environment and the availability of resources for secondary water level station maintenance made this impractical. Locations for stable secondary water level station platforms near the MCBCL marsh research sites were limited by suitable monitoring infrastructure, and the best options were a concrete bulkhead and a marina dock about 24 km apart. NCCOS installed secondary water level stations at these two locations. The monitoring program was supplemented by tertiary stations at some of the research sites.

The Mile Hammock Bay (MHB) water level station (34.55388 N, 77.326181W) was established at approximately 2.5 km from the New River Inlet. The Gottschalk Marina Wallace Creek (GMWC) water level station (34.67723N, 77.362721W) was established approximately 26.5 km from the New River Inlet (Figure 2). The GMWC station became operational on May 15, 2008 and ceased operation on August 26, 2016 at the close of the DCERP project. The MHB station remained in operation from February 21, 2008 until November 6, 2018, supporting a NCCOS-funded thin-layer sediment application project after the close of the DCERP program. In 2011, one year of data were shared with CO-OPS for preliminary analysis and official CO-OPS station numbers were assigned to the stations: 8656648 (GMWC) and 8657098 (MHB) as part of the data ingestion process. A summary of the 2008–2016 results was published in the DCERP2 final monitoring report (Currin et al., 2018) and the 2008–2018 data are archived at the National Centers for Environmental Information (Hilting et al., 2019).

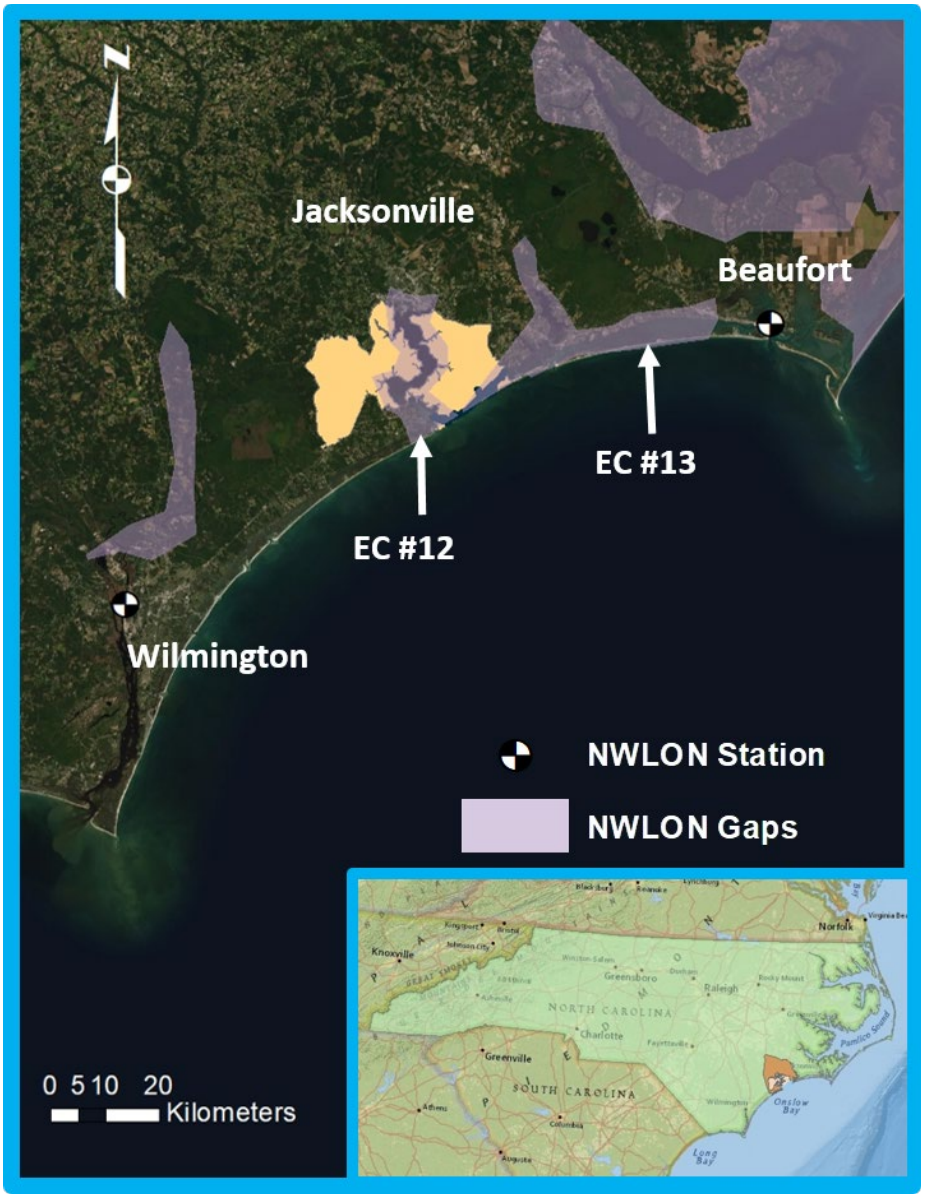

Figure 1. The location of Marine Corps Base Camp Lejeune (MCBCL; tan shaded area), the nearest National Water Level Observation Network (NWLON) stations, and spatial gaps in NWLON coverage. The AIWW is in NWLON Gap East Coast (EC) #13 between the mainland and barrier islands. The New River Estuary is within NWLON Gap EC #12.

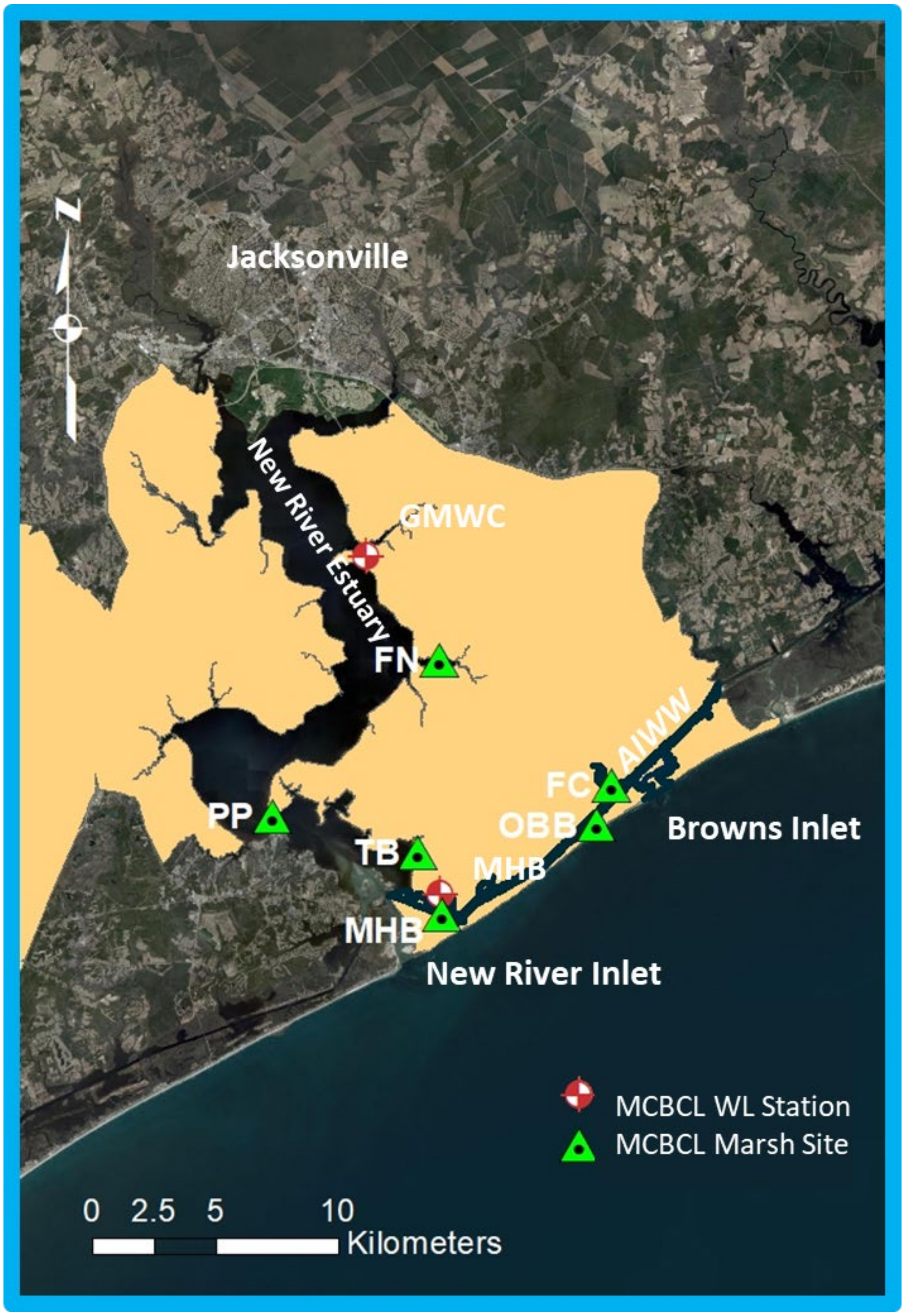

Figure 2. Marine Corps Base Camp Lejeune (MCBCL) (shaded area) with locations of the Gottschalk Marina Wallace Creek (GMWC) and Mile Hammock Bay (MHB) water level (WL) stations and marsh research sites. Research sites names are Freeman Creek (FC), French Creek (FN), MHB, Onslow Beach Backbarrier (OBB), Traps Bay (TB), and Pollocks Point (PP). The MHB research site is located on the barrier island across the Atlantic Intracoastal Water Way (AIWW) from the MHB water level station.

2.1.1 MCBCL Secondary Water Level Station Design and Vertical Control

The MCBCL secondary water level stations were designed to maintain Yellow Springs Instruments (YSI) 600LS vented sondes at a fixed vertical and horizontal position. We followed

NGS and CO-OPS guidelines to establish and maintain vertical control of the water level stations throughout the study (Zilkoski et al., 1997, 2008; NOS, 2013b; Hensel et al., 2015; Hailegeberel et al., 2018). Station structure and vertical control methods, results, and sources of error are detailed in Appendix A and are described briefly here. The station was attached to a stable structure and repeated measurements were made to establish and maintain the instrument's Sensor Zero Point (SZP) (the bottom of the instrument) relative to an accessible reference point known as the Survey Leveling Point (SLP). Global Positioning System (GPS) data were collected to determine the elevation of a Local Control Mark (LCM). Lastly, leveling and direct measurements were used to transfer the LCM elevation to the SZP through the SLP and an intermediate reference point on the water level station that we call the Top of the Interior Pipe (TIP). Each step of the vertical control process contributed to the uncertainty of water level measurements and tidal datums.

2.1.2 Data Collection, Instrument Calibration, Quality Control, and Data Compilation

The YSI 600LS vented sondes recorded temperature, salinity, and water level at six-minute intervals. The sondes automatically determined salinity, on the unitless Practical Salinity Scale, from sonde temperature and conductivity readings and automatically compensated transducer readings for density to determine water level. Reported values were the average of one minute of sampling (sampling rate is proprietary). The data were downloaded every 1–2 months using a YSI 650 data logger and compiled for each sonde deployment. Initially we used using anti-fouling paint to protect the sondes' non-sensor surfaces from fouling, but transitioned to wrapping them with cellophane and electric tape, as it was just as effective and more efficient. The sondes were replaced every 3 to 9 months to reduce the potential for issues associated with sensor fouling. To ensure that a replacement sonde was always available, six sondes were regularly serviced and repaired as needed. Storm plans included removing the sonde and external battery prior to a storm or simply downloading data, closing the vent tube, and removing the external battery.

There were a total of 26 sonde deployments at MHB and 19 at GMWC. Prior to deployment and immediately post deployment the sondes underwent standard YSI calibration procedures to check that measurements were within instrument specifications (accuracies of ± 0.003 m water depth, ± 0.251 +/- 0.5 % + 0.001 milliSiemans per centimeter (mS cm^{-1}) specific conductance, and ± 0.01 degrees Celsius [°C]) (YSI Incorporated, 2012). Post deployment calibration procedures included checking for drift associated with fouling and instrument calibration. Upon immediate return to the lab and prior to cleaning, the sondes were set to record at one-minute intervals while immersed in a series of media (site water, deionized water, and conductivity standard solution [50 mS cm^{-1}; YSI #3169]) for a minimum of one hour each. After cleaning, the sondes were re-immersed in the same series for the same minimum period. Comparisons of the data from the fouled and cleaned immersions with that of pre-deployment calibration data allowed for the detection of drift due to fouling or instrument sensors.

Drift and offsets in water level, specific conductance, and temperature calibration sometimes occurred over the course of the deployments. When offsets were detected, the data were carefully reviewed to see if a shift in instrument performance could be detected. The compiled deployment water level, temperature, and salinity data of each station were compared to each other and the water level data were compared to the Beaufort station data to check for consistency in their relative trends. This quality control measure helped us identify the exact timing of events such as a shift in sensor elevation due to a boat strike and a minor structural failure (Appendix A, Table A1). Data with uncertain sensor elevation or abrupt shifts in temperature or salinity were removed. However, it was common to have a minor calibration drift in time (up to 2 minutes), depth (a few mm), temperature (< 1 °C), or specific conductance (< 1 mS cm^{-1}) over the course of a deployment. Because the timing of drift is difficult to identify, minor drift was accepted and accounted for in the water level error budget as a 0.01 m calibration error. Error budgets were not established for the salinity and temperature data.

Battery and structural failures, sensor malfunctions, and removal of data during quality control resulted in data gaps. Data gaps also occurred regularly during downloads (< 30 min) and instrument change outs (< 3 hours). Once reviewed for quality control, the water level data from all deployments were compiled into a master database and referenced to the North American Vertical Datum of 1988 (NAVD 88). Gaps in water level data that were < 3 hours were linearly interpolated (avoiding interpolation across peaks and troughs). Salinity and temperature data were compiled into a database but their data gaps were not interpolated. Water level data were collected from May 15, 2008 to August 26, 2016 (8.3 years) at GMWC with a single gap > 3 hours (of 6 days), which occurred 5/27/2016–6/2/2016. This station provided an 8-year continuous record between May 2008 and May 2016 (Table 1). At MHB, eight data gaps of 7 to 61 days in duration occurred between February 21, 2008 and November 6, 2018 (10.7 years of data collection). The longest continuous record at MHB was from February 27, 2013 to December 24, 2016 (3.8 years). The MHB station was located in an open basin with greater exposure to storm surges. The removal of MHB sondes prior to some storms, and sensor failure due to fouling associated with high salinity waters contributed to the greater number of data gaps in the MHB record.

Table 1. The periods and durations of continuous six-minute water level data and the duration of the data gap preceding each period of continuous data at each station. N/A is not applicable. MHB is Mile Hammock Bay and GMWC is Gottschalk Marina Wallace Creek.

Station	**Continuous record start date**	**Continuous record end date**	**Duration of continuous record (Days)**	**Duration of data gap (Days)**
MHB	2/21/2008	2/29/2008	8	N/A
MHB	4/10/2008	6/22/2009	438	41
MHB	7/31/2009	10/20/2011	811	40
MHB	12/7/2011	2/14/2013	435	48
MHB	2/27/2013	12/24/2016	1396	13
MHB	1/4/2017	1/28/2017	24	11
MHB	3/30/2017	8/2/2018	490	61
MHB	8/9/2018	9/10/2018	32	7
MHB	9/26/2018	11/6/2018	41	16
GMWC	5/15/2008	5/27/2016	2934	N/A
GMWC	6/2/2016	8/26/2016	85	6

Tertiary stations were deployed at several marsh research sites using ONSET HOBO U20 pressure transducer loggers. Loggers were suspended in PVC wells installed in the marsh and/or just offshore of the marsh, with an additional logger installed at a higher elevation nearby to collect barometric pressure data. For a limited assessment of tidal attenuation in the AIWW, three loggers were attached to channel markers. We used one of two logger models, U20-001-04-Ti or U20-001-01-Ti, to record water pressure and model U20-001-04 to record atmospheric pressure. The data were downloaded regularly using the HOBO Waterproof Shuttle U-DTW-1 and the program HOBOware Pro v 3.7.17 was used to compensate the water pressure for barometric pressure to obtain water level. The water level loggers have an accuracy of up to 0.003 m (ONSET, 2020). However, because logger sensor stability is not rigorously controlled and deployments are short term, datums based on logger data are less accurate than MHB and GMWC datums. We also used tertiary station data to compare in situ-measured inundation with inundation determined using data from Beaufort, MHB, or GMWC for the period of contemporaneous data collection.

2.2 Data Analyses

2.2.1 Tidal Datums and Temporal Trends

Tidal datums are standard elevations defined by phases of the tide (e.g., mean low water [MLW]) that are specific to location and commonly referenced to fixed points on land (NOS, 2003). A list of common tidal datums and their abbreviations are provided in Appendix B Table B-1. Tidal datums presented in this memorandum include mean higher high water (MHHW), mean high water (MHW), mean sea level (MSL), MLW, mean lower low water (MLLW), the great diurnal range (GT = MHHW − MLLW), and the mean range of tide (MN = MHW − MLW). There are different types of tidal datums and different methods for their calculation (Licate et al., 2017). The National Tidal Datum Epoch (NTDE) datum represents average observations over a designated 19-year epoch; the current NTDE is 1983-2001. There is no commonly accepted term to refer to tidal datums that are not referenced to (or are independent of) a NTDE; for this memorandum we adopt the term “Non-Epoch” tidal datum to represent observations over periods shorter than 19 years. For secondary or tertiary stations on the East Coast, the Modified Range Ratio method is used to determine NTDE-equivalent datums by a procedure called Monthly Mean Simultaneous Comparison (MMSC). In this method, the secondary or tertiary station is considered a subordinate station that is referenced to a control station, typically a nearby NWLON station. Errors in the computation of NTDE-equivalent datums are associated with the geographic distance and differences in tidal timing and tidal range between the control station and the subordinate station and these errors decrease with the length of the record (Bodnar, 1981). There is no computation error for 19-year NTDE or Non-Epoch datums because they are based on observations. NTDE tidal datums represent average conditions over a standard 19-year period, which allows for comparisons between stations and provides common reference elevations for navigation, flooding thresholds, and coastal boundary delineation. Non-Epoch monthly tidal datums provide a summary of changes over time. They are used to identify temporal trends including seasonal cycles, sea level trends, and interannual variability.

We used CO-OPS’ Tidal Analysis Datum Calculator (Licate et al., 2017) to produce Non-Epoch monthly tidal datums and Non-Epoch and NTDE-equivalent annual and multi-annual tidal datums for periods of continuous water level data between 2008–2018 at MHB, GMWC, and Beaufort. The program was also used to produce tertiary station Non-Epoch datums for their short periods of deployment. The Beaufort station served as the control station for NTDE-equivalent datum computation. At MHB, where continuous data were limited by eight data gaps

(Table 1), Non-Epoch and NTDE-equivalent annual and multi-annual datums were computed for eight full year periods (none of which covered a calendar year), a two-year period, and a three-year period. At GMWC, where continuous water level was recorded from May 2008 to May 2016, datums were computed for calendar years (2009–2015) and for the 8-year period between May 2008 and May 2016. NOS derived thresholds for minor, moderate and major flooding were derived following Sweet et al., 2018 using NTDE-equivalent MLLW and GT values based on the longest multiannual period at each site. Flooding frequency was determined from the number of days per year with at least one hourly water level value above an elevation threshold.

The seasonal cycles of Non-Epoch MHHW, MHW, MSL, MLW, and MLLW were determined by calculating the average value for each calendar month over each time series. After subtraction of the seasonal cycle from the monthly means, de-seasonalized monthly MSL was used to calculate the rate and 95% CI of RSLR level at each station using an autoregressive model with an order of one in R (R Core Team, 2013) following Zervas, 2009. Interannual variability was determined as the monthly MSL residual, after removal of the 2008–2018 trend and the 2008–2018 seasonal cycle. A 5-month running average of interannual variability was also calculated to detect positive (> 0.1 m) and negative (< -0.1 m) anomalies sometimes associated with oceanographic and atmospheric oscillations (Zervas, 2009). Note that seasonal cycle and the interannual variability of the Beaufort station in this memorandum differ from those on the CO-OPS website (NOAA, 2021) because we use the 2008–2018 data, as opposed to the entire time series, to de-seasonalize and de-trend the monthly MSL records. This was done to facilitate comparison with the limited time-series of MHB and GWMC results.

2.2.2 Error Budget of Water Level and Tidal Datums

The vertical control and data processing methods describe attempts to maximize data accuracy and, thus, their utility in addressing coastal resilience questions. To quantify the 95% CI uncertainty associated with water level values and tidal datums, we used the International Hydrographic Organization (IHO) error budget equation (NOS, 2017).

The 95% CI combined uncertainty is

$$CI = b + 1.96s$$

Where,
b = the sum of systematic errors and biases and
s = square root of the sum of squares of the component random errors at the one standard deviation (SD) level.

Because the terms accuracy and uncertainty are sometimes applied inconsistently (e.g., see Bodnar, 1981 and Gill, 2014) and because there are two types of error that contribute to uncertainty, we describe the terms here. As defined by the Nondestructive Testing Resource Center (2020), accuracy is the agreement between a measurement and the true (or accepted reference) value whereas error is the disagreement between a measurement and the true value. Uncertainty is an interval around a measured value within which the true value is asserted to lie with some measure of confidence.

Uncertainty affecting both water level values and tidal datums includes systematic and random errors (NOS, 2017). Systematic errors, or biases, deviate by a fixed amount from the true value of measurement. For a single deployment of a water level sensor instrument, an offset in calibration would be a systematic error because all water level measurements would be off by the same amount and direction. Random errors are a function of the distribution of values around a mean and are a measure of the precision of a measurement. With repeated measurements, systematic errors can become random errors. For example, the calibration offset for a series of different instruments is a random error, as it is unlikely that each instrument will have a calibration offset of the same amount and direction. Other sources of random error are instrument accuracy, leveling, and direct measurements. Leveling and direct measurement error are summarized in Appendix A.

The two sources of systematic error in our error budget are the NTDE-equivalent tidal datum computation error and the error in the Online Positioning User Service project-determined elevation (Appendix A). We used the Bodnar (1981) equations to calculate the NTDE-equivalent tidal datum computation error at MHB and GMWC for 1, 3, 6, and 12 month periods. Equation input included the distance between the subordinate stations and the control station (Beaufort) (63 km), differences in subordinate and control MLW tide times (4.2 hours for GMWC and 1.1 hours for MHB) and the ratio of subordinate to control MN. We used the published NTDE MN for Beaufort station (0.95 m) and the NTDE-equivalent MN calculated for three years at MHB (0.42 m) and for eight years at GMWC (0.18 m). These results and a linear regression from one year to 19 years (also following Bodnar, 1981) were used to generate curves illustrating the decrease of datum computation error with length of time.

2.2.3 Inundation and Sensitivity Analysis

Inundation was determined using hourly water level data in a spreadsheet calculator as the duration (percent time), that water was above a specified elevation for a specified period such as a month, season, or year. The source of water level data used for the calculation varied by site. To evaluate whether the Beaufort, MHB, or GMWC data could be used to calculate site-specific inundation, tertiary station water level data were collected over 2–11 months at several of the marsh research sites. Sensitivity analyses were used to compare inundation for the range of marsh elevations at each site using the in situ (tertiary station) water level data with inundation calculated for the same period and elevations using Beaufort, MHB, and/or GMWC water level data. The criterion for acceptance of a longer term station for site-specific inundation calculations was that inundation duration calculated using the longer term station data would be within 5% of that calculated using the in situ stations. Sensitivity analyses were also conducted to evaluate the impact of the water level error budget on inundation results. We applied a combined uncertainty of 0.06 m 95% CI for the interface between water level and marsh surface elevation to calculate the uncertainty of annual inundation duration for marsh elevations at 0.1 m intervals using three sources of water level data (Beaufort, MHB, and GMWC). Water level uncertainty (0.04 m 95% CI) was calculated using the IHO error budget equation (NOS, 2017) and marsh surface elevation error was assumed to be 0.02 m 95% CI.

2.2.4 Salinity and Temperature

As with the water level data, the salinity and temperature 6-minute records have data gaps caused by data downloads (typically 30 minutes), instrument change outs (typically 1–3 hours), and instrument failures, however, data gaps in the salinity and temperature records were not filled. (See Hilting et al., 2019 for the number, timing, and duration of the salinity and temperature data gaps.) Gaps > 3 hours in duration (0.2 to 113.1 days) occurred seven times for MHB temperature and eight times for MHB salinity. At GMWC, there are only two data gaps > 3 hours (0.2 and 6.3 days) in both salinity and temperature. The 6-minute data were compiled and used to calculate monthly mean (± standard error [se]), maximum, and minimum values for months with at least 99.5% complete records. These monthly means were then averaged per calendar month over the study period to determine the seasonal cycle. A simple linear regression analysis was used to evaluate the relationship between monthly salinity at MHB and at GMWC and the modified Palmer Drought Severity Index (PDSI; a measure of dryness based on precipitation and temperature) for the Southern Coastal Plain of NC (North Carolina Climate Office, 2019).

3. Results

Water level results from MHB and GMWC are shown in comparison to results from the Beaufort station from 2008–2018. The Beaufort data were critical to the MHB and GMWC results, providing a temporally-complete verified record against which MHB and GMWC water level data could be referenced. Comparisons between stations are biased by data gaps in the MHB and GMWC records.

3.1 Temporal Trends

3.1.1 Hourly Water Level and Events

A comparison of hourly water level at the two MCBCL stations and the Beaufort station between 2008 and 2018 illustrates similarities in tidal patterns, differences in tidal range, and the impact of extreme events on water levels (Figure 3). The highest observed water levels occurred during storms or hurricanes: 1.56 m NAVD 88 at Beaufort (Hurricane Florence, September 2018), 1.03 m NAVD 88 at MHB (Hurricane Irene, August 2011), and 1.08 m NAVD 88 at GMWC (remnants of Tropical Storm Nicole, September 2010). High water of ~ 1 m NAVD 88 was also observed at MHB during Tropical Storm Joaquin (October 2015) and Hurricane Matthew (October 2016). At GMWC, the second highest water level (0.93 m NAVD 88) was observed during Tropical Storm Joaquin (October 2015). The lowest water levels occurred in January 2009: −1.2 m NAVD 88 at Beaufort, -0.70 m NAVD 88 at MHB and -0.50 m NAVD 88 at GMWC (Figure 3; Appendix B).

During the period of observation (excluding data gaps), NOS minor flood thresholds (0.67 m NAVD 88 at MHB and 0.66 m NAVD 88 at GMWC) were exceeded on 19 days at MHB and nine days at GWMC. In Beaufort, where hourly records are complete, the NOS minor flooding threshold (0.99 m NAVD 88) was exceeded on 17 days between 2008 and 2018. Moderate flooding thresholds were exceeded two days in Beaufort (9/13/2018 and 9/14/2018 during Hurricane Florence), two days at GMWC (9/30/2010 and 10/1/2010 during Extra-Tropical Storm Nicole), and not at all at MHB. Hurricane Florence occurred after the GMWC station was decommissioned and during a gap in the MHB record. However, a tertiary station across the AIWW from the MHB station recorded water levels as high as 1.62 m NAVD 88, well above the NOS major flood threshold of 1.34 m NAVD 88 and 0.06 m higher than water levels observed in Beaufort.

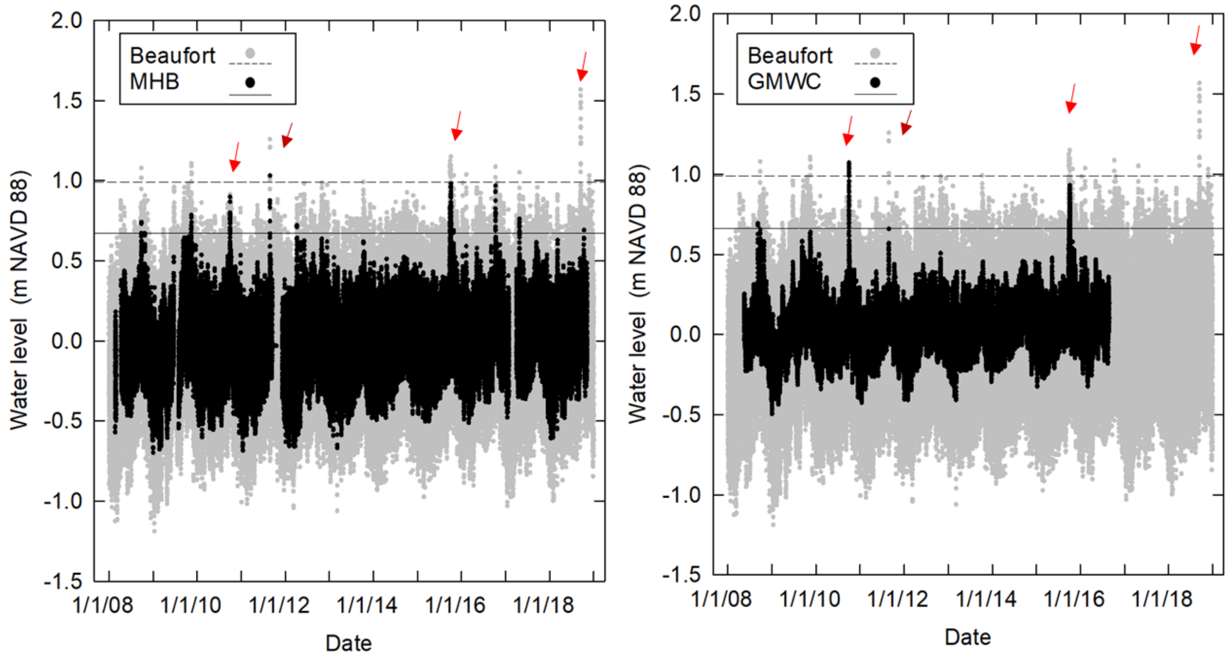

Figure 3. Hourly water level collected at Mile Hammock Bay (MHB) and Gottschalk Marina Wallace Creek (GMWC) in relation to data from the nearest NWLON station (8656483 in Beaufort, NC) from 2008 to 2018. The solid line represents the NOS minor flooding thresholds at MHB (0.67 m NAVD 88) and GMWC (0.68 m NAVD 88). The dashed line represents the minor NOS flooding threshold at Beaufort, NC (0.99 m NAVD 88). Small arrows indicate events noted in text.

3.1.2 Variability Based on Monthly Mean Sea Level

Monthly MSL, RLSR rates, and interannual variability at Beaufort, MHB, and GMWC are shown in Figure 4 and seasonal cycles are shown in Figure 5. Note that comparisons of these sources of temporal variability between stations are biased by data collection period and data gaps. Beaufort RSLR rates are reported for 1/2008–12/2018, MHB for 5/2008–10/2018 (with a total of 12 months missing), and GMWC trends are for 6/2008–4/2016 (with 0 months missing).

The temporal patterns of monthly MSL are similar at each station, however, average MSL is about 0.01 m higher at MHB (-0.02 m NAVD 88) and 0.07 m higher at GMWC (0.04 m NAVD 88) than at Beaufort (-0.03 m NAVD 88) (Figure 4 top panels). The RSLR rate**,** based on de-seasonalized monthly MSL, is similar at MHB (9.7 ± 5.1 mm y^{-1}) and Beaufort (9.6 ± 3.8 mm y^{-1}) (Figure 4 middle panels). The GMWC rate of 12.6 ± 7.2 mm y^{-1} is approximately 3 mm y^{-1} greater than Beaufort and MHB rates but has a larger 95% CI.

Interannual variability (de-seasonalized and de-trended monthly MSL) had a similar pattern and range (~ 0.30 m) at all three stations (Figure 4 lower panels). Anomalies were more frequent prior to April 2010. Negative anomalies (values < -0.1 m) occurred in December 2008, February 2009, November 2013, March 2017, and January 2018. Positive anomalies (values > 0.1 m) occurred during four or five months at all three stations between June 2009 and March 2010 and one month in 2010, 2012, 2015, 2016, and 2018 at one or more stations. The 5-month running average of interannual variability indicated positive anomalies (> 0.1 m) in November 2009 (MHB and GMWC) and January 2010 (all three stations).

The seasonal cycle of monthly MSL varied by 0.22 m (GMWC), 0.23 m (MHB), and 0.26 m (Beaufort) with minima in the winter and maxima in the early fall (Figure 5). At Beaufort and MHB, there was greater seasonal variability in monthly MLLW and MLW (~ 0.28 m) than for MHHW and MHW (0.19 to 0.24 m). The seasonal variability at GMWC was ~0.21 m for MHHW, MHW, MLW, and MLLW.

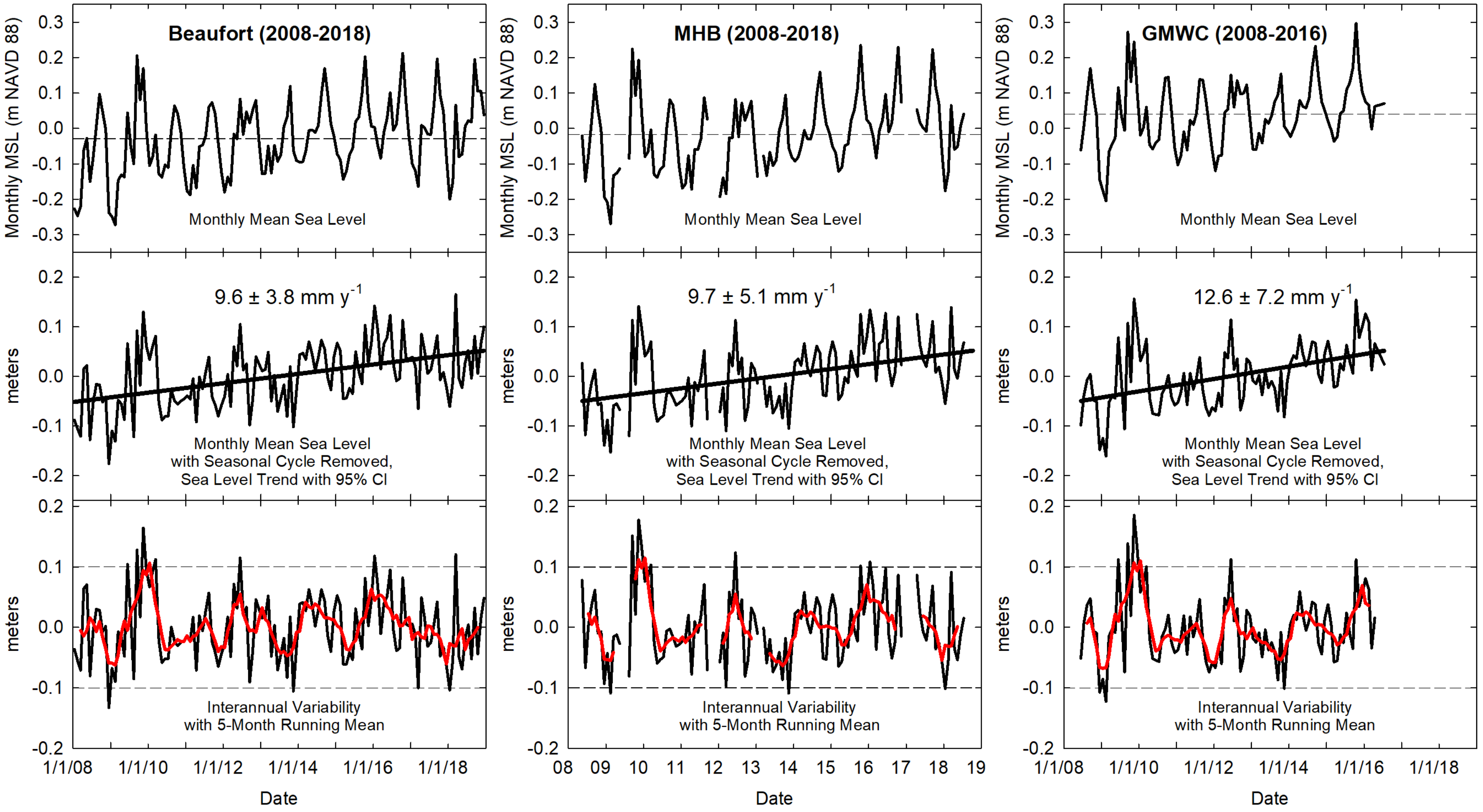

Figure 4. Temporal variability based on monthly mean sea level (MSL) at Beaufort, Mile Hammock Bay (MHB) and Gottschalk Marina Wallace Creek (GMWC) for observations recorded between 2008 and 2018. Monthly data was continuous at Beaufort (1/2008 to 12/2018) and at GMWC (6/2008 to 4/2016). Twelve months are missing from the MHB record (5/2008 -10/2018). Top panels: monthly MSL (solid line) and the average over time (dashed line). Middle panels: linear trends of monthly MSL (after removal of the seasonal cycle) with relative sea level rise rates and 95% confidence intervals (CI). Bottom panels: interannual variability (monthly MSL after removal of trend and the seasonal cycle). The red line represents the five-month running average and the dashed lines indicate anomaly thresholds at 0.1 and -0.1 m. Seasonal cycles are presented in Figure 5.

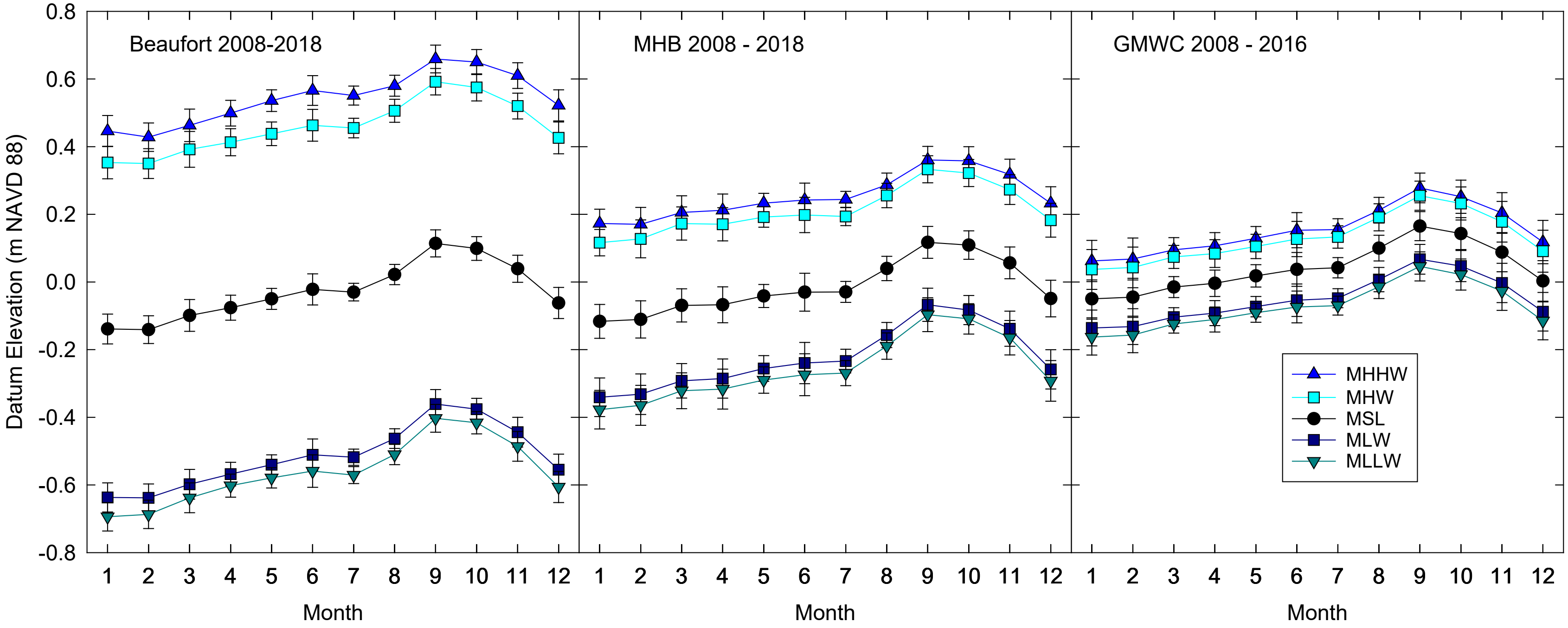

Figure 5. The seasonal cycle at Beaufort, Mile Hammock Bay (MHB), and Gottschalk Marina Wallace Creek (GMWC) based on monthly Non-Epoch tidal datums. The seasonal cycle at Beaufort is based the average of each calendar month over 11 years (2008-2018). At MHB, the seasonal cycle is based on an average of eight years for February and December; 10 years for April, August, September, and October; and nine years for the remaining months. The seasonal cycle at GMWC was based on calendar month averages over eight years except for April, which was averaged over seven years. Tidal datums are mean higher high water (MHHW), mean high water (MHW), mean sea level (MSL), mean low water (MLW), mean lower low water (MLLW).

The relative scale of RSL, MSL seasonal cycles, and interannual variability in water level at MHB and GMWC was consistent with that at Beaufort. Tidal range accounted for the largest station-to-station differences in water level variability. The scale (maximum minus minimum values) of each type of temporal variability illustrated in Figures 3, 4, and 5 for each station is shown in Table 2 along with their tidal ranges (Figure 5 and Appendix A). All three stations experienced similar ranges of variability for monthly MSL (~ 0.5 m; Figure 4, top panels), interannual variability (~ 0.3 m; Figure 4 bottom panels), the seasonal cycle (~ 0.25 m; Figure 5) and RSL (~ 0.1 m). Notable differences between stations are in the ranges of the highest to lowest water levels and in the tidal cycle. Other than differences in the impact of extreme events (Figure 3), the greatest variability among the stations was GT. As noted in Section 2.2.1, the seasonal cycle, interannual variability, and RSL trends reported here for Beaufort differ from published values because they are limited to 2008–2018. For comparison, the scale of the seasonal cycle (1953-2018) is 0.20 m and the scale of interannual variability at (calculated by removing 1953–2018 seasonal cycle and the 1953-2018 trend of 3.1 mm y^{-1} from monthly MSL) is 0.42 m (based on Beaufort station data downloaded from NOAA, 2021).

Table 2. The scale, or range, of major sources of temporal variability in water level between 2008 and 2018 for the period of record at each station. The difference between the highest and lowest observed monthly water levels is represented by Highest - Lowest WL. GT (m) is the great diurnal range (MHHW - MLLW), MN is the mean range of tide (MHW - MLW), and Monthly MSL is the range of values in the top panels of Figure 4. Interannual variability is the range of values in the bottom panels of Figure 4. Seasonal cycle is the range of MSL values in Figure 5 and Change in RSL is the change in relative sea level over the observation period (sea level trend* number of years).

Station	Period (year/month)	Missing Months (n)	Highest - Lowest WL (m)	GT (m)	MN (m)	Monthly MSL (m)	Interannual Variability (m)	Seasonal Cycle (m)	Change in RSL (m)
Beaufort	1/08–12/18	0	2.78	1.08	0.95	0.48	0.30	0.26	0.10
MHB	5/08–10/18	11	1.67	0.51	0.44	0.50	0.29	0.23	0.11
GMWC	6/08–7/16	2	1.57	0.23	0.18	0.50	0.31	0.22	0.10

3.2 Tidal Datums and NTDE-Equivalent Datums Computation Error

All calculated annual and multi-annual Non-Epoch and NTDE-equivalent tidal datums are provided in Appendix B. Of these results, three datums (MHHW, MSL, and MLLW) at MHB and GMWC are presented along with Beaufort datums in Figure 6. Although annual Non-Epoch datums increased by 7–12 mm y^{-1} over the study period (reflecting RSLR), year-to-year differences ranged from -0.05 m to +0.09 m (reflecting interannual variability). Annual Non-Epoch datums were higher than annual NTDE-equivalent datums by 0.02 m to 0.05 m (reflecting sea level rise since 1992 — the midpoint of the 1983-2001 NTDE). NTDE-equivalent annual MSL datums varied by up to 0.03 m with the period of observations used in the calculations.

As noted in Section 2.2.1, the computation error of NTDE-equivalent datums decreases with the length of records used in the calculation. Uncertainty for computations based on 1 year of observations at MHB and GMWC was ~0.04 m, just above the CO-OPS targeted tidal datum uncertainty of 0.036 m 95% CI (for subordinate stations deployed for three months) to meet most user requirements (Gill, 2014) (Figure 7). Three years of continuous multi-annual records at MHB resulted in a NTDE-equivalent tidal datum computation uncertainty of 0.033 m. At GMWC, where continuous records are available for 8 full years, uncertainty was 0.025 m.

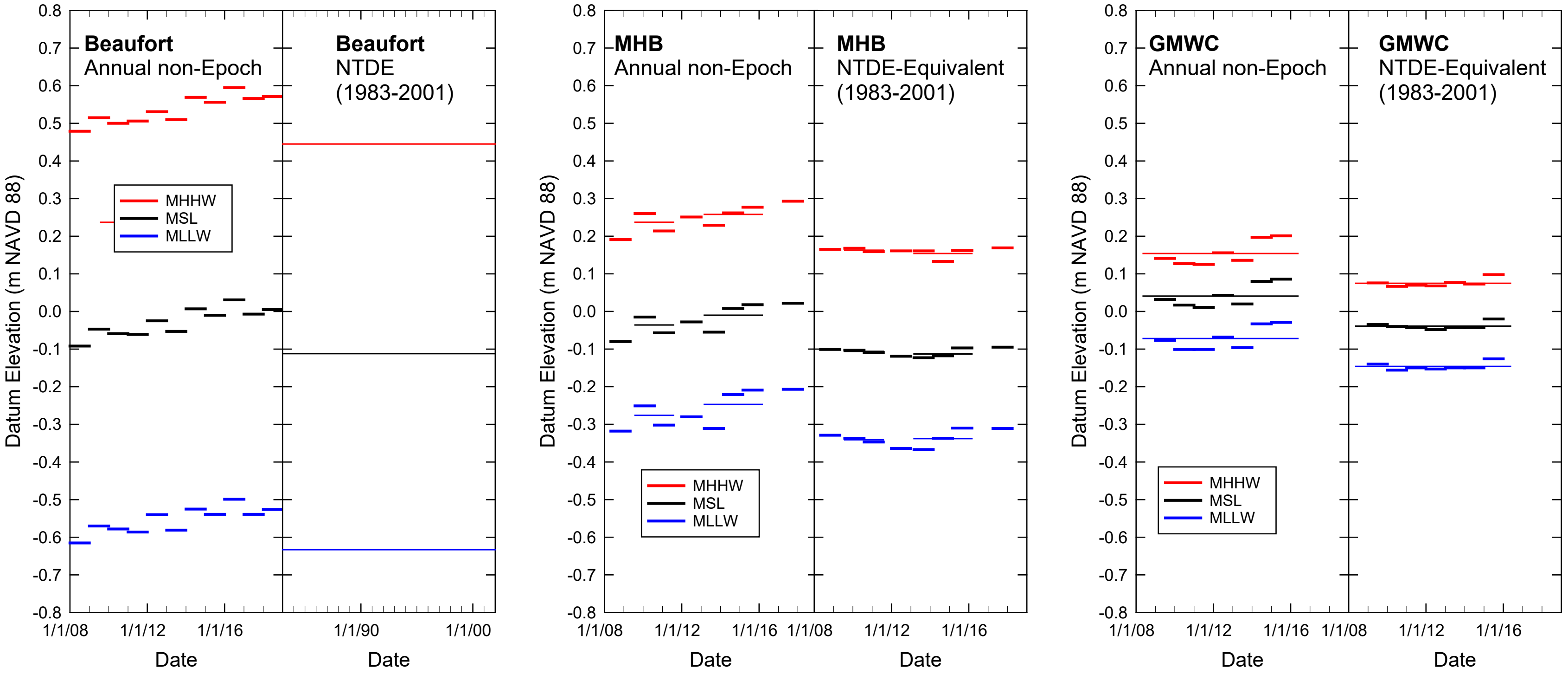

Figure 6. Annual Non-Epoch and National Tidal Datum Epoch (NTDE) (or equivalent) tidal datums for Beaufort, Mile Hammock Bay (MHB), and Gottschalk Marina Wallace Creek (GMWC). Bold lines represent datums based on 12 months of continuous observations. Thin lines indicate multi-annual datums. Beaufort and GMWC annual datums consist of full calendar years. The start date of MHB annual datums varies depending on periods of continuous records (i.e., they do not always begin in January). Note the change in timescale for the Beaufort NTDE panel. MHHW = mean higher high water, MSL = mean sea level and MLLW = mean lower low water.

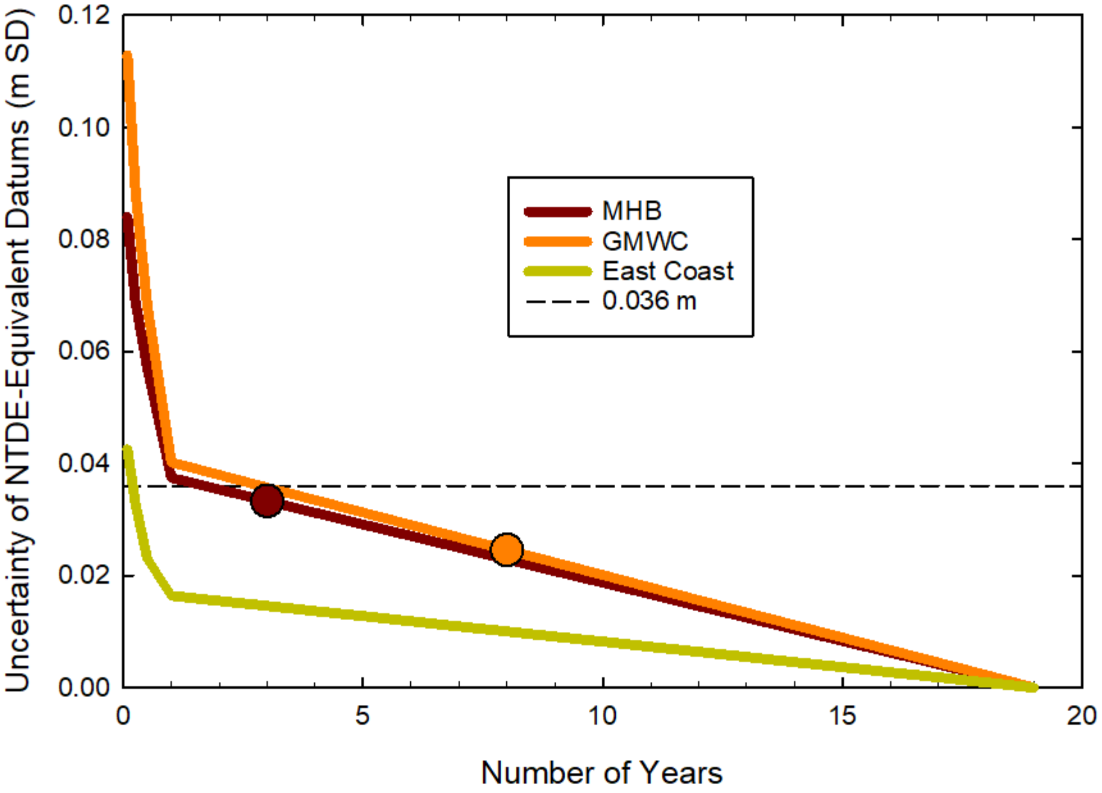

Figure 7. The computation error of NTDE-equivalent tidal datums calculated over increasing time intervals following Bodnar (1981) (see Methods). The green line represents a generalized curve for the East Coast (Swanson, 1974). The brown and orange lines were calculated for Mile Hammock Bay (MHB) and Gottschalk Marina Wallace Creek (GMWC), respectively, using the Beaufort station as a control. The circles indicate the computation error of NTDE-equivalent datums for MHB and GMWC based on the longest multi-annual period of continuous records (3 and 8 years, respectively). The dashed line at 0.036 m represents the tidal datum uncertainty for three-month time series to meet most CO-OPS user requirements (Gill, 2014). Note that Bodner (1981) used the term accuracy instead of uncertainty; we follow Gill (2014) in using the term uncertainty.

3.3 Error Budget of Water Level and Tidal Datums

Applying all sources of random and systematic error (except for tidal datum computation error) to the IHO equation results in a 95% CI combined error of 0.041 m and 0.035 m for water level values and for Non-Epoch datums at MHB and GMWC, respectively (Table 3). Adding the systematic error associated with tidal datum computation results in an error budget of 0.060 m at GMWC and 0.074 m at MHB for NTDE-equivalent datums.

Table 3. Error budget for water level, Non-Epoch datums, and National Tidal Datum Epoch (NTDE)-equivalent datums based on the International Hydrographic Organization error budget equation (NOS, 2017). Sources of random error include instrument accuracy, calibration error, and the leveling and measurement error described in Appendix A. S is the square root of the sum of squares of random error sources. 1.96*S is the 95% confidence interval (CI) combined random error. BM = Bench Mark, SLP = Survey Leveling Point, TIP = Top of the Interior Pipe, SZP = Sensor Zero Point. The error in the orthometric elevation of the Local Control Mark (LCM) and the NTDE-equivalent tidal datum computation are systematic errors. The tidal datum computation error is based on 3 years at MHB and 8 years at GMWC (Figure 7).

Station			GMWC	MHB
Systematic Error	LCM error (m RMS)		0.014	0.015
	Tidal datum computation error (m SD)		0.025	0.033
Random Error	Instrument accuracy (m)		0.003	0.003
	Calibration error (m)		0.010	0.010
	Leveling error (m SD)	BM MILE to MHB SLP		0.006
		TIP to SLP	0.003	0.004
	Measurement error (m SD)	TIP to SZP	0.001	0.004
	S (square root of sum of squares of random errors)		0.011	0.013
	1.96*S		0.021	0.026
Uncertainty of water level and Non-Epoch tidal datums (m 95% CI) (1.96*S + LCM error)			0.035	0.041
Uncertainty of NTDE-equivalent tidal datums (m 95% CI) (1.96*S + LCM error + tidal datum computation error)			0.060	0.074

3.4 Inundation

Results of the inundation sensitivity analyses identified sites where Beaufort, MHB, or GMWC data could be used to calculate site-specific inundation. Proximity was not the greatest factor influencing these comparisons. For example, marsh inundation duration calculated using Beaufort water level data for the FC marsh, which was located ~60 km away, was similar to inundation calculated using a 7-month in situ tertiary station, despite the distance and the 0.14 m greater GT at Beaufort. This finding was because the duration of tidal flooding at Beaufort and FC (within the elevation range of the FC marsh) was within 5% of each other (meeting our criterion for acceptance of the longer-term station for inundation calculations). A similar analysis indicated that GMWC water level data could be used for inundation calculations at a research site 7 km downstream from the French Creek station (FN) (Figure 2). In addition, we found that nearby sites (MHB and TB, less than 2 km apart; Figure 2) could have very different tidal dynamics. At one of the two research areas at the TB site (inside a sandbar across the mouth of the creek), comparisons indicated that MHB and TB high tides had similar tidal timing and elevations but the low tide was attenuated inside the sandbar.

For the DCERP project, Beaufort, MHB, or GMWC water level data were used to calculate inundation duration for varying periods (months, seasons, and years) and marsh elevations (for sites meeting the sensitivity analysis criterion) (Currin et al., 2018a). As an example, Figure 8 (in this memorandum) shows how variability in annual inundation duration for marsh elevations of 0.0 and 0.1 m NAVD 88 depends on site-specific water levels. For marshes at 0 m NAVD 88 elevations, the annual inundation would have varied by 10%, 16%, and 21% at marshes near Beaufort, MHB, and GMWC, respectively, and the average inundation time would be 47% near Beaufort and MHB and 60% near GMWC. At this elevation, average inundation duration at marsh sites near GMWC would have been longer and more variable than inundation at sites near MHB and Beaufort, which have higher tide ranges. For marshes at a higher elevation (0.1 m NAVD 88) the average inundation time would be lower: 39% (near Beaufort), 31% (near MHB), and 33% (near GMWC). Annual variability in inundation is greater for the site with the narrowest tidal range.

Another sensitivity analysis was used to evaluate the impact of uncertainty in water level and marsh surface elevation on inundation duration uncertainty. For a combined uncertainty of 0.06 m for water level and marsh surface elevation, the sigmoidal relationship between surface elevation and inundation is essentially linear between the elevations of MHHW and MLLW (Figure 9). The steepness of the slope between MHHW and MLLW increases as tide range narrows from Beaufort to MHB to GMWC. Consequently, the impact of the water level and marsh elevation uncertainty on the uncertainty of marsh inundation duration increases with decreasing tide range. For example, the 95% CI for inundation duration calculated for a marsh at an elevation of 0.1 m NAVD 88 ranges from 38–47% near Beaufort, 23–44% near MHB, and 25–60% near GMWC. This analysis demonstrates that calculations of inundation duration in percent time could be off by ± 5% (Beaufort), ± 10% (MHB), and ± 19% (GMWC) for the same amount of water level and marsh surface elevation uncertainty.

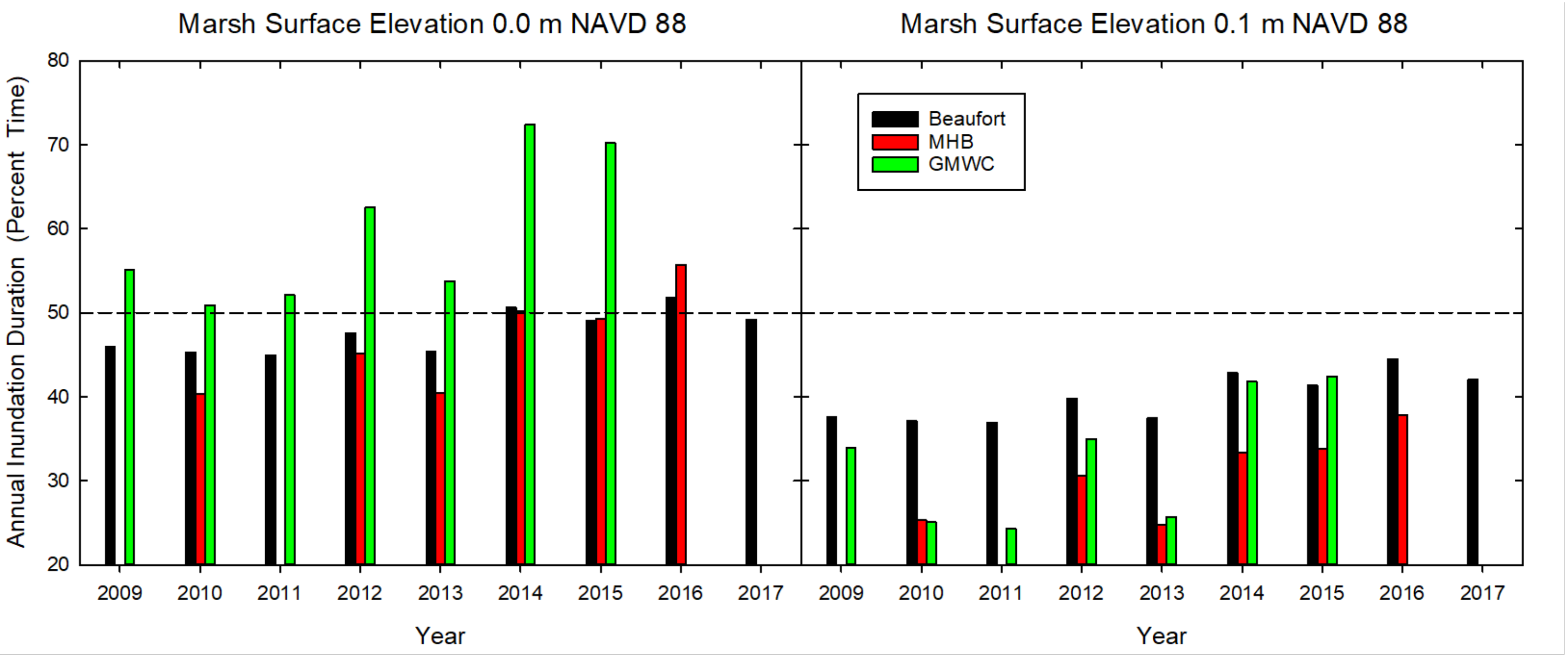

Figure 8. Annual inundation duration (percent time) calculated for a surface elevation of 0.0 m (left) and 0.1 m (right) NAVD 88 using three sources of water level data (Beaufort, Mile Hammock Bay [MHB], and Gottschalk Marina Wallace Creek [GMWC]). Years with observations covering less than 95% of the year are excluded.

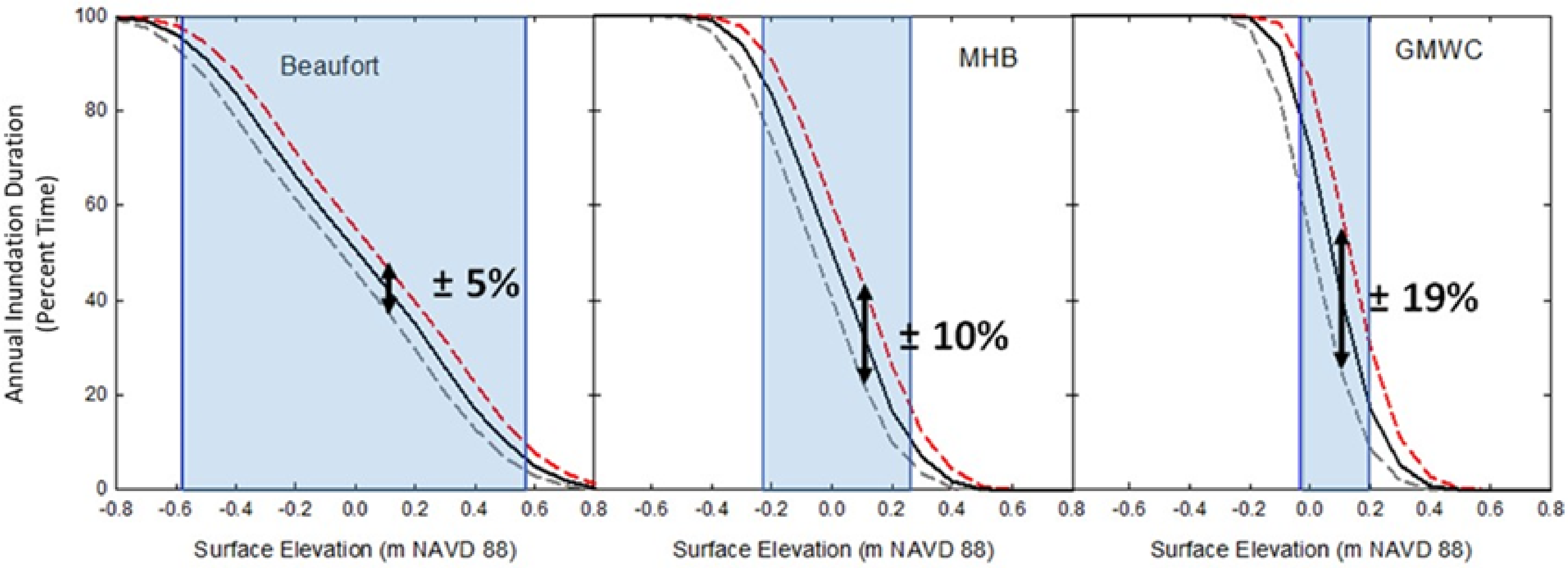

Figure 9. Inundation duration (percent time + 95% confidence interval [CI]) calculated for the year 2014 using Beaufort, Mile Hammock Bay (MHB), and Gottschalk Marina Wallace Creek (GMWC) water level data for a series of surface elevations. The distance between the red dashed line (upper limit of 95% CI) and the blue dashed line (lower limit of 95% CI) represent the 95% CI based on a 0.06 m combined uncertainty for water level and marsh surface elevation. The year 2014 was selected because it was one of the two calendar years with continuous data at all three stations. The blue area represents elevations between annual (2014) MHHW and MLLW for each station. The black arrows represent the width of the 95% CI for an elevation of 0.1 m NAVD 88. MHHW = mean higher high water and MLLW = mean lower low water.

3.5 VDatum Comparison

NOAA's Vertical Datums Transformation Tool (VDatum) provides modeled estimates of NTDE-equivalent tidal datums for many coastal locations along with the maximum uncertainty associated with regional models (e.g., 0.076 m 95% CI for the New River Estuary) (White et al., 2016; VDatum, 2020). Table 4 shows the offsets between the tidal ranges estimated by VDatum and those measured by secondary or tertiary stations in the DCERP study. At two research sites (Trap's Bay [TB] and FN), measured and VDatum-estimated GTs are within the VDatum CI. Elsewhere, VDatum estimates do not match GTs based on observations. For example, a short-term deployment of loggers in the AIWW showed a decrease in tidal range with distance along the AIWW from FC to Onslow Beach Backbarrier (OBB) to MHB but VDatum results indicate an increase in tidal range from FC to OBB and a GT that is 0.16 m less at MHB than measured values.

Table 4. The great diurnal range (GT = MHHW–MLLW) at Marine Corps Base Camp Lejeune research sites and stations based on measured data and VDatum Online Tool (VDatum, 2020). FC = Freeman Creek, OBB = Onslow Beach Backbarrier, MHB = Mile Hammock Bay, TB = Traps Bay, PP = Pollocks Point, FN = French Creek, and GMWC = Gottschalk Marina Wallace Creek. The TB research site included locations on either side of a sandbar; a partner secondary station was installed outside the bar for 15 months. The site inside the sandbar is unrepresented in this table. AIWW = Atlantic Intracoastal Waterway. GT at OBB is assumed to be less than that at FC based on a short-term study of loggers deployed on channel markers in the AIWW near FC, OBB, and MHB. MHHW = mean higher high water and MLLW = lean lower low water. See Figure 2 for site and station locations.

Site or Station Name	Measured Tidal Range Data Source	Nearest Inlet	Distance from Inlet (km)	Measured GT (m)	VDatum GT (m)	VDatum - Measured GT (m)
FC	Tertiary station (7 months)	Brown's	2	0.94	1.3	0.36
OBB	Tertiary stations in the AIWW	Brown's	3.5	<0.94	1.37	> 0.43
MHB	Secondary station (3 years)	New River	2.5	0.49	0.34	-0.15
TB	Secondary station (15 months)	New River	3.9	0.33	0.31	-0.02
PP	N/A	New River	8.5	n/a	0.17	n/a
FN	Tertiary station (4 months)	New River	19.5	0.21	0.2	-0.01
GMWC	Secondary station (8 years)	New River	26.5	0.22	n/a	n/a

3.6 Salinity and Temperature Observations

At both MCBLC secondary tidal stations, salinity was highly variable with monthly extremes greater than the seasonal range. Monthly mean salinity ranged from 20 to 35 at MHB and from 2 to 25 at GMWC with the highest monthly mean occurring in July 2011 (Figure 10 top panels). Over the study period, the average monthly mean salinity was 30 at MHB and 14 at GMWC. The highest observed salinity value was 36 at MHB (September 2010 and July and August 2011) and 28 at GMWC in August 2011. Minimum salinity values occurred in September 2018 at MHB (1.69) and in October 2010 at GMWC (0). A larger seasonal range in monthly mean salinity (10 to 18) was observed at GMWC than at MHB (27 to 32) and SDs for each month were 1–3 greater at GMWC than at MHB (Figure 11 top panels). A significant regression equation was found between monthly mean salinity and the PDSI for both stations: [F (1,111) = 93.50, $p<0.0001$, r^2 of 0.45 (MHB) and F (1, 94) = 64.82, $p<0.0001$, r^2 of 0.40 (GMWC)] (Figure 12).

Seasonal temperature fluctuations were fairly uniform both spatially (i.e., at both stations) and annually with winter months exhibiting more variability than summer months. Monthly mean temperature values ranged between 6 °C (both stations) and 30 °C (MHB) and 31 °C (GMWC); at both stations the average monthly mean water temperature was ~20 °C (Figure 10 bottom panels). The maximum observed temperature at GMWC (35.3 °C) occurred in June 2010. At MHB, the maximum temperature of 34 °C occurred in July 2018. The lowest observed temperatures (0 °C) occurred in January 2018 at MHB and in December 2010, January 2014, and February 2015 at GMWC. The range of seasonal variability in temperature was similar at both stations: 8 °C to 30 °C (GMWC) and 9 °C to 29 °C (MHB), with maxima in July and minima in December (Figure 11 bottom panels). Monthly variability was greatest in the winter months, especially in December and March.

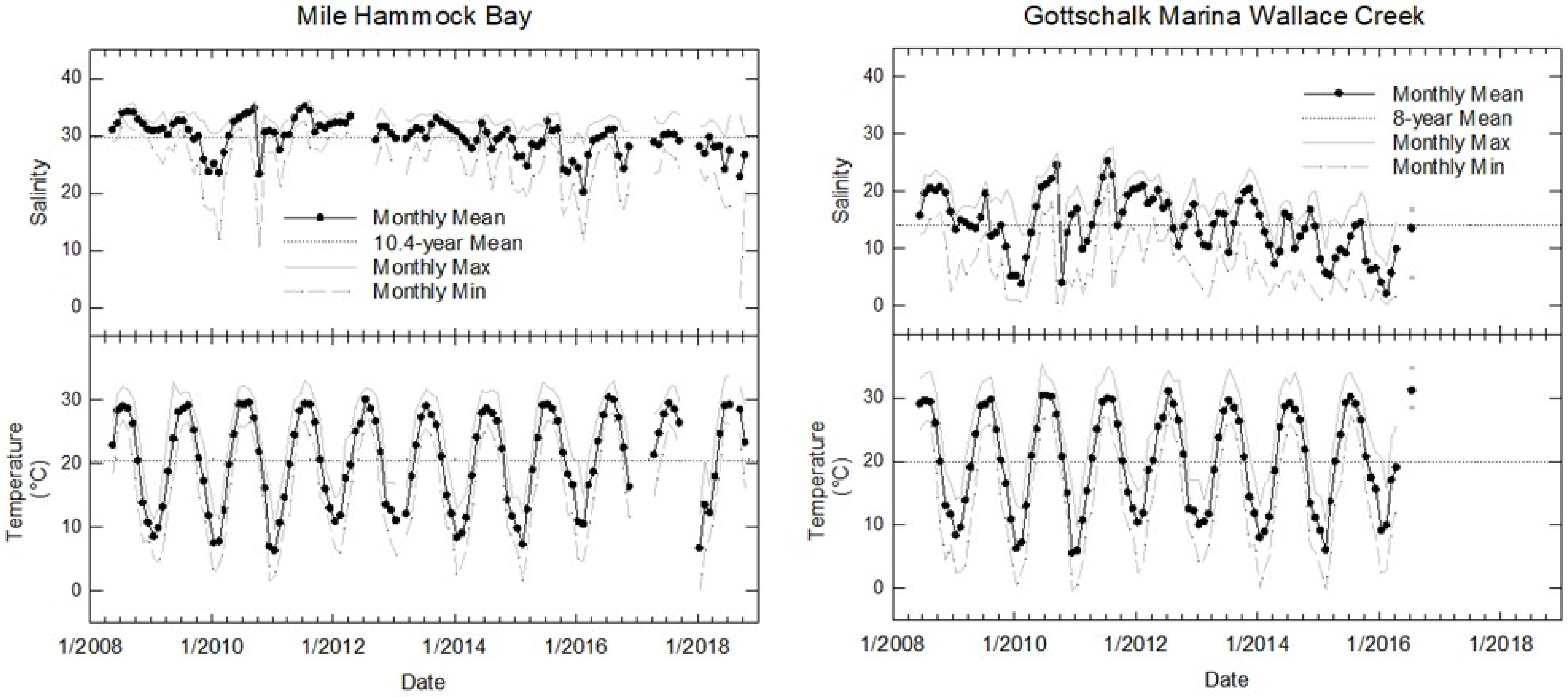

Figure 10. Monthly statistics (mean, maximum, and minimum) for salinity and temperature at Mile Hammock Bay and Gottschalk Marina Wallace Creek. Only months with records covering 99.5% or more of the month are shown. Salinity is unitless. °C = degree Celsius.

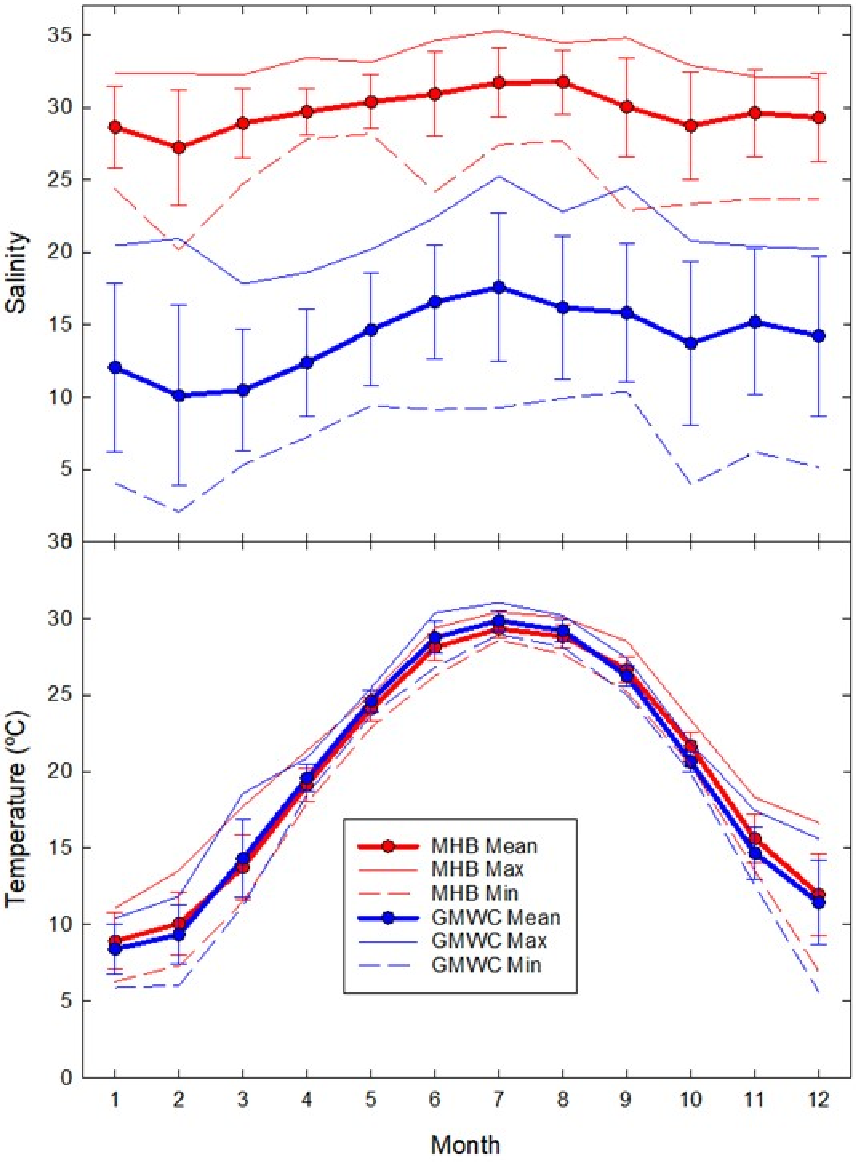

Figure 11. The seasonal cycle of salinity and temperature is based on the average of calendar month monthly means over the study period. MHB is Mile Hammock Bay and GMWC is Gottschalk Marina Wallace Creek. Statistics include the mean ± standard deviation (SD), maximum, and minimum values for each month. Months with less with 99.5% of the month recorded are excluded. For GMWC, the monthly means represent eight full years from 5/2008 to 4/2016. (July 2016, with 100% of the month recorded, is excluded so that the number of years represented by each month is the same.) For MHB, the number of years represented by each monthly mean ranges from eight (February and December) to 11 (September). January, March, August, and November represent nine years and April, May, June, July, and October represent 10 years). The number of years represented by each monthly temperature value is the same as for salinity except that May, June, July, and August represent 11 years. Salinity is unitless. °C = degree Celsius.

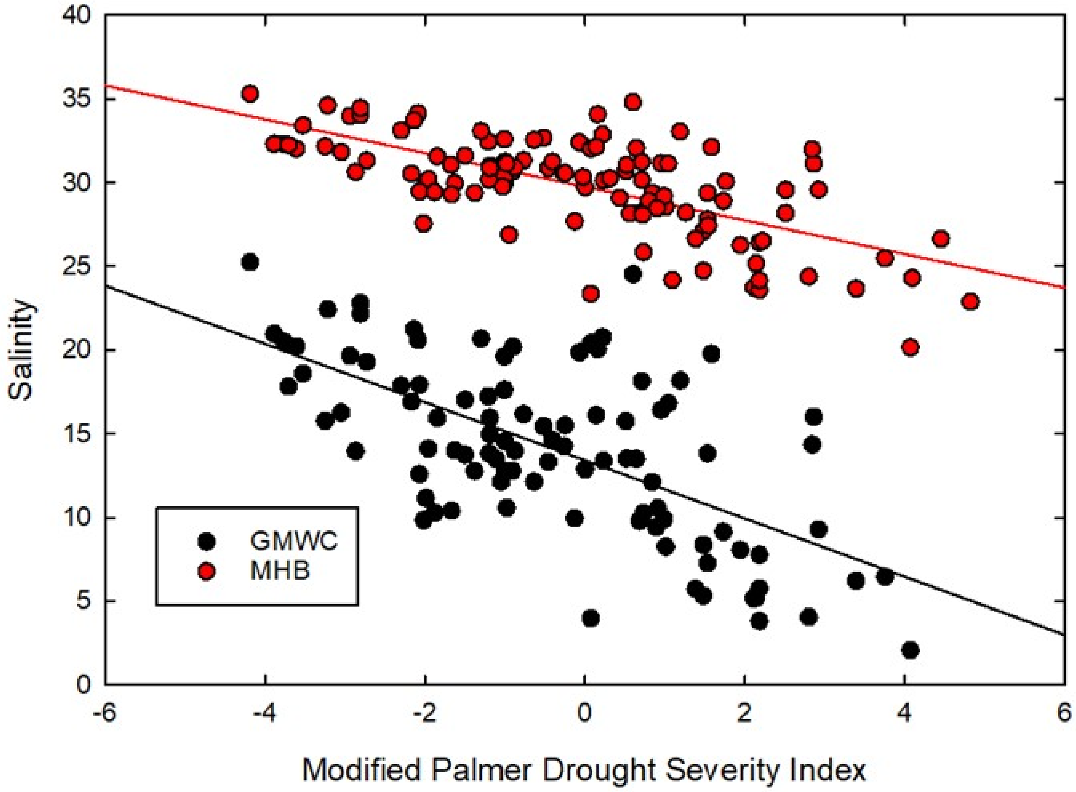

Figure 12. Linear regressions of Mile Hammock Bay (MHB) and Gottschalk Marina Wallace Creek (GMWC) monthly mean salinity with the modified Palmer Drought Severity Index (PDSI) for the Southern Coastal Plain of North Carolina (North Carolina Climate Office, 2019). See text for regression results.

4. Lessons Learned

The data presented in this memorandum illustrate spatial and temporal dynamics in water level, temperature, and salinity along an estuarine gradient within an NWLON gap. The data are especially valuable as climatological baseline because they show a relationship between temporal variability and regional climate and sea level.. Monthly mean salinity values were sensitive to short-term precipitation events but also correlated with drought conditions. The observed rates of sea level rise (9.7 mm y^{-1}at MHB; 12.6 mm y^{-1}at GMWC) were much higher than the long-term rates (1953-2021) recorded at the Beaufort station (3.29 mm y^{-1}; NOAA, 2021) and may have been influenced by the 2011–2015 recurrence of a short-lived, rapid sea level rise acceleration on the US East Coast (Valle-Levinson et al., 2017). As GSLR rates continue to accelerate and the climate warms, these data will help evaluate the impacts of rising sea levels and temperatures on estuarine salinity, temperature, and water levels. While the initial project needs were focused on sea level trends and inundation, there were also lessons learned about water level data analyses and water level station networks. These may be useful in helping others improve their own monitoring networks and may be extended to water level data applications beyond coastal resilience.

Throughout the monitoring program we followed available guidance to establish and maintain water level sensor elevations, collect accurate data, and minimize data gaps but we did not have a clear understanding of the level of accuracy required for specific applications at specific locations. At the time of station site selection, we did not understand how rapidly the tidal range changed along the AIWW and, in some cases, from site to site. After calculating error budgets, conducting sensitivity analyses, and determining our own water level data requirements for performing inundation analysis, we realized that preliminary in situ data collection at each site could have greatly improved our planning process and monitoring network. We found that localized data was more critical for some applications and at some sites than others. For example, given their high CIs, MHB and GMWC RSLR ~ 10-year rates were well-represented by the Beaufort station more than 60 km away with a greater oceanic influence. Conversely, spatial differences in the frequency of flooding events, a metric associated with sea level rise, suggests that localized data would be required for coastal flooding applications.

Understanding interannual variability was not an initial goal of the project but this variability is the cause of the high CI of the ~ 10 year RSLR rates and may be informative for applications such as modeling future water levels. CO-OPS applies thresholds to interannual variability to evaluate climatic drivers of anomalous water levels at NLWON stations but the same thresholds may not be applicable for estuarine stations. For example, anomalies at Beaufort (and other East Coast stations) have been associated with the coupling of changes in current transport and wind forcing (Sweet et al., 2009) and with El Niño/Southern Oscillation (Zervas, 2009). Although we observed some of the same anomalies at MHB and GMWC, it may be more problematic to relate a specific threshold exceedance in an estuary to a specific climatic driver, as estuarine water levels may be disproportionately impacted by stream discharge rates.

Another application of water level data is using NTDE-equivalent datums to examine spatial variability between sites or across regions. The value in NTDE-equivalent datums is that short observations from different locations and different collection periods are normalized to the same 19-year period allowing direct comparison. While we did not establish accuracy criteria for our datums, we learned how NTDE-equivalent tidal datum accuracy can be improved by longer data collections. It took two (MHB) and three (GMWC) years of data for the datum computation uncertainty at MHB and GMWC to reach the 95% CI of 0.036 m that Gill (2014) recommended. We also observed that MHB and GMWC datums varied by up to 0.03 m depending on the specific year of observations used for the datum computation (Appendix B Table B6). Hensel et al. (2015) indicate that secondary water level stations can provide *satisfactory* tidal datums but the definition of satisfactory depends upon the user's requirements for specific applications. Our level of uncertainty was an improvement over that of local VDatum modeled datums (0.08 m). In theory, if we had determined that this level of uncertainty was acceptable for our needs, we would not have needed to collect water level data for NTDE-equivalent datums. However, site-specific comparisons of VDatum modeled datums and our calculated datums show the need to verify the performance of VDatum with in situ data.

A major goal of the project was to evaluate the response of marshes to sea level rise and increasing inundation. Based on our water level data requirements for inundation analysis (calculated percent inundation duration using MHB, GMWC or Beaufort station data was within 5% of that using in situ data), we found the need for localized data for inundation calculations was site-specific. The Beaufort station data met out criterion for calculating inundation at the FC site, despite the 60 km distance and 0.14 m difference in tidal range. Although the tidal range differences resulted in differences in the depth of inundation, *at the elevation range of the FC* *marsh*, the duration of inundation was similar. Had the marsh been situated closer to MHHW, the difference in calculated inundation duration would have been greater. In another example, a sandbar at the TB site, created very different inundation patterns from the MHB station just 2 km away. Inundation analysis at TB would have required in situ data over the study period.

The error budget and sensitivity analysis helped identify sources of error that could be improved and evaluate the need for greater accuracy. We demonstrated that the relationship of water level and marsh elevation uncertainty to inundation uncertainty depends on tidal range. With a narrow tidal range, there is greater need for more accurate water level and marsh elevation data to reduce inundation uncertainty. Tidal range will have a similar impact on interpretations of the relative position of a marsh surface in the tidal frame, which is a proxy for inundation.

There were also several lessons learned about data collection and station maintenance. As continuous data is important for several applications, more frequent downloads or telemetry would have help us identify problems and reduce the duration of data gaps. We found it very useful to compare data from two or more stations to check for consistency and offsets, following each data download. This helped us to isolate the exact moment of a boat strike displacing the sonde and identify questionable data for removal.

5. Recommendations for Coastal Wetland Water Level Monitoring Programs

Many programs with water level data needs may require localized water level data collection. This is especially important within NWLON gaps or in any large area where tidal characteristics change over short distances. Collecting accurate water level data can be resource intensive in terms of time and funding and compromises are often required in terms of the siting, number, and type of water level stations as well as the duration of station deployments and the frequency of GPS data collection. Evaluating site-specific and application-specific requirements prior to project commencement can help to identify the best locations for a network of secondary and/or tertiary stations, prioritize resource investment, and set the stage for efficient data collection. We recommend Hensel et al., 2015 and other literature cited in this memorandum as guidance for station installation, the vertical control process, error budgets, and data management. Here we provide additional recommendations based on lessons learned from the decade-long monitoring program in the New River Estuary, NC that may be useful for a range of water level data applications.

Monitoring Design (station siting). We recommend early concurrent deployment of in situ tertiary stations at each research site for at least one month to calculate monthly NTDE-equivalent tidal datums, which can be used to estimate how tidal characteristics vary from site to site and in comparison to existing sources of longer-term data. The NTDE-equivalent tidal datums can be compared with VDatum modeled datums to evaluate the utility of VDatum for specific sites. The preliminary water level data can also be used in sensitivity analyses to evaluate the use of nearby sources of water level data for site-specific inundation calculations. If inundation calculated using a nearby station is within 5% (or another user specified criterion) of inundation calculated using the in situ station, longer-term data collection at both sites may not be required. One exception in the need for localized data may be for determining RSLR for projects spanning 10 years or less. Given the uncertainty associated with short-term RSL trends, it is unlikely that significant differences from the nearest NWLON station would be detected unless the two locations are experiencing different vertical land motion rates or directions.

Duration of Data Collection. In addition to determining where water level data should be collected, researchers must also determine the duration of data collection and consider requirements for elevation accuracy. For inundation calculations and flooding frequency, we recommend collecting data continuously over the study period. Full months of continuous data are required to determine tidal datums (Licate et al., 2017), which are used to calculate seasonal cycles, interannual variability, and RSLR (Zervas, 2009). A minimum of one year of observations will reduce seasonal bias in NTDE-equivalent tidal datums and computation uncertainty will decrease with the length of the record.

Elevation Accuracy. Elevation accuracy needs will depend on the data application and the researcher's acceptable error. For example, differences in tidal range and timing between sites can be determined without referencing water level to land, eliminating the need for vertical control. Inundation calculations, which require elevation data for both land surface and water level, may have stringent vertical control requirements. A sensitivity analysis applying a range of elevation offsets to preliminary data for inundation calculations may be helpful in evaluating acceptable error. For inundation calculations, and for determining the relative position of the marsh surface in the tidal frame, elevation accuracy requirements will also depend on tidal range. We recommend conducting a sensitivity analysis to evaluate the benefits of obtaining higher quality elevation data for sites with different tidal ranges. For marshes with very narrow tidal ranges (~ 0.2 m), a reduction in combined elevation uncertainty of several centimeters may not reduce inundation uncertainty to levels required for some applications. On the other hand, higher quality elevation data may not measurably improve inundation uncertainty for marshes with tidal ranges > 1m.

Efficient Data Collection Plan. It is very important to design the station structure to maximize stability and access. In euhaline environments, we recommend the use of stainless steel hardware, and anti-fouling paint on PVC pipes, and avoiding the use of untreated wood below the water surface. The SLP and SZP should be positioned so that relative distance between them can be easily measured. Frequent GPS data collection can help identify seasonal signals and longer-term trends of vertical land motion. If GPS data collection is limited to one or two observations per year, it should be conducted at the same time of the year to reduce the noise associated with seasonal signals and satellite ephemeris. Submitting static GPS reoccupations of published NSRS BMs to NGS will help document the stability of the published values. We recommend following Hensel et al., 2015 in leveling the station to the LCM before and after each instrument change out or structural change to the station.

Frequent review of both vertical control (including leveling) and water level data is important. It can help reduce data gaps associated with structural or instrument failure and identify inconsistencies associated with human or instrument error. We recommend installing telemetry or downloading station data on a regular basis (monthly, if possible) and comparing compare data from two or more stations immediately after downloads to check for consistency and offsets. We recommend planning for instrument sensor drift, setting standards for data quality acceptance, making adjustments when necessary, and planning for preventative maintenance and emergencies. This may include replacing structural components of the station periodically and having spare sondes calibrated and ready to deploy in case of a unexpected problem with a deployed instrument. A storm plan should be developed to protect a vented sonde from immersion or any instrument from structural damage.

Data Management Approaches. Data management approaches should consider how and at what stage gaps will be filled and reference water levels will be adjusted to orthometric elevation. It is likely that the offsets from the sensor to SLP may change over time and that the quality of the LCM elevation may improve with repeated GPS data collections. It is important to evaluate the pre and post calibration offsets before merging data from different deployments. Gaps within and between deployments will need to be filled for most application needs, including tidal datums. Linear interpolation can be used to fill gaps < 3 hours (avoiding interpolation over peaks and valleys) and did not fill larger gaps. Options for filling gaps > 3 hours and < 1 week include adjusting data from a nearby station with similar tidal characteristics.

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Appendix A: Vertical Control of Marine Corps Base Camp Lejeune Secondary Water Level Stations

Contents

List of Tables

List of Figures

List of Abbreviations

BM	Bench Mark
CO-OPS	Center for Operational Oceanographic Products and Services
CORS	Continuously Operating Reference System
GMWC	Gottschalk Marina Wallace Creek
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
LCM	Local Control Mark
m	Meter
MHB	Mile Hammock Bay
NAVD 88	North America Vertical Datum of 1988
NGS	National Geodetic Survey
NSRS	National Spatial Reference System
OPUS	Online Positioning User Service
PM	Published Bench Mark
PVC	Polyvinyl Chloride
RMS	Root Mean Square
RTK	Real Time Kinematic
SB	Sonde Base
SD	Standard Deviation
SLP	Survey Leveling Point
SZP	Sensor Zero Point
TEP	Top of the Exterior Pipe
TIP	Top of the Interior Pipe
TRM	Temporary Reference Mark
US	United States
VRS RTN	Virtual Reference Station Real Time Network
YSI	Yellow Springs Instruments

A.1 Introduction

The steps to establishing vertical control of a water level station include:

1. establishing a Sensor Zero Point (SZP) and a Survey Leveling Point (SLP) at each water level station,
2. establishing a local vertical control network with a Local Control Mark (LCM) near the water level station,
3. connecting the station's LCM to the National Spatial Reference System (NSRS) using the local vertical control network and differential leveling or Global Navigation Satellite System (GNSS),
4. obtaining the SLP elevation relative to the LCM via leveling, and
5. measuring the vertical distance from the SLP to the station's SZP.

Each vertical control process can contribute uncertainty to the water level measurements and tidal datums. This appendix describes the Marine Corps Base Camp Lejeune stations, their local control networks, and the procedures used to establish vertical control and their contributions to the error budget.

A.2 Station Design and Structural Support

The secondary water level stations were designed to maintain Yellow Springs Instruments (YSI) Incorporated 600LS vented data sondes at a stable elevation relative to a SLP. Sondes were calibrated to record water level relative to the Sonde Base (SB; also designated as the SZP) after measuring the distance between the sensor and the SB. Vertical control of the SLP and SZP was maintained throughout the study following the National Oceanographic and Atmospheric Administration's National Geodetic Survey (NGS) and Center for Operational Oceanographic Products and Services (CO-OPS) guidelines. SZP orthometric elevations were used to determine water level relative to the North American Vertical Datum of 1988 (NAVD 88).

The structural designs of the water level stations at each were similar but the stations were attached to different types of support structures (Figure A1). The Gottschalk Marina Wallace Creek (GMWC) station was installed on a 50' x 125' marina platform consisting of treated timber pilings with 2" x 8" decking. The marina platform has existed since the 1950s and was maintained and upgraded during the period of station operation. The station at Mile Hammock Bay (MHB) was located on a steel sheet pile bulkhead installed in the mid-1980s. The sheet piles are capped with 18" x 24" reinforced concrete lined with heavy timbers (12" x 12"). Backing boards, attached to a running joist on the marina platform at GMWC and to the end of the timber pile clamp at MHB, supported the station assembly. At MHB, the height of the bulkhead above the water (> 2 m) necessitated the use of two backing boards. At installation

(2/21/08), the top of the MHB station was positioned about 0.5 meters (m) below the top of the bulkhead. The structure was reconfigured on 5/30/08 for easier access.

Figure A2 illustrates the structural design of both stations following the modifications at MHB; each component is identified with a letter key in the figure. At GMWC, a single backing board (a) was attached by four 4” galvanized wood screws (b) to a wood piling joist support. At MHB, two 2” x 8” treated timber backing boards (a) were secured by eight 4” galvanized wood screws (b) to a heavy timber on the west bulkhead and attached to the steel sheet pilings. At both stations, the lower end of the backing board was regularly submerged. At MHB, where average monthly salinities (20-35) were 10 to 18 greater than at GMWC, the regularly submerged section of the backing board disintegrated within a couple of years. This necessitated a design modification to eliminate the need for the submerged portion of the backing board. At both stations, three 2” galvanized straps (c) secured a 2” schedule 40 polyvinyl chloride (PVC) pipe (the exterior pipe) (d) to the backing board(s). At MHB, where the height of the bulkhead above the water was greater than two m, we coupled two lengths of PVC pipe for a total length of about 3.7 m. Anti-fouling paint was applied to the regularly submerged portion of the exterior pipes but the pipe at MHB was still prone to fouling due to high salinity. The use of a coupler made it easier to replace the submerged portion of the pipe for maintenance. A 3/16th inch bolt (e) was installed through the exterior pipe a few inches above the bottom of the pipe. At GMWC, the bolt was directly attached to the backing board. The sonde battery, vent and data cable (f) attached to the sonde (g) ran through a 1.5” schedule 40 PVC pipe (the interior pipe) (h). A zinc sacrificial anode (i) was attached to the sonde’s stainless steel bulkhead connector to the cable. The assembled sonde (g) and interior pipe (h) were positioned inside of the exterior pipe (d) so that the SB (k) rested on the bolt (e). Three stainless steel screws (j) secured the interior pipe (h) through drilled holes to the exterior pipe (d) to prevent upward movement of the sonde (g). The contact between the SB and the bolt through the exterior pipe formed the SZP (k). A bolt (GMWC) or screw (MHB) secured to the top of the backing board was established as a SLP (l).

At installation, the MHB SLP was located below the top of the bulkhead. Within three months, the structure was modified with longer pipes and backing boards for better access. This structural change resulted in raising the vertical position of the SLP by more than one m and lowering the SZP by 0.01 m. At both sites, structural maintenance and repairs were required periodically. Some of these changes resulted in adjustments to the vertical position of the SZP at MHB but not at GMWC (Table A1).

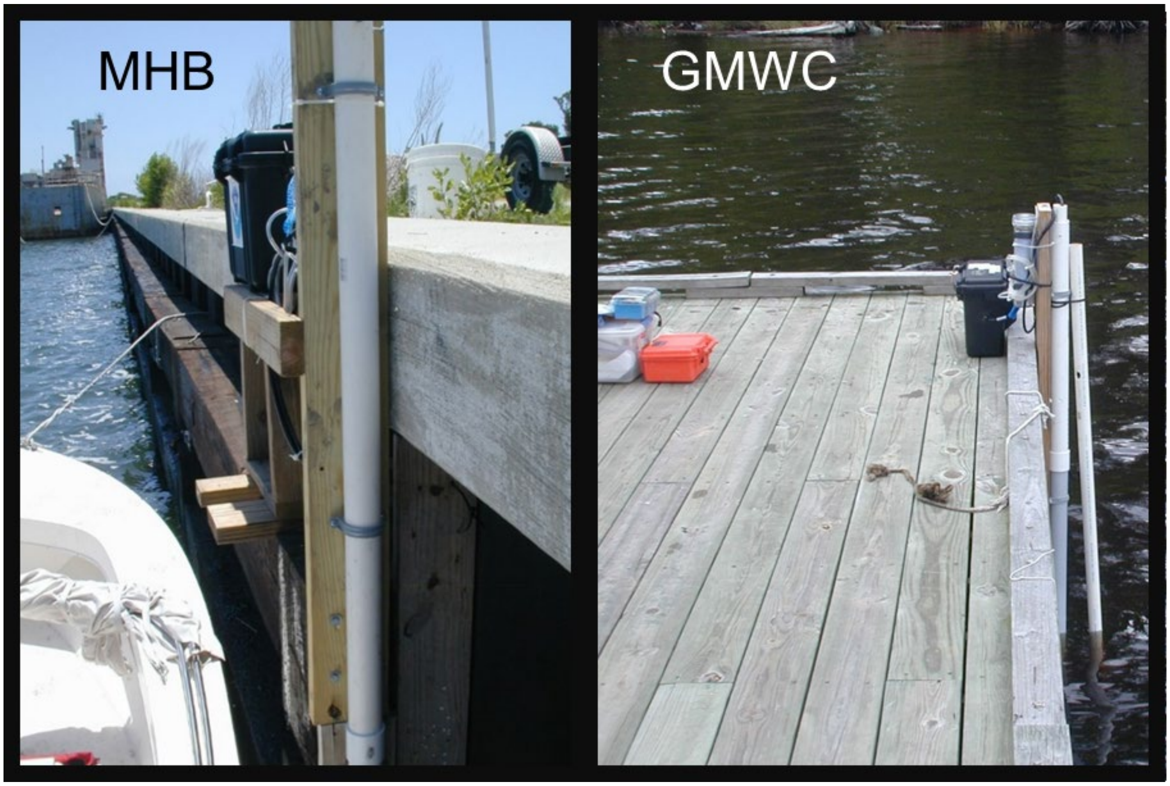

Figure A1. The support structures for the secondary water level stations at Mile Hammock Bay (MHB) and Gottschalk Marina Wallace Creek (GMWC). The sondes were positioned inside a 4” PVC pipe fixed to backing boards. At GMWC, a second PVC pipe positioned seaward from the dock protected the station from boating activity. See text for further description.

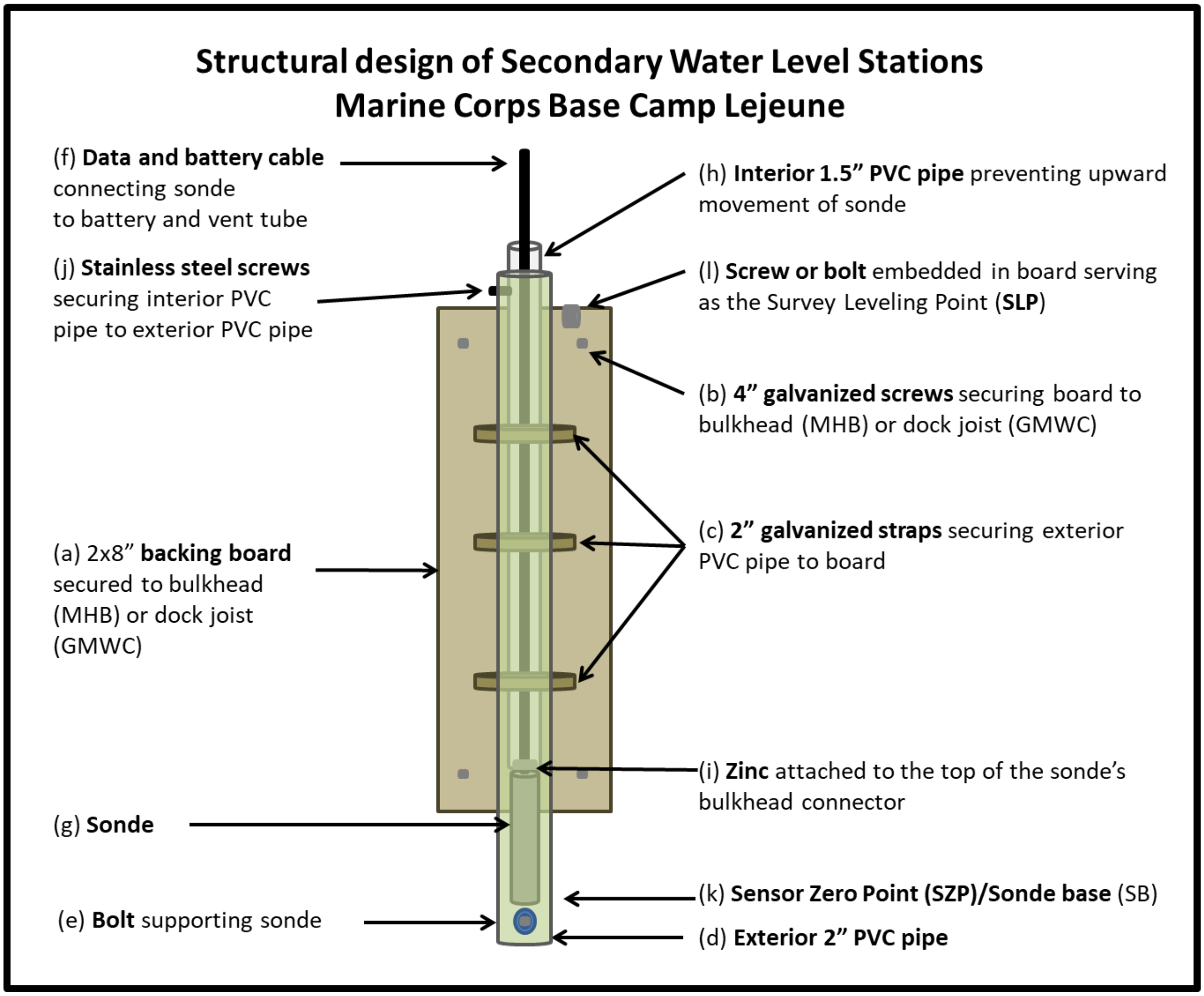

Figure A2. Structural components of the secondary water level stations at Marine Corps Base Camp Lejeune. The SLP is shown to the right of the exterior and interior pipes for illustrative purposes only. It was located in the middle of the top of the backing board. Not to scale.

Table A1. List of structural changes at Mile Hammock Bay (MHB) *and Gottschalk Marina Wallace Creek (GMWC) secondary water level stations and their effect on th*e Survey Leveling Point (SLP) or Sensor Zero Point (SZP) elevation.

Station	Date	Event	SLP/SZP elevation change
MHB	2/21/2008	Installation	
MHB	5/30/2008	Backing board replaced, SLP raised, & exterior pipe length increased	SLP was raised by 1.23 m, SZP was lowered by 0.01 m
MHB	6/22/2009	Vessel strike	SZP elevation unstable
MHB	7/8/2009	Structural repair	SZP raised by 0.06 m
MHB	9/15/2011	Vessel strike or backing board failed	SZP elevation unstable
MHB	12/7/2011	Lower section of backing board & lower section of exterior pipe replaced	SZP lowered by 0.03 m
MHB	3/28/2013	Lower section of exterior pipe replaced	SZP raised by 0.01 m
MHB	9/4/2014	Lower section of exterior pipe replaced	none
MHB	12/4/2017	Lower section of exterior pipe replaced	none
GMWC	5/15/2008	Installation	
GMWC	7/8/2009	Lower section of exterior pipe replaced	none
GMWC	2/26/2010	Replaced brackets after vessel strike	none
GMWC	9/4/2014	Backing board replaced	none
GMWC	8/26/2016	Last day of data collection	none
GMWC	9/12/2016	Station disassembled	none

A.3 The Marine Corps Base Camp Lejeune Local Vertical Control Network

A local vertical control network has an anchor of at least three permanent LCMs with high accuracy elevation with respect to the NSRS (Hensel *et al.*, 2015). For a secondary water level station vertical control network, one of the LCMs is in close proximity to the station's SLP, along with additional nearby reference marks that can be used to connect the SLP to the LCM and check for vertical stability. The elevation of a LCM, determined through geodetic connections to the NSRS, are used to transfer NSRS elevations to other marks in the local vertical control network including the SLP (Hensel *et al.*, 2015). In some cases, the SLP may be designated as a LCM.

At Marine Corps Base Camp Lejeune, a local vertical control network comprised of published bench marks (PMs; a bench mark (BM) with a published NSRS elevation), serving as secondary base stations, LCMs, and reference marks were established following NGS guidelines (Zilkoski et al., 2008). Nearby reference marks were established at MHB and GMWC water level stations to check for station stability and to tie the station to the NSRS via a LCM using leveling (Figure A3). Most of the marks at MHB and GMWC were established in 2008 and some were used temporarily. Reference marks at MHB included three large concrete bollards in close proximity and in clear view of the station. All MHB marks were Class C in stability. Class D reference marks at GMWC included two bolts located on the marina dock deck and a bolt on the top of a fire hydrant on the shoreline. Temporary reference marks (TRMs; steel rods ~ 2 m in length driven into the ground with a few centimeters exposed at the surface) were established at each site in 2009. Class C BMs **(**BM PLINA at GMWC and BM MILE at MHB) were installed in 2011 as LCMs. At GMWC, the TRM and fire hydrant were used only temporarily. In 2016, the SLP served as the second and final LCM at GMWC reducing the need to level over several hundred m from BM PLINA. At MHB, Bollard 5 and TRM were discontinued after BM MILE was established.

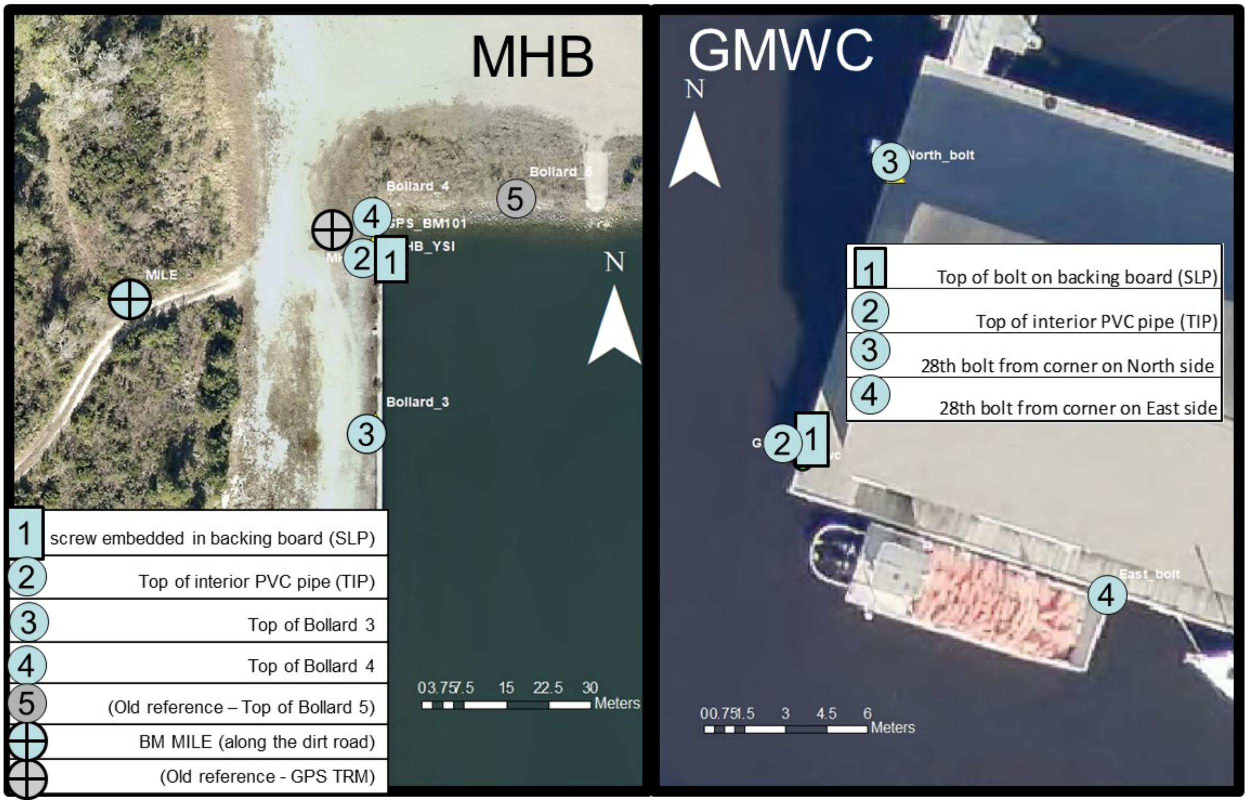

Figure A3. The location of nearby marks in the vertical control networks for Mile Hammock Bay (MHB) and Gottschalk Marina Wallace Creek (GMWC). The discontinued marks at GMWC (BM PLINA, temporary reference mark (TRM), and the bolt on the fire hydrant) are at least 100 m to the south.

A.4 Geodetic Connections

The vertical position of a LCM can be determined through differential leveling or GNSS survey techniques. The type and quality of these surveys influence the uncertainty of the vertical position. In differential leveling, a PM serves as a starting point from which leveling runs are made to the LCM. For differential leveling techniques, the vertical uncertainty of the LCM's elevation is determined by the accuracy and stability of the starting PM's elevation and the quality of the leveling runs. The highest order of vertical leveling, First-Order, class 1 (Federal Geodetic Control Committee, 1984), results in higher accuracy than GNSS methods (Hensel *et* *al.*, 2015). The primary drawbacks of differential leveling are 1) distance from a PM to points of interest, 2) time and number of personnel required, 3) cost of equipment, and 4) the need for a highly experienced field team. Over relatively short distances, however, Second- and Third-Order leveling accuracies can be comparable to those of GNSS accuracies (Hensel *et al.*, 2015).

GNSS Real Time Kinematic (RTK) survey techniques include Vertical Reference Station Real Time Network (VRS RTN), Classic RTK, and static GNSS observations. VRS RTN and Classic RTK surveys can be made with cellular (VRS RTN) or radio (Classic RTK) connections to the NSRS through the Continuously Operating Reference Stations (CORS) network (an active network; Prusky, 2011) (VRS RTN) or through a PM (Classic RTK). Orthometric elevations can be estimated in the field using models applied in the data logger for VRS RTN and Classic RTK surveys.

Static GNSS surveys require post processing procedures to connect to the NSRS and can result in a high level of accuracy over a relatively short time (Henning, 2011). Post-processing procedures include NGS Online Positioning User System (OPUS) and OPUS Projects (OPUS Projects, 2015). OPUS is used to post-process single static occupations and OPUS Projects is used to post-process multiple static occupations made using multiple receivers. Although GNSS data is collected, OPUS and OPUS Projects are currently limited to processing the US Global Positioning System (GPS) data. OPUS and OPUS Projects are used to determine ellipsoid height from GPS data. The conversion of ellipsoid heights (post-processed from GPS data) to orthometric elevations requires further post processing using gravimetric models, which are updated and improved periodically. The gravimetric model that was current at the end of our study period was GEOID12B.

Drawbacks of all types of GNSS surveys are expense of equipment, required software expertise, and quality control considerations, such as atmospheric and space weather impacts. The quality of GNSS data collections can be reduced by poor space weather, length of data collection, multipath error (reflected signals), less than optimal satellite configuration, improper equipment set up, interference associated with the transmitted power levels of adjacent band radiofrequency systems (US Department of Transportation, 2018) or intentional jamming, *e.g.*, see Gallagher (2018). Orthometric elevations are also subject to the accuracy of the geoid model in the region.

The preferred method of differential leveling for transferring NSRS elevations to the LCMs at water level stations and research sites was not the best option for this study due to the distance from PMs to the study area. Simultaneous static GNSS data were collected on PMs, LCMs, and other reference marks multiple times between 2011 and 2016. Instrumentation included two Trimble 5800 dual frequency full wavelength receivers, supplemented in 2012 with two Trimble R6-3 receivers. One receiver was used as a rover during VRS RTN data collection and two or more receivers were used in static collections. The field data were collected on a Trimble TSC2 handheld with Survey Controller software (v12.22).

An OPUS Project was created in 2015 with the submission of simultaneous GPS data collections and a fully constrained vertical adjustment was completed in January 2017 resulting in coordinate positions (North American Datum of 1983 [2011], International Terrestrial Reference Frame 2008), ellipsoid heights (GRS80), and orthometric elevations for all LCMs including BM MILE and the GMWC SLP. Baseline orthometric elevation accuracies, referenced to the North Carolina Geodetic Survey CORS station in Jacksonville, NC (NCJV, PID DK6239), were 0.015 m root mean square (RMS) at BM MILE and 0.014 m RMS at GMWC SLP, with all marks indicating a 0.015 m peak-to-peak error (95% confidence interval). These systematic errors (deviating by a fixed amount from the true value) contributed to the water level and tidal datums error budget (Table 3). The orthometric elevation of the SLP at GMWC was 1.61 ± 0.014 m NAVD 88 (GEOID12B). The orthometric elevation of the BM MILE at MHB was 2.09 ± 0.015 m NAVD 88 (GEOID12B).

A.5 Leveling the Survey Leveling Point to the Local Control Mark

Leveling from the LCM to nearby reference marks and the SLP was performed before and after each sonde change out (sonde replacement) or structural change at GMWC (19 times) and at MHB (23 times) following NGS and CO-OPS recommendations (Hensel *et al.*, 2015). By following protocols required for high accuracy geodetic leveling over short distances (< 60 m) an optical level or laser level may provide similar results as a digital level although neither is as precise as a digital level (Hensel *et al.*, 2015). Initially, we used a CST-Berger Lasermark LMH self-leveling rotary laser, 06-805 aluminum or fiberglass staff rod, and a Lasermark Universal Laser Detector LD400. The Lasermark LMH laser model was replaced in December 2011 by the self-leveling dual-slope rotary model (LM800). Both models had accuracies that decreased linearly with distance (± 0.0015 m at 30 m). Rod graduations were in 0.005 m and measurements were estimated to the mm. The laser level was set up near the water level station with receiver sensitivity set to the highest level (narrowest beam reception). The rod was placed on marks and plumbed and the laser receiver was moved vertically along the rod until a constant signal (or tone) was achieved. The value on the rod at the point where the receiver intercepted the laser beam was recorded in a field data sheet.

Leveling results were used to transfer the orthometric elevation of BM MILE to the SLP at MHB, introducing additional source of error (0.006 m standard deviation [SD]) to the MHB SLP orthometric elevation. The orthometric elevation of the SLP at MHB was 0.90 m NAVD 88 from 2/21/08 to 5/30/08. Following structural changes to the station, the MHB SLP was 2.12 m NAVD 88 from 5/30/08 to 12/4/17. Because the SLP served as the final LCM at GMWC, no leveling error was introduced to the SLP elevation.

A.6 Measuring the vertical distance from the Sensor Zero Point to the Survey Leveling Point

Before and after sonde change outs and structural changes, we measured the offset between the SZP and SLP (Equation 1; Figure A4). Hensel *et al.* (2015) suggest that this measurement can be made directly using a steel-tape but the structural design of our stations required a combination of laser leveling and direct measurements. The SLPs were located on the middle of the top of the backing board and were not in a direct vertical line with the SZP or a direct horizontal line with the top of either pipe. The Top of the Interior Pipe (TIP) served as the intermediate reference point between the SLP and SZP for our results. Comparisons indicated that the Top of the Exterior Pipe (TEP) was an equally good common reference point. The vertical distance from the SLP to the TIP or TEP (TIP – SLP or TEP – SLP) was determined by laser leveling, and the vertical distance from the TIP or TEP to the SZP (TIP – SZP or TEP – SLP) was determined by direct measurement.

$$SLP\ to\ SZP = (TIP - SZP) - (TIP - SLP) = (TEP - SZP) - (TEP - SLP) \quad \text{Eq. 1}$$

The interior pipe and sonde were removed from the exterior pipe and the total length of the interior pipe and the sonde (equal to the vertical distance from TIP to SZP; c in Figure A3) were measured with a steel tape. [The alternate measurement, referencing the SZP to the TEP instead of the TIP (Figure A4) can be determined by inserting a steel tape in the exterior pipe and resting its end on the bolt installed to support the sonde.] The SZP orthometric elevation was calculated by subtracting the vertical distance between the SZP and the SLP (Equation 1) from the elevation of the SLP (Equation 2)

$$SZP\ (m\ NAVD\ 88) = SLP\ (m\ NAVD\ 88) - (SLP\ to\ SZP)\ (m) \quad \text{Eq. 2}$$

Periodic maintenance and repair of the water level stations sometimes resulted in changes in the vertical position of the SLP or SZP affecting the values used in Equation 2 (Table A1). Documenting these changes is important for detecting potential shifts in sensor elevation and maintaining vertical control. The SLP at MHB from 5/30/08 to 12/4/17 was 2.12 m NAVD 88. Prior to its relocation on 5/30/08, the SLP at MHB was at a lower elevation (0.90 m NAVD 88). Measurements of TIP to SZP (Table A2) and TIP to SLP (Table A3) were used in Equation 1 to determine the SZP elevation. Results indicate that the elevation of the SZP (-0.70 m NAVD 88) was stable relative to the SLP at GMWC throughout the study period (Table A4). However, the relative elevation of the SZP to the SLP changed five times at MHB in association with structural changes to the station (Table A1).

A.7 Marine Corps Base Camp Lejeune Vertical Control Error

The transfer of orthometric elevations from the SLP to the SZP introduced two additional sources of error. The variability in leveling and direct measurements was evaluated for each period within which there were known changes in the station structure. At GMWC, structural changes did not affect the relative positions of the SLP and SZP but the use of a longer sonde for three deployments affected the position of the TIP relative to the SZP and SLP. At MHB, the length of the interior pole was lengthened at the same time the SLP was raised on 5/30/08. Table A2 summarizes the variability in the TIP to SZP values used in Equation 1 and their contribution to the error budget. Table A3 provides the same summary information for the leveling-determined vertical offsets of the SLP to TIP. Leveling from BM MILE to the SLP provided an additional source of error (SD = 0.006 m) to the error budget for MHB.

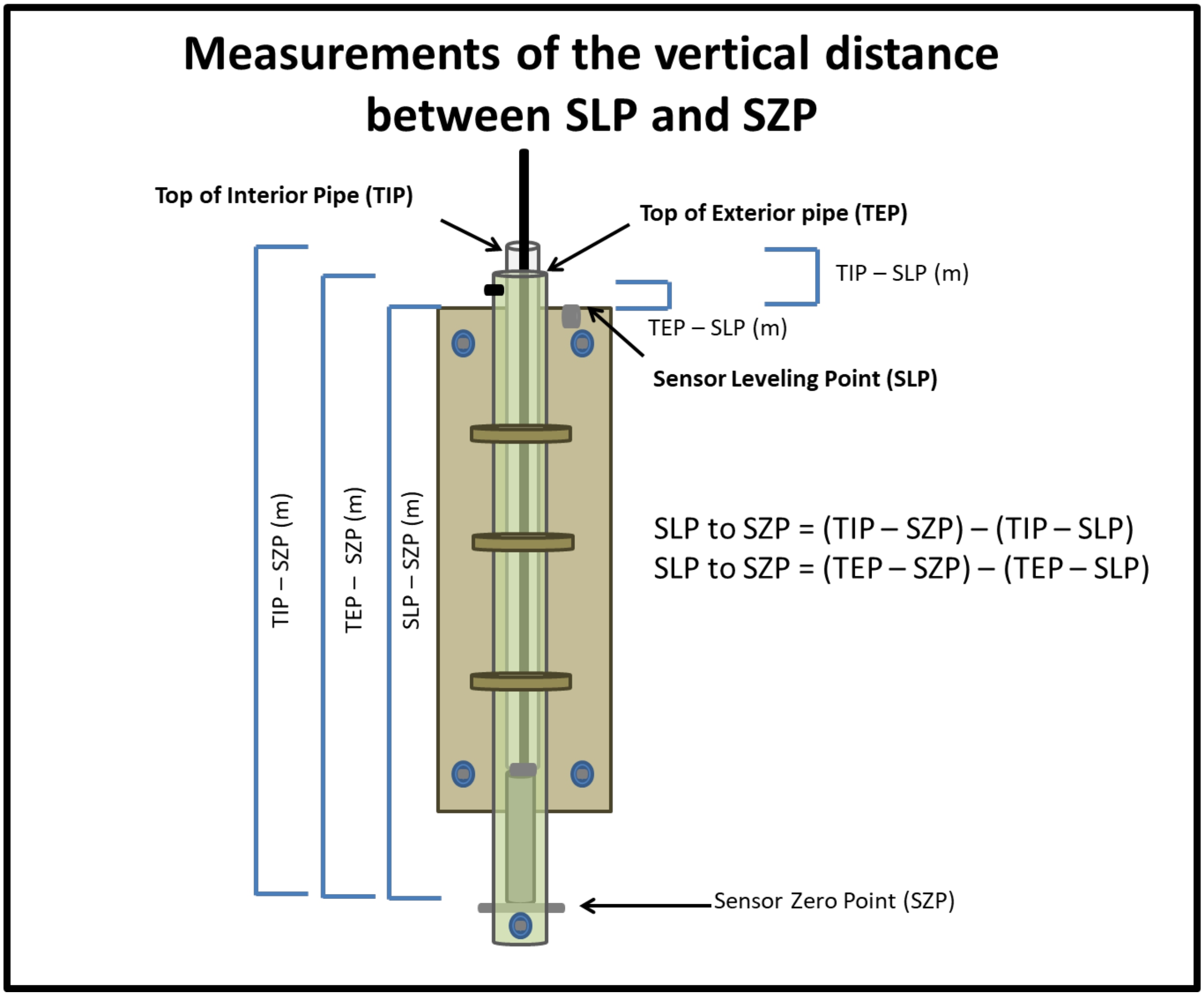

Figure A4. Measurements of the vertical distance between the Survey Leveling Point (SLP) and Sensor Zero Point (SZP). The SLP is shown to the right of the exterior and interior pipes for illustrative purposes only. It was located in the middle of the top of the backing board. Not to scale.

Table A2. Summary of the Top of the Interior Pipe (TIP) to Sensor Zero Point (SZP) measurements at Mile Hammock Bay (MHB) and Gottschalk Marina Wallace Creek (GMWC). All statistics are in meters. All but one sonde were a standard length (normal); one sonde 0.03 m longer than others (long) was deployed three times at GMWC. The distance between the TIP to SZP for the longer sonde at GMWC was measured four times but one of those measurements is considered an error and not included in the summary statistics.

			Vertical Distance from TIP to SZP (m)							
station	**period**	**sonde type**	**n**	**mean**	**median**	**sd**	**se**	**max**	**min**	**range**
MHB	2/21/2008-5/30/2008	normal	1	2.417						
MHB	5/30/2008-12/4/2017	normal	39	3.706	3.705	0.004	0.001	3.714	3.699	0.015
GMWC	5/15/2008-8/26/2016	normal	26	2.309	2.309	0.001	0	2.312	2.307	0.005
GMWC	5/15/2008- 8/26/2016	long	3	2.343	2.343	0.001	0	2.344	2.343	0.001

Table A3. Summary of the vertical distance from the Top of the Interior Pipe (TIP) to the Survey Leveling Point (SLP) for periods between structural change at Mile Hammock Bay (MHB) and grouped by sonde length at Gottschalk Marina Wallace Creek (GMWC). All statistics are in meters. One sonde that was 0.03 m longer (long) than all others (normal) was deployed three times at GMWC. The normal length sondes were deployed 19 times at GMWC and for all deployents at MHB. The standard deviation (SD) is included in the error budget (Table 4).

				Vertical Distance from TIP to SLP (m)					
Station	**Period**	**Sonde length**	**n**	**mean**	**median**	**sd**	**se**	**max**	**min**
GMWC	5/15/2008-8/26/2016 (19 deployments)	normal	39	-0.003	-0.003	0.003	0.000	0.003	-0.010
GMWC	5/15/2008-8/26/2016 (3 deployments)	long	6	0.030	0.030	0.003	0.001	0.035	0.027
MHB	2/21/2008-5/30/2008	normal	1	0.025				0.025	0.025
MHB	5/30/2008-6/22/2009	normal	9	0.088	0.089	0.002	0.001	0.090	0.085
MHB	7/8/2009-12/7/2011	normal	16	0.149	0.150	0.004	0.001	0.154	0.136
MHB	12/7/2011-3/28/2013	normal	8	0.113	0.113	0.003	0.001	0.116	0.109
MHB	3/28/2013-12/4/2017	normal	20	0.131	0.131	0.004	0.001	0.138	0.125

Table A4. Transfer of Survey Leveling Point (SLP) elevations to the Sensor Zero Point (SZP) at Mile Hammock Bay (MHB) and Gottschalk Marina Wallace Creek (GMWC) using Equation 2. The SLP at MHB was lower prior to 5/30/2008. The orthometric elevation of the SLP at GMWC was determined by OPUS Projects in 2017. The orthometric elevation of the SLP at MHB was determined by transferring the OPUS Projects-determined elevation of Bench Mark (BM) MILE to the SLP using leveling data collected throughout the study period. (For dates prior to the establishment of BM Mile in 2011, the transfer was a two-step process, from BM MILE to Bollard 4 and from Bollard 4 to the SLP). See Table A2 for the source of Top of the Interior Pipe (TIP) to SZP values and Table A3 for the source of TIP to SLP values. The single sonde 0.03 m longer (long) than the others (normal) was deployed three times at GMWC. OPUS Projects elevations are accurate to 0.01 m and leveling and direct measurements supporting the SLP to SZP calculations are made at the mm scale.

Station	Sonde Type	Period	SLP (m NAVD 88)	TIP to SZP (m)	TIP to SLP (m)	SLP to SZP (m)	SZP (m NAVD 88)
MHB	normal	2/21/2008-5/30/2008	0.90	2.417	0.025	2.392	-1.49
MHB	normal	5/30/2008-6/22/2009	2.12	3.706	0.088	3.618	-1.50
MHB	normal	7/8/2009-12/7/2011	2.12	3.706	0.149	3.557	-1.44
MHB	normal	12/7/2011-3/28/2013	2.12	3.706	0.113	3.593	-1.47
MHB	normal	3/28/2013-12/4/2017	2.12	3.706	0.131	3.575	-1.46
GMWC	normal	2008-2016 (19 deployments)	1.61	2.309	-0.003	2.312	-0.70
GMWC	long	2008-2016 (3 deployments)	1.61	2.343	0.030	2.313	-0.70

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Appendix B. Tidal Datums

Contents

List of Tables

List of Abbreviations

GMWC	Gottschalk Marina Wallace Creek
MHB	Mile Hammock Bay
NTDE	National Tidal Datum Epoch
NWLON	National Water Level Observation Network

See Table B2 for Tidal Datum abbreviations

Tidal Datum Tables

Appendix B contains tidal datums for Mile Hammock Bay (MHB), Gottschalk Marina Wallace Creek (GMWC), and the National Water Level Observation Network station in Beaufort, NC (8656483). Non-Epoch (by First Reduction) and National Tidal Datum Epoch (NTDE)-equivalent Datums (by Monthly Means Simultaneous Comparison) were calculated using the National Oceanic and Atmospheric Administration's Center for Operational Oceanographic Products and Service's Tidal Analysis Datum Calculator (Licate *et al.*, 2017). The NTDE datums at Beaufort, NC were downloaded from NOAA (2020). See text for description of NTDE-equivalent and Non-Epoch tidal datums and methods of computation. Table B1 summarizes the datums in Appendix B. Table B2 provides a list of tidal datum descriptions and abbreviation. Table B3 provides multiyear tidal datums and Tables B4 to B9 annual tidal datums.

Table B1. List of tidal datums calculated for different periods for the National Water Level Observation Network station # 8656483 at Beaufort, NC (Beaufort), Gottschalk Marina Wallace Creek (GMWC), and Mike Hammock Bay (MHB).

Station	Period	Duration (years)	type
Beaufort	1983-2001	19	NTDE
Beaufort	2008	1	Non-Epoch
Beaufort	2009	1	Non-Epoch
Beaufort	2010	1	Non-Epoch
Beaufort	2011	1	Non-Epoch
Beaufort	2012	1	Non-Epoch
Beaufort	2013	1	Non-Epoch
Beaufort	2014	1	Non-Epoch
Beaufort	2015	1	Non-Epoch
Beaufort	2016	1	Non-Epoch
Beaufort	2017	1	Non-Epoch
Beaufort	2018	1	Non-Epoch
GMWC	2009	1	Non-Epoch and NTDE-equivalent
GMWC	2010	1	Non-Epoch and NTDE-equivalent
GMWC	2011	1	Non-Epoch and NTDE-equivalent
GMWC	2012	1	Non-Epoch and NTDE-equivalent
GMWC	2013	1	Non-Epoch and NTDE-equivalent
GMWC	2014	1	Non-Epoch and NTDE-equivalent
GMWC	2015	1	Non-Epoch and NTDE-equivalent
GMWC	5/2008-5/2016	8	Non-Epoch and NTDE-equivalent
MHB	8/2009-7/2010	1	Non-Epoch and NTDE-equivalent
MHB	9/2010-7/2011	1	Non-Epoch and NTDE-equivalent
MHB	1/2011-12/2012	1	Non-Epoch and NTDE-equivalent
MHB	3/2013-2/2014	1	Non-Epoch and NTDE-equivalent
MHB	3/2014-2/2015	1	Non-Epoch and NTDE-equivalent
MHB	3/2015-2/2016	1	Non-Epoch and NTDE-equivalent
MHB	4/2017-3/2018	1	Non-Epoch and NTDE-equivalent
MHB	8/2009-7/2011	2	Non-Epoch and NTDE-equivalent
MHB	3/2013-2/2016	3	Non-Epoch and NTDE-equivalent

Table B2. Descriptions and abbreviations of tidal datums presented in Table B3 and B4.

Datum	Abbreviation
Date and time of Highest Water Level	HWL date
Highest Water Level	HWL (m NAVD 88)
Lowest water level	LWL (m NAVD 88)
Date and time of lowest water level	LWL date
Mean Higher High Water	MHHW (m NAVD 88)
Mean High Water	MHW (m NAVD 88)
Diurnal Tide Level (Mean of MHHW and MLLW)	DT (m NAVD 88)
Mean Tide Level (Mean of MHW and MLW)	MTL (m NAVD 88)
Mean Sea Level (Mean of hourly heights) over the NTDE	MSL (m NAVD 88)
Mean Low Water	MLW (m NAVD 88)
Mean Lower Low Water	MLLW (m NAVD 88)
Mean diurnal high water inequality (difference in elevation in MHHW and MHW)	DHQ (m)
Mean diurnal low water inequality (difference in elevation between MLLW and MLW)	DLQ (m)
Great diurnal range (difference in elevation between MHHW and MLLW)	GT (m)
Mean range of tide (difference in elevation between MHW and MLW)	MN (m)

Table B3. Multi-year tidal datums. See Table B1 for station names and Table B2 for datum description.

Parameter/Datum	Multi-year NTDE-Equivalent Tidal Datums			NTDE Tidal Datums	Multi-year Non-Epoch Tidal Datums		
	MHB	**MHB**	**GMWC**	**Beaufort**	**MHB**	**MHB**	**GMWC**
Data Start	8/1/2009	3/1/2013	5/15/2008	1/1/1983	8/1/2009	3/1/2013	5/15/2008
Data End	7/31/2011	2/28/2016	5/16/2016	12/31/2001	7/31/2011	2/28/2016	5/16/2016
Mean Water Level (m NAVD 88)	-0.036	-0.01	0.041		-0.036	-0.01	0.041
Highest Water Level (m NAVD 88)	0.928	0.98	1.078		0.928	0.98	1.078
Lowest Water Level (m NAVD 88)	-0.69	-0.683	-0.603		-0.69	-0.683	-0.603
Months in the datums analysis	24	36	96	228	24	36	96
Years in the datums analysis	2	3	8	19	2	3	8
HWL date	9/30/2010	10/5/2015	9/30/2010	9/14/2018	9/30/2010	10/5/2015	9/30/2010
HWL (m NAVD 88)	0.917	0.975	1.072	1.55	0.917	0.975	1.072
LWL (m NAVD 88)	-0.689	-0.663	-0.499	-1.384	-0.689	-0.663	-0.499
LWL date	1/14/2011	3/6/2013	1/1/2009	3/8/2004	1/14/2011	3/6/2013	1/1/2009
MHHW (m NAVD 88)	0.163	0.154	0.075	0.445	0.237	0.258	0.154
MHW (m NAVD 88)	0.124	0.109	0.05	0.358	0.194	0.218	0.13
DT (m NAVD 88)	-0.089	-0.092	-0.036	-0.094	-0.019	0.005	0.041
MTL (m NAVD 88)	-0.093	-0.102	-0.038	-0.116	-0.024	0	0.04
MSL (m NAVD 88)	-0.106	-0.113	-0.039	-0.112	-0.036	-0.01	0.041
MLW (m NAVD 88)	-0.31	-0.312	-0.126	-0.59	-0.243	-0.219	-0.05
MLLW (m NAVD 88)	-0.341	-0.338	-0.146	-0.633	-0.276	-0.247	-0.072
DHQ (m)	0.04	0.045	0.025	0.087	0.043	0.039	0.024
DLQ (m)	0.031	0.026	0.02	0.044	0.033	0.028	0.023
GT (m)	0.504	0.492	0.221	1.079	0.513	0.505	0.226
MN (m)	0.434	0.421	0.176	0.948	0.437	0.437	0.18

Table B4. Annual Non-Epoch tidal datums at Mile Hammock Bay (MHB). See Table B2 for datum descriptions.

Parameter/Datum	Full Year Non-Epoch Tidal Datums at MHB							
Data Start	5/1/2008	8/1/2009	8/1/2010	1/1/2012	3/1/2013	3/1/2014	3/1/2015	4/1/2017
Data End	4/30/2009	7/31/2010	7/31/2011	12/31/2012	2/28/2014	2/28/2015	2/29/2016	3/31/2018
Mean Water Level (m NAVD 88)	-0.08	-0.015	-0.057	-0.028	-0.055	0.008	0.018	0.022
Highest Water Level (m NAVD 88)	0.751	0.787	0.928	0.728	0.627	0.533	0.98	0.766
Lowest Water Level (m NAVD 88)	-0.699	-0.6	-0.69	-0.663	-0.683	-0.482	-0.514	-0.611
Months in the datums analysis	12	12	12	12	12	12	12	12
Years in the datums analysis	1	1	1	1	1	1	1	1
HWL date	9/25/2008	11/14/2009	9/30/2010	6/4/2012	10/9/2013	9/11/2014	10/5/2015	4/24/2017
HWL (m NAVD 88)	0.748	0.786	0.917	0.728	0.626	0.528	0.975	0.758
LWL (m NAVD 88)	-0.699	-0.6	-0.689	-0.659	-0.663	-0.481	-0.513	-0.609
LWL date	1/1/2009	2/11/2010	1/14/2011	3/14/2012	3/16/2013	4/13/2014	2/29/2016	1/9/2018
MHHW (m NAVD 88)	0.191	0.26	0.214	0.251	0.229	0.262	0.277	0.293
MHW (m NAVD 88)	0.143	0.215	0.173	0.211	0.188	0.229	0.238	0.251
DT (m NAVD 88)	-0.063	0.004	-0.044	-0.014	-0.041	0.021	0.034	0.043
MTL (m NAVD 88)	-0.07	-0.002	-0.047	-0.019	-0.047	0.018	0.028	0.035
MSL (m NAVD 88)	-0.08	-0.015	-0.057	-0.028	-0.055	0.008	0.018	0.022
MLW (m NAVD 88)	-0.282	-0.22	-0.266	-0.248	-0.282	-0.192	-0.182	-0.18
MLLW (m NAVD 88)	-0.318	-0.251	-0.302	-0.28	-0.311	-0.221	-0.209	-0.207
DHQ (m)	0.049	0.045	0.041	0.04	0.041	0.033	0.039	0.042
DLQ (m)	0.035	0.032	0.035	0.032	0.029	0.028	0.027	0.027
GT (m)	0.509	0.512	0.516	0.531	0.541	0.483	0.486	0.5
MN (m)	0.425	0.435	0.439	0.459	0.47	0.422	0.419	0.431

Table B5. Annual National Tidal Datum Epoch (NTDE) equivalent tidal datums at Mile Hammock Bay (MHB). See Table B2 for datum descriptions.

Parameter/Datum	**Full Year NTDE-Equivalent Tidal Datums at MHB**							
Data Start	5/1/2008	8/1/2009	8/1/2010	1/1/2012	3/1/2013	3/1/2014	3/1/2015	4/1/2017
Data End	4/30/2009	7/31/2010	7/31/2011	12/31/2012	2/28/2014	2/28/2015	2/29/2016	3/31/2018
Mean Water Level (m NAVD 88)	-0.08	-0.015	-0.057	-0.028	-0.055	0.008	0.018	0.022
Highest Water Level (m NAVD 88)	0.751	0.787	0.928	0.728	0.627	0.533	0.98	0.766
Lowest Water Level (m NAVD 88)	-0.699	-0.6	-0.69	-0.663	-0.683	-0.482	-0.514	-0.611
Months in the datums analysis	12	12	12	12	12	12	12	12
Years in the datums analysis	1	1	1	1	1	1	1	1
HWL date	9/25/2008	11/14/2009	9/30/2010	6/4/2012	10/9/2013	9/11/2014	10/5/2015	4/24/2017
HWL (m NAVD 88)	0.748	0.786	0.917	0.728	0.626	0.528	0.975	0.758
LWL (m NAVD 88)	-0.699	-0.6	-0.689	-0.659	-0.663	-0.481	-0.513	-0.609
LWL date	1/1/2009	2/11/2010	1/14/2011	3/14/2012	3/16/2013	4/13/2014	2/29/2016	1/9/2018
MHHW (m NAVD 88)	0.165	0.168	0.159	0.161	0.161	0.133	0.162	0.169
MHW (m NAVD 88)	0.123	0.128	0.119	0.117	0.112	0.097	0.117	0.123
DT (m NAVD 88)	-0.082	-0.084	-0.094	-0.102	-0.103	-0.102	-0.074	-0.071
MTL (m NAVD 88)	-0.087	-0.089	-0.098	-0.109	-0.114	-0.106	-0.085	-0.081
MSL (m NAVD 88)	-0.101	-0.103	-0.109	-0.119	-0.123	-0.118	-0.097	-0.095
MLW (m NAVD 88)	-0.297	-0.305	-0.315	-0.334	-0.34	-0.31	-0.286	-0.286
MLLW (m NAVD 88)	-0.329	-0.337	-0.347	-0.364	-0.367	-0.337	-0.31	-0.311
DHQ (m)	0.042	0.04	0.039	0.044	0.049	0.036	0.045	0.046
DLQ (m)	0.032	0.031	0.032	0.03	0.027	0.028	0.024	0.025
GT (m)	0.494	0.504	0.506	0.525	0.528	0.471	0.472	0.48
MN (m)	0.42	0.433	0.434	0.451	0.452	0.407	0.403	0.409

Table B6. Annual Non-Epoch tidal datums at Gottschalk Marina Wallace Creek (GMWC). See Table B2 for datum descriptions.

Parameter/Datum	**Full Year Non-Epoch Tidal Datums at GMWC**						
Data Start	1/1/2009	1/1/2010	1/1/2011	1/1/2012	1/1/2013	1/1/2014	1/1/2015
Data End	12/31/2009	12/31/2010	12/31/2011	12/31/2012	12/31/2013	12/31/2014	12/31/2015
Mean Water Level (m NAVD 88)	0.032	0.017	0.011	0.043	0.02	0.08	0.086
Highest Water Level (m NAVD 88)	0.642	1.078	0.659	0.516	0.454	0.46	0.935
Lowest Water Level (m NAVD 88)	-0.501	-0.397	-0.425	-0.412	-0.603	-0.249	-0.335
Months in the datums analysis	12	12	12	12	12	12	12
Years in the datums analysis	1	1	1	1	1	1	1
HWL date	11/15/2009	9/30/2010	8/27/2011	10/30/2012	10/16/2013	9/11/2014	10/5/2015
HWL (m NAVD 88)	0.641	1.072	0.614	0.512	0.454	0.457	0.933
LWL (m NAVD 88)	-0.499	-0.39	-0.424	-0.411	-0.408	-0.248	-0.329
LWL date	1/1/2009	12/15/2010	5/1/2011	1/4/2012	1/4/2012	11/22/2014	1/8/2015
MHHW (m NAVD 88)	0.141	0.127	0.125	0.156	0.136	0.197	0.201
MHW (m NAVD 88)	0.115	0.102	0.1	0.134	0.113	0.173	0.178
DT (m NAVD 88)	0.032	0.013	0.012	0.044	0.02	0.082	0.086
MTL (m NAVD 88)	0.031	0.012	0.011	0.043	0.019	0.08	0.085
MSL (m NAVD 88)	0.032	0.017	0.011	0.043	0.02	0.08	0.086
MLW (m NAVD 88)	-0.053	-0.077	-0.079	-0.047	-0.074	-0.013	-0.007
MLLW (m NAVD 88)	-0.077	-0.101	-0.101	-0.068	-0.096	-0.033	-0.029
DHQ (m)	0.026	0.024	0.025	0.022	0.023	0.024	0.023
DLQ (m)	0.024	0.024	0.022	0.02	0.022	0.02	0.022
GT (m)	0.218	0.227	0.226	0.224	0.231	0.23	0.23
MN (m)	0.168	0.179	0.179	0.181	0.186	0.186	0.186

Table B7. Annual National Tidal Datum Epoch (NTDE) equivalent tidal datums at Gottschalk Marina Wallace Creek (GMWC). See Table B2 for datum descriptions.

Parameter/Datum	Full Year NTDE-Equivalent Tidal Datums at GMWC						
Data Start	1/1/2009	1/1/2010	1/1/2011	1/1/2012	1/1/2013	1/1/2014	1/1/2015
Data End	12/31/2009	12/31/2010	12/31/2011	12/31/2012	12/31/2013	12/31/2014	12/31/2015
Mean Water Level (m NAVD 88)	0.032	0.017	0.011	0.043	0.02	0.08	0.086
Highest Water Level (m NAVD 88)	0.642	1.078	0.659	0.516	0.454	0.46	0.935
Lowest Water Level (m NAVD 88)	-0.501	-0.397	-0.425	-0.412	-0.603	-0.249	-0.335
Months in the datums analysis	12	12	12	12	12	12	12
Years in the datums analysis	1	1	1	1	1	1	1
HWL date	11/15/2009	9/30/2010	8/27/2011	10/30/2012	10/16/2013	9/11/2014	10/5/2015
HWL (m NAVD 88)	0.641	1.072	0.614	0.512	0.454	0.457	0.933
LWL (m NAVD 88)	-0.499	-0.39	-0.424	-0.411	-0.408	-0.248	-0.329
LWL date	1/1/2009	12/15/2010	5/1/2011	1/4/2012	1/4/2012	11/22/2014	1/8/2015
MHHW (m NAVD 88)	0.076	0.067	0.07	0.068	0.077	0.073	0.098
MHW (m NAVD 88)	0.051	0.046	0.045	0.042	0.048	0.046	0.072
DT (m NAVD 88)	-0.032	-0.045	-0.04	-0.043	-0.037	-0.039	-0.014
MTL (m NAVD 88)	-0.034	-0.043	-0.043	-0.047	-0.042	-0.043	-0.017
MSL (m NAVD 88)	-0.035	-0.04	-0.043	-0.048	-0.043	-0.043	-0.02
MLW (m NAVD 88)	-0.118	-0.132	-0.131	-0.136	-0.132	-0.132	-0.107
MLLW (m NAVD 88)	-0.14	-0.156	-0.15	-0.153	-0.15	-0.15	-0.126
DHQ (m)	0.025	0.021	0.026	0.026	0.029	0.027	0.027
DLQ (m)	0.022	0.025	0.019	0.017	0.018	0.018	0.019
GT (m)	0.216	0.224	0.22	0.221	0.228	0.224	0.224
MN (m)	0.168	0.178	0.175	0.178	0.18	0.179	0.178

Table B8. Annual Non-Epoch tidal datums at Beaufort, NC from 2008-2013. See Table B2 for datum descriptions.

Parameter/Datum	**Full Year Non-Epoch Tidal Datums at Beaufort**					
Data Start	1/1/2008	1/1/2009	1/1/2010	1/1/2011	1/1/2012	1/1/2013
Data End	12/31/2008	12/31/2009	12/31/2010	12/31/2011	12/31/2012	12/31/2013
Mean Water Level (m NAVD 88)	-0.092	-0.047	-0.059	-0.061	-0.025	-0.053
Highest Water Level (m NAVD 88)	1.087	1.13	0.921	1.28	1	0.997
Lowest Water Level (m NAVD 88)	-1.139	-1.188	-0.938	-1.018	-1.074	-1.066
Months in the datums analysis	12	12	12	12	12	12
Years in the datums analysis	1	1	1	1	1	1
HWL date	9/25/2008	11/14/2009	9/30/2010	8/27/2011	10/29/2012	10/9/2013
HWL (m NAVD 88)	1.067	1.114	0.893	1.271	1.002	0.986
LWL (m NAVD 88)	-1.123	-1.169	-0.937	-1.005	-1.06	-1.06
LWL date	3/9/2008	1/12/2009	3/1/2010	2/19/2011	3/9/2012	3/6/2013
MHHW (m NAVD 88)	0.479	0.515	0.5	0.506	0.531	0.51
MHW (m NAVD 88)	0.376	0.419	0.413	0.416	0.45	0.429
DT (m NAVD 88)	-0.068	-0.027	-0.039	-0.04	-0.004	-0.035
MTL (m NAVD 88)	-0.095	-0.05	-0.06	-0.062	-0.026	-0.054
MSL (m NAVD 88)	-0.092	-0.047	-0.059	-0.061	-0.025	-0.053
MLW (m NAVD 88)	-0.565	-0.52	-0.533	-0.54	-0.501	-0.538
MLLW (m NAVD 88)	-0.615	-0.57	-0.578	-0.586	-0.54	-0.581
DHQ (m)	0.103	0.096	0.088	0.09	0.081	0.081
DLQ (m)	0.049	0.05	0.045	0.046	0.039	0.043
GT (m)	1.094	1.085	1.078	1.093	1.071	1.091
MN (m)	0.941	0.939	0.946	0.957	0.951	0.967

Table B9. Annual Non-Epoch tidal datums at Beaufort, NC from 2014-2018. See Table B2 for datum descriptions.

Parameter/Datum	Full Year Non-Epoch Tidal Datums at Beaufort (continued)				
Data Start	1/1/2014	1/1/2015	1/1/2016	1/1/2017	1/1/2018
Data End	12/31/2014	12/31/2015	12/31/2016	12/31/2017	12/31/2018
Mean Water Level (m NAVD 88)	0.007	-0.01	0.031	-0.007	0.005
Highest Water Level (m NAVD 88)	0.936	1.171	1.087	1.052	1.587
Lowest Water Level (m NAVD 88)	-0.955	-0.999	-0.905	-1.058	-1.021
Months	12	12	12	12	12
Years in the datums analysis	1	1	1	1	1
HWL date	10/5/2014	10/4/2015	10/8/2016	4/24/2017	9/14/2018
HWL (m NAVD 88)	0.932	1.137	1.048	1.015	1.561
LWL (m NAVD 88)	-0.952	-0.97	-0.887	-1.039	-1.021
LWL date	2/1/2014	2/22/2015	4/9/2016	1/14/2017	2/2/2018
MHHW (m NAVD 88)	0.569	0.556	0.595	0.566	0.571
MHW (m NAVD 88)	0.494	0.474	0.515	0.483	0.489
DT (m NAVD 88)	0.022	0.008	0.048	0.014	0.022
MTL (m NAVD 88)	0.007	-0.013	0.03	-0.008	0.004
MSL (m NAVD 88)	0.007	-0.01	0.031	-0.007	0.005
MLW (m NAVD 88)	-0.479	-0.499	-0.455	-0.499	-0.48
MLLW (m NAVD 88)	-0.525	-0.539	-0.499	-0.539	-0.526
DHQ (m)	0.075	0.082	0.08	0.083	0.082
DLQ (m)	0.045	0.04	0.044	0.041	0.046
GT (m)	1.093	1.095	1.094	1.106	1.097
MN (m)	0.973	0.973	0.971	0.982	0.969

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