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Numerical Simulation of Tides and Storm Surges at Chignecto Isthmus During Post-Tropical Storm Fiona

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Executive Summary

A numerical modelling investigation of the combined effects of tides and storm surges on total water levels at Chignecto Isthmus was performed for post-tropical storm Fiona, which impacted Atlantic Canada in 2022, and two other hypothetical extreme scenarios. The analysis is intended to assist the provinces of Nova Scotia and New Brunswick in understanding the effects of tides, storm surges and sea-level rise (SLR) on extreme high-water levels along the Chignecto Isthmus.

The study made use of a TELEMAC-2D hydrodynamic model of the Bay of Fundy and adjacent coastal floodplains, developed by the Ocean, Coastal and River Engineering Research Centre of the National Research Council Canada (NRC-OCRE), which was forced by tides, and atmospheric data (surface wind fields and pressures) from the European Centre for Medium-Range Weather Forecasts' 5th generation reanalysis (ERA5). The model was calibrated and validated using water level records in the Cumberland Basin, measured by the TransCoastal Adaptations Centre for Nature-Based Solutions at Saint Mary's University (TCA-SMU) and the Geological Survey of Canada during field campaigns from 2020-2022.

Modelling scenarios were developed in consultation with a project Technical Advisory Committee, and included:

- 2022 post-tropical storm Fiona;
- A hypothetical future storm event (based on the 1976 Groundhog Day storm) coinciding with a high-tide event at the peak of the lunar nodal cycle (which will occur in 2033);
- A hypothetical future storm event (based on the 1976 Groundhog Day storm) coinciding with a high-tide in 2100 based on relative SLR projections for the RCP8.5 emissions scenario;
- Sensitivity testing to determine the effect of shifts in the timing of a storm event (based on the 1976 Groundhog Day storm) relative to high tide on resulting total water levels.

Key findings from the analysis are summarized as follows:

Effects of post-tropical storm Fiona: The storm surge from post-tropical storm Fiona in the Cumberland Basin represented a relatively small contribution to peak water levels along the Chignecto Isthmus, which were primarily dominated by the astronomical tide. Both negative and positive storm surges (up to +0.15 m) occurred in the Cumberland Basin during Fiona's passage up the eastern seaboard. However, positive storm surges occurred close to the astronomical low tide, and therefore the resulting total water levels did not exceed those associated with astronomical high tides, or local dyke crest elevations. This illustrates the importance of the timing of storm passage through the region relative to astronomical tides on high-water levels, and the associated potential for overtopping of dykes.

Storm track and wind direction: The study suggests that storms resulting in sustained southwesterly winds over the Cumberland Basin (i.e. with storm tracks slightly to the west of the basin) are likely to generate more significant storm surges on the Chignecto Isthmus due to the orientation of the longest fetches in the Bay of Fundy and the Cumberland Basin. A hypothetical storm directly impacting the Chignecto Isthmus, with winds directed towards the shore and coinciding with the highest astronomical tides, resulted in total water levels that reached and, in some places, exceeded the elevations of the existing dyke system.

Sea-Level Rise: The highest astronomical tides do not exceed the elevations of the dykes under present-day (i.e. reference year of 2021) sea levels. However, a relative SLR of +0.63 m (corresponding to year 2100 projections for the RCP8.5 emissions scenario) would result in the highest astronomical tides exceeding dyke crest elevations, even without any storm surges or wave effects.

Timing of storms: Timing of storm surges relative to tides, and tide-surge interactions, can greatly affect peak total water levels. The model showed that a storm with peak local windspeed coinciding at or near the time of high tide can significantly affect storm surge. For hypothetical atmospheric events similar to the Groundhog Day storm, total water levels increased by more than 1 meter at the time of the highest astronomical tide, when peak local winds peaked 2.5 hours before it. The findings highlight a crucial 4-to-6-hour window during each 12.4-hour tidal cycle where storm timing can significantly impact peak water levels, especially during spring tides. Outside this window, especially at low tide, the impact is much less. In the low-lying region of the Chignecto Isthmus, the timing of storm surges relative to astronomical tides is of critical importance in determining the potential for flooding.

The Chignecto Isthmus, connecting New Brunswick and Nova Scotia, is to a certain extent protected from tide- and storm surge-driven flood hazards by coastal dykes. However, a combination of future projected SLR, increasing tidal ranges during the lunar nodal cycle (18.6 years), and extreme weather events will result in more frequent, and higher, peak water levels. This study quantifies the contributions of tides and storm surges to water levels during post-tropical storm Fiona, and several hypothetical storm events, highlighting the importance of storm track and timing relative to tides. Model results show that storm surges compounding with high tides within a critical 4-to-6-hour window of the 12.4-hour tidal cycle can result in significantly higher peak water levels, especially during spring tides that occur approximately every 15 days. Storm tracks, and the resulting wind directions, are also crucial in determining the impacts of storms on peak total water levels in the Cumberland Basin. In fact, the timing of storms relative to astronomical tides, and storm wind directions, are more important in determining peak water levels in the Cumberland Basin than storm intensity. By 2100, SLR projections for the RCP8.5 emissions scenario indicate that the highest astronomical tides will exceed current dyke elevations, underscoring the need for adaptation of flood risk management infrastructure and strategies.

There were a number of study limitations and sources of modelling uncertainty, linked to the limited availability of bathymetric data, the absence of long-term water-level records, and the omission of subsurface drainage, groundwater flow, precipitation, and upland (freshwater) discharges from the model. Recommendations were provided to address data gaps and uncertainty, and to leverage the hydrodynamic model as a tool for future probabilistic flood risk assessments, and design of flood risk management strategies or infrastructure adaptation plans.

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List of Acronyms

CGVD2013	Canadian Geodetic Vertical Datum 2013
CHC	Canadian Hydraulic Centre
CHS	Canadian Hydrographic Service
CSRS	Canadian Spatial Reference System
DEM	Digital Elevation Model
ECCC	Environment and Climate Change Canada
EDF	Electricité de France
ELG	New Brunswick Environment and Local Government
ERA5	European Centre for Medium-Range Weather Forecasts fifth generation reanalysis for global climate and weather data
HHWLT	Higher high water large tide
IPCC AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate Change
MMRA	Maritime Marshland Rehabilitation Administration
MSC	Meteorological Survey of Canada
NAD83	North American Datum of 1983
NRC-OCRE	National Research Council Canada – Ocean, Coastal and River Engineering Research Centre
NSCC-AGRG	Nova Scotia Community College Applied Geomatics Research Group
RCP	Representative Concentration Pathways
RMSE	Root Mean Square Error
SLR	Sea-level rise
SWE	Surface water elevation
TCA-SMU	TransCoastal Adaptations Centre – Saint Mary's University
UTC	Universal Time, Coordinated
UTM	Universal Transverse Mercator
WGS84	World Geodetic System 1984

1. Introduction

The Ocean, Coastal and River Engineering Research Centre (OCRE) of the National Research Council Canada (hereafter referred to as “NRC-OCRE”) and TransCoastal Adaptations Centre for Nature-based Solutions at Saint Mary’s University (hereafter referred to as “TCA-SMU”) have prepared this report for the Technical Advisory Committee comprised of New Brunswick Environment and Local Government / Nouveau Brunswick Environnement et Gouvernements locaux (hereafter referred to as “ELG”), New Brunswick Department of Transportation and Infrastructure / Nouveau Brunswick Ministère des Transports et Infrastructure, Nova Scotia Department of Public Works and Nova Scotia Department of Environment and Climate Change.

The National Research Council is the Government of Canada’s premier research organization supporting industrial innovation, the advancement of knowledge and technology development, and fulfilling government mandates. NRC-OCRE supports a broad cross section of industry sectors by developing creative and practical solutions to engineering challenges in rivers, lakes and marine environments, with a particular focus on harsh and extreme conditions. The Research Centre provides expertise and tools to identify, adapt, and integrate advanced solutions into systems that improve the performance and safety of ocean, coastal, and marine operations, meet the challenges of climate change, and protect infrastructure, property and people from severe weather events and other environmental risks. The NRC-OCRE owns and operates comprehensive test facilities, including ice tanks, wave basins, wave flumes, and state-of-the-art numerical hardware and tools, located both in St. John’s and Ottawa.

TransCoastal Adaptations Centre for Nature-based Solutions at Saint Mary’s University is a centre of expertise in the application of nature-based climate change adaptation and coastal habitat restoration projects. With over 20 years of experience, the team consists of leading experts in coastal geomorphology, coastal habitat restoration and monitoring, climate change vulnerability assessment and adaptation, and applied research, with specific experience and expertise in the Bay of Fundy region of Nova Scotia. Collectively, the team at TCA-SMU has extensive experience in leading projects and studies in the Bay of Fundy, focused on salt marsh restoration and managed dyke realignment and have restored over 400 ha of tidal wetlands in Nova Scotia across 14 different sites over the last 18 years. In addition, TCA-SMU has access to state-of-the-art technology, software, lab, and field instrumentation within its two research centres funded by the Canadian Foundation for Innovation: MP_SpARC and In_CoaST. Over the last decade TCA-SMU has conducted comprehensive vulnerability assessments of Fundy dykelands and worked closely with the Nova Scotia Department of Agriculture. The team has gained extensive experience and developed standard operating and safety procedures for working within the physically and environmentally challenging environment of the Bay of Fundy.

1.1. Background

In 2023, ELG, in consultation with the Technical Advisory Committee, invited the NRC-OCRE to submit a proposal to numerically simulate the tide- and storm surge-driven water levels that occurred in the Bay of Fundy during the passage of post-tropical storm Fiona, to inform planning and funding applications for potential coastal dyke infrastructure adaptation by governments of New Brunswick, Nova Scotia and other partners. It was proposed to make use of an existing, two-dimensional hydrodynamic model of Cumberland

Basin and the adjacent coastal floodplain to address this need. The NRC-OCRE has been developing this model since 2020 with input from partners including TCA-SMU.

1.1.1. Post-Tropical Storm Fiona

Storm surges generated by the post-tropical storm Fiona had significant impacts on the Maritime provinces, including substantial coastal erosion on parts of Prince Edward Island (Mulligan et al., 2023). Pasch et al. (2023) referred to the event as the “deepest cyclone on record... to make landfall in Canada”, while Contant (2022) reported it as the “costliest extreme weather event ever recorded in Atlantic Canada”.

Notably, the northerly-moving track of post-post tropical storm Fiona passed more than 200 km to the east of Cumberland Basin (Figure 1.1a) (National Oceanic and Atmospheric Administration, 2024), and the peak storm surge occurred about mid-way between neap and spring tides, potentially mitigating the impacts at Chignecto Isthmus. Additionally, there are no permanent tide gauges in Cumberland Basin and the timing of peak storm surge relative to the peak astronomical tide is uncertain. This has significant implications for flood hazard potential, given the large tidal ranges in this part of the Bay of Fundy. In the Cumberland Basin, the peak surface wind generated from the southeast reached speeds up to 15.8 m/s (Copernicus Climate Change Service, 2017). However, significantly higher wind speeds were recorded near the eye of the storm, reaching up to 30 m/s (Figure 1.1b).

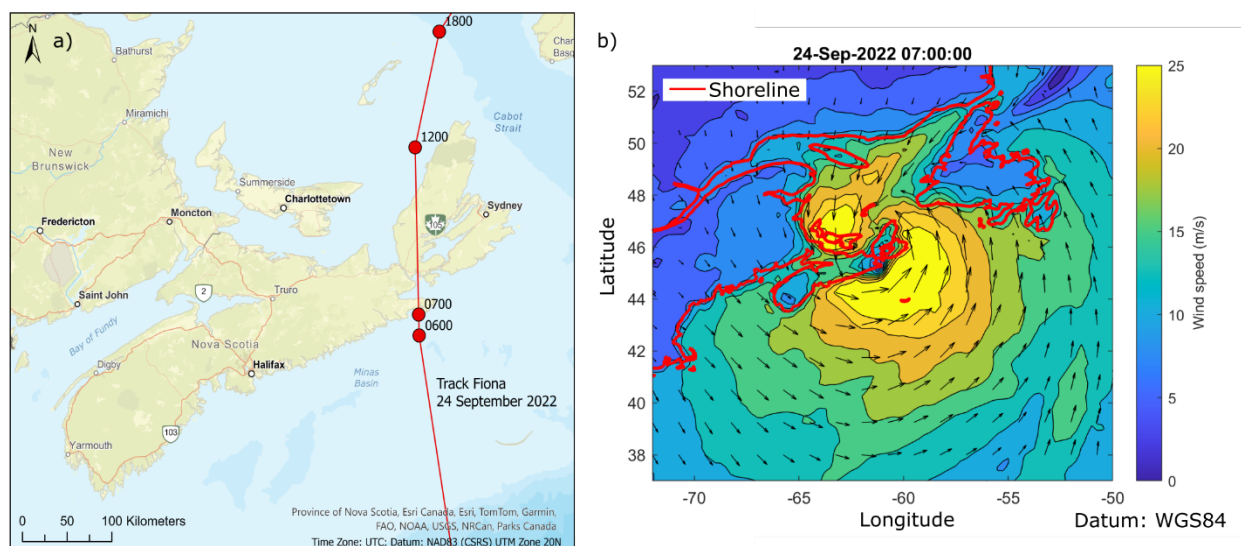


Figure 1.1 Post-tropical storm Fiona on September 24th 2022 a) Storm track as it made landfall on Cape Breton (National Oceanic and Atmospheric Administration, 2024); b) Wind field (Copernicus Climate Change Service, 2017).

1.1.2. Chignecto Isthmus and Coastal Dyke Infrastructure

Chignecto Isthmus is a low-lying land formation connecting the provinces of New Brunswick and Nova Scotia, and separating the Bay of Fundy from Northumberland Strait (Figure 1.2). The Chignecto Isthmus is home to an extensive network of coastal dykes, originally built in the 17th century and upgraded in the mid-20th century by the Maritime Marshland Rehabilitation Administration (MMRA). These dykes,

maintained by the provinces since the MMRA upgrades, were designed to an agricultural standard, and offer some protection against tides, storm surges, and sea-level rise (SLR), for assets including transportation infrastructure (i.e. Trans-Canada Highway, CN railway, local roads), energy and communication infrastructure, nearby communities, cultural and national historic sites, private properties and water and wastewater infrastructure.

Relative SLR and the potential impacts of extreme weather events, such as post-tropical storm Fiona in September 2022, threaten the integrity of the dykes and pose risks landward of the dykes. Post-tropical storm Fiona was one of the largest and most intense storms recorded in the region (Government of New Brunswick, n.d.).



Figure 1.2 Location of Chignecto Isthmus and Cumberland Basin – adapted from Government of New Brunswick (n.d.).

1.1.3. Brief Background to Tides in the Bay of Fundy

Tidal motion is the oscillation of ocean waters under the influence of the gravitational forces of the Moon and the Sun. The Bay of Fundy experiences semidiurnal tides, meaning it has approximately two high and two low tides each day, or two 12.4-hour tidal cycles. The height of the tide varies predictably based on the interactions between the motions of the Moon, the Sun and the Earth. Among the main variations are spring and neap cycles due to the moon phases. Twice each lunar month (~ 29.5 days), during the new moon and full moon phases, the gravitational forces of the Moon and the Sun reinforce each other, resulting in higher high tides and lower low tides, known as spring tides. Neap tides occur during the first and third quarter moon phases, resulting in a smaller difference between high and low tides than average.

Additionally, the Moon follows an elliptical orbit around the Earth, completing a cycle approximately every 27 days. When the Moon is closest to the Earth (perigee) the tidal range increases. When the Moon is furthest from the Earth (apogee) the tidal range decreases. About 6-8 times a year, a new or full moon coinciding with the perigee, result in perigean spring tides, which have an even greater tidal range.

Moreover, the Moon's declination relative to the equator varies due to the precision of its orbital plane, known as the lunar nodal cycle, which takes approximately 18.6 years to complete. Consequently, variations in the tidal range are observed over an 18.6-year period.

Local observed tidal levels are also influenced by the topography of continental shelves. The Bay of Fundy acts like a funnel, amplifying the tidal signal. Consequently, these variations due to the interactions between the Moon, the Sun and Earth have a significant influence, leading to substantial differences in tidal range throughout the day, across the months, and over the years.

1.1.4. Existing NRC-OCRE Hydrodynamic Model of Cumberland Basin

With financial support from the Canadian Safety and Security Program, and in collaboration with TCA-SMU and Natural Resources Canada-Geological Survey of Canada, NRC-OCRE had previously developed a calibrated and validated tidal hydrodynamic model of Cumberland Basin and adjacent coastal floodplains. Under NRC's Climate-Resilient Built Environment Initiative and the Federal Government's National Adaptation Strategy, the model is being used in research on the potential for Nature-based Solutions (managed dyke realignment and marsh restoration) to contribute to flood risk management, and to assess the potential impacts of such solutions on water levels and circulation in a highly tidal and dynamic region such as the Bay of Fundy.

1.2. Objectives

The objectives of the study described herein were to evaluate:

- Tides and storm surges surge contributions to total water levels at Chignecto Isthmus during post-tropical storm Fiona;
- Water levels associated with two agreed upon (in collaboration with the Technical Advisory Committee) hypothetical extreme scenarios.

2. Available Data

2.1. Bathymetry and Topography

The Chignecto Isthmus covers an extensive region within the provinces of New Brunswick and Nova Scotia. Consequently, multiple bathymetric and topographic data sources were required (Figure 2.1).

- The Canadian Hydrographic Service (CHS) provided the NRC-OCRE with single-beam echo soundings and navigational charts under Memorandum of Understanding (MOU) #2021-0106-1260-NRC. More specifically, CHS provided Charts 4010 and 4130, and echo soundings collected within the Bay of Fundy, Cumberland Basin and Petitcodiac River. The echo soundings are depicted as bright blue marks in the map of Figure 2.1. While this dataset offers a starting point, the model would benefit from more recent measurements of the bathymetry and a higher resolution dataset throughout the waters of the Cumberland Basin.
- A high-resolution Digital Elevation Model (DEM) of Converse Marsh provides partial bathymetry of the Missaguash River, the recent dyke breach at the marsh (Bowron et al., 2020), and the newly contributing tributary to the Missaguash River. The DEM was derived using Structure from Motion (SfM) from orthomosaics collected using Wingtra One drone flown at 80 m during low tide. The extent of this DEM is outlined by a green rectangle in Figure 2.1.
- In August 2021, the Nova Scotia Community College Applied Geomatics Research Group (NSCC-AGRG) collected airborne LiDAR and imagery over an established marsh restoration site near Aulac, Nova Scotia in the upper reaches of the Cumberland Basin (Crowell, 2021). Since terrestrial LiDAR does not penetrate the water surface, it was flown during low tide to measure a significant portion of the tidal flats in the area. The LiDAR dataset was processed into a raster image with a resolution of 1.5 m. The extent of this dataset is outlined by the yellow rectangle in Figure 2.1.
- The province of New Brunswick provides a collection of publicly accessible DEMs processed from LiDAR surveys under the geoNB online portal service (Service New Brunswick, 2020). The DEMs are composed of grid tiles that were developed in 2017 and 1 m resolution data encompassing the model domain within the province of New Brunswick (as outlined in pink in Figure 2.1).
- Similar to New Brunswick, the province of Nova Scotia provides a collection of publicly accessible DEMs through a portal titled geoNOVA (Government of Nova Scotia, 2020). The datasets are composed grid tiles of 1 m resolution (as outlined in orange in Figure 2.1).
- The Canadian National Vector (CanVec) DEM at a resolution of 0.75 arc second and altimetric accuracy of 5 to 10 m (Natural Resources Canada, 2016) acted as a surrogate where other topographic datasets were not available or inconsistent (the extent of the DEM is outlined in grey in Figure 2.1).
- In 2005 a TELEMAC-2D model was developed by NRC's Canadian Hydraulic Centre (CHC) – now a part of the NRC-OCRE – for AMEC to study the Petitcodiac River; which also included the upper reaches of the Bay of Fundy including Cumberland Basin (AMEC Earth and Environmental, 2005). For this model, hereafter referred to as the CHC model, the bathymetry of Cumberland Basin and the Bay of Fundy were developed by digitizing CHS Charts 4010 and 4030; while the bathymetry of the Petitcodiac River was developed from historically surveyed lines (AMEC Earth and Environmental, 2005). The extent used from this model's bathymetry is provided in blue outline in Figure 2.1.

NRC-OCRE's Cumberland Basin hydrodynamic model topography and bathymetry is based on a combination/merger of bathymetric and topographic datasets available at the time of model development, each with varying degrees of accuracy and resolution. **Although these datasets are understood to be the best available information at the time of development, the model is constrained by the limited availability of data, particularly for the subtidal and offshore regions of the Cumberland Basin. Please refer to Section 7, point 1. for further discussion and recommendations.**

The model does not include bridges, aboiteaux, culverts, or other subterranean drainage systems in the Chignecto Isthmus, except for the water control structure at Tantramar River and the aboiteau at La Planche River. The model is therefore not expected to accurately portray flood inundation extents landward of the dyke system, and likely provides a conservative estimate of tide- and storm surge-generated water levels on the seaward side of the dykes. Please refer to Section 7, point 2. for further discussion and recommendations.

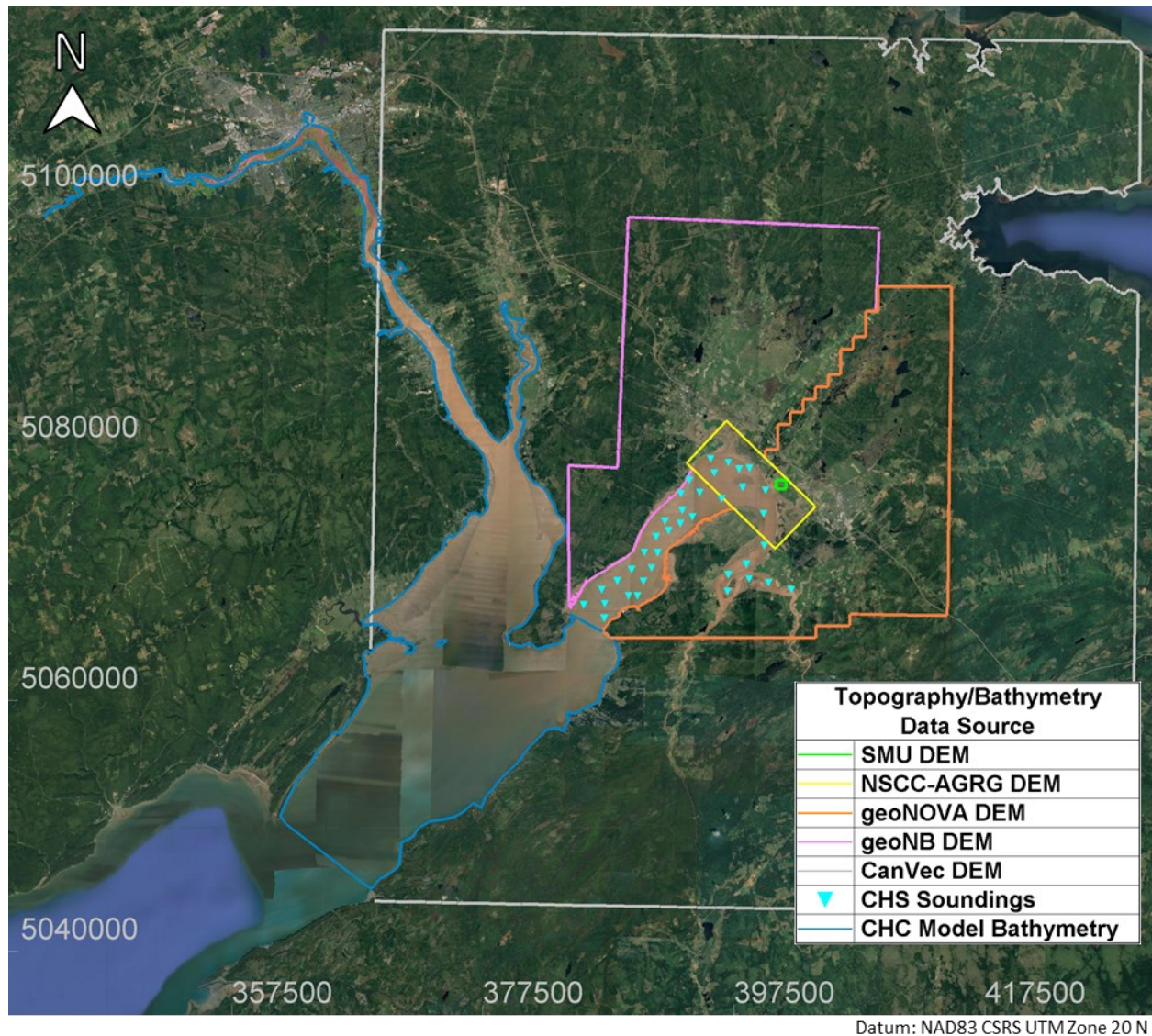


Figure 2.1 The map indicates the location of each data source, distinguished by different colours and points, used to create the bathymetry and topography of the Cumberland Basin hydrodynamic model. All basemap images in this report are from Google © 2020 unless otherwise indicated.

2.2. Dyke Centrelines and Elevations

The sources of dyke data available to the study are listed below. The dyke elevations vary throughout their entire length, as illustrated in Figure 2.2.

- **New Brunswick Dykes:** Centreline elevations for dykes in New Brunswick in the Chignecto Isthmus were surveyed in 2017. This dataset included dykes at Aulac River, Missaguash River, Town of Sackville and community of Westcock.
- **Nova Scotia Dykes:** In 2020, the Nova Scotia Department of Agriculture surveyed centreline elevations for dykes located along the Missaguash and La Planche rivers.

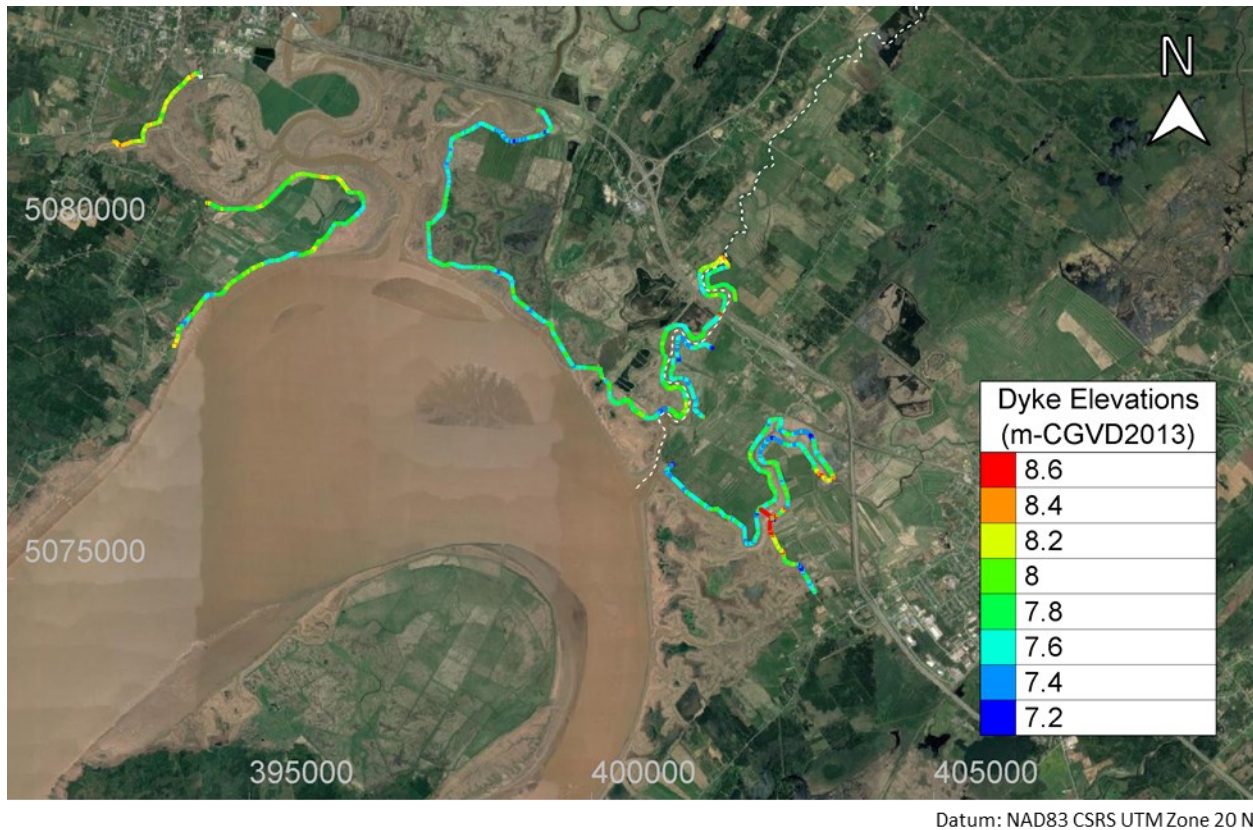


Figure 2.2 Location of dyke centrelines.

2.3. Land Cover

Land cover data were acquired to guide selection and tuning of roughness coefficients during model calibration. A WorldView-2 satellite image collected at low tide was commissioned in October 2020. It provided a detailed observation of the land cover including tidal and intertidal regions of Cumberland Basin, tributaries and their stream networks, and flood plains where water inundation is only observed during periods of high-water levels or flooding. Post-processing of the image produced six land classes: water, sand and railroad, mud and road, buildings, short vegetation such as grasses and long vegetation such as large shrubs and trees (Manson et al., 2022). The final available land cover with all identified classes is shown in Figure 2.3. Typical Strickler roughness coefficients for the given land cover were based on Lambkin (n.d.) and Chow (1959) as shown in Table 2.1.

Table 2.1 Typical Strickler roughness coefficients for given land cover attributes

Land Cover Attribute	Strickler Roughness Coefficient ($s/m^{1/3}$)	Source
Water (riverbed)	30 – 40	Chow
Short vegetation (grasses)	20 – 40	Chow
Sand (rippled to unrippled) / Railroad	32 – 49	Lambkin
Mud / Road (including asphalt, also includes some fallow fields)	53	Lambkin
Tall Vegetation (large shrubs and trees > 1 m in height)	5 – 9	Chow
Buildings	5	Chow

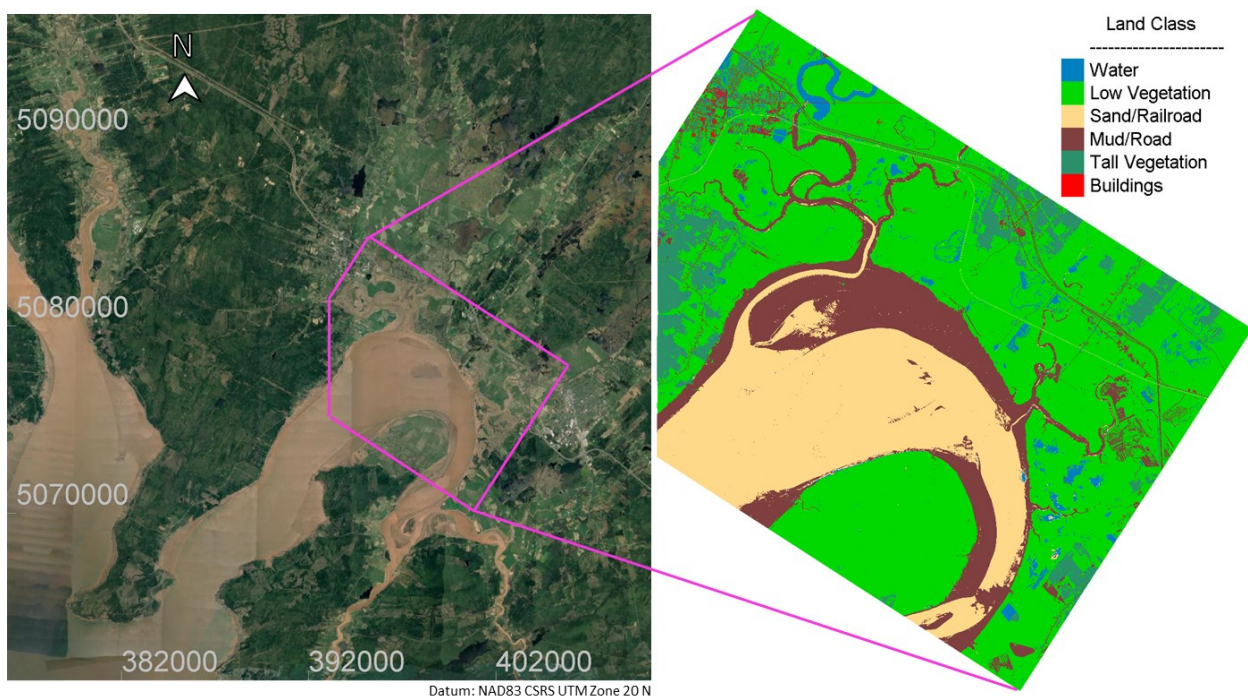


Figure 2.3 Land cover data of the Upper Cumberland Basin from an October, 2020 WorldView-2 earth observation satellite image (right). The satellite view of the region (left) is provided as reference.

2.4. Water Levels

2.4.1. Predicted Water Levels

In 2011, Cousineau et al. (2012) developed a 2D hydrodynamic model to simulate tidal flows, circulation patterns and currents in the Bay of Fundy and the Gulf of Maine. Although it covers a large geographic

area, including the continental shelf in the Northwest Atlantic Ocean located south of Maine and Nova Scotia, the model also predicts the circulation patterns and currents approaching Cumberland Basin (Figure 2.4). This model (hereafter referred to as the regional model) was used to provide boundary conditions for tidal water surface elevation (or water levels) in the Cumberland Basin hydrodynamic model. The open water boundary of the regional model (outlined in yellow in Figure 2.4) is driven by the harmonic constants from the TPXO 7.2 database, which consists of tides generated by a series of models that simulate global tides (Egbert & Erofeeva, 2002). The regional model uses a World Geodetic System 1984 (WGS84) Canadian Spatial Reference System (CSRS) Universal Transverse Mercator (UTM) Zone 19N (or WGS84 CSRS UTM Zone 19 N) and a mean sea level vertical datum. The resolution of the regional model ranges between 200 to 1000 m at the offshore extent, and approximately 300 m at the location of the Cumberland Basin model's boundary.

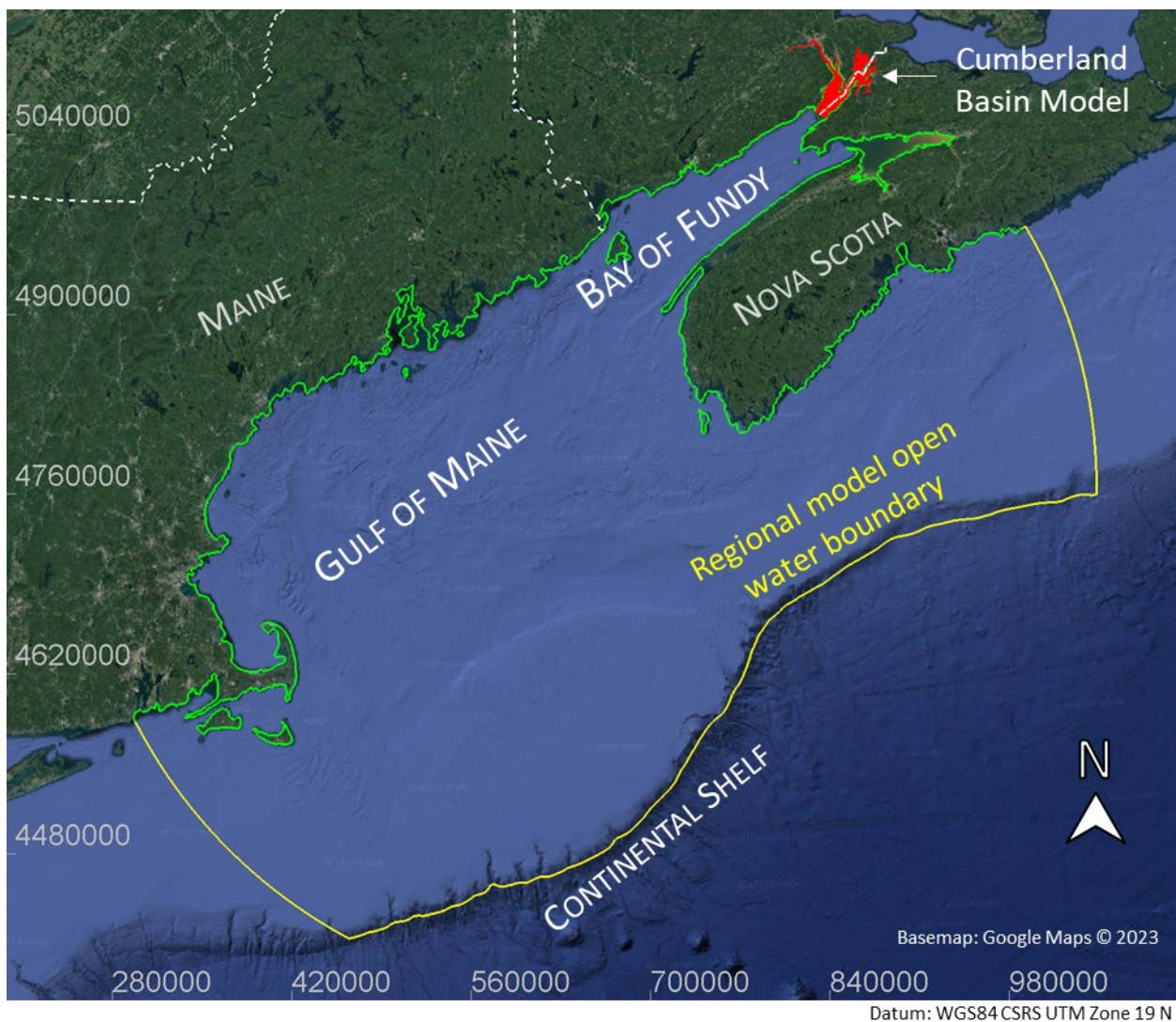


Figure 2.4 Extent of the regional model by Cousineau et al. (2012) is shown by yellow (open water boundary of the model) and green (land) outlines. The Cumberland Basin model extent is superimposed in a red polygon.

2.4.2. Observed Water Levels

In 2020, TCA-SMU collected water pressure data with wave loggers in the Missaguash River and in a borrow pit in the neighbouring Converse Marsh (Figure 2.5 inset and Table 2.2) (Virgin et al., 2020). Resulting water levels are provided in Figure 2.6. In 2021, the Geological Survey of Canada (branch of the Natural Resources Canada) and TCA-SMU conducted field survey campaigns within the intertidal zone of Cumberland Basin to collect water levels, wave heights and water current velocities (Manson et al., 2022). The authors used wave loggers to collect water pressure at Converse Marsh and Allen Creek, and a water level gauge to collect water depth at Wood Point (Figure 2.5 and Table 2.2). Resulting water levels for all three locations are provided in Figure 2.7, Figure 2.8 and Figure 2.9, respectively. These datasets were used to calibrate and validate the Cumberland Basin hydrodynamic model.

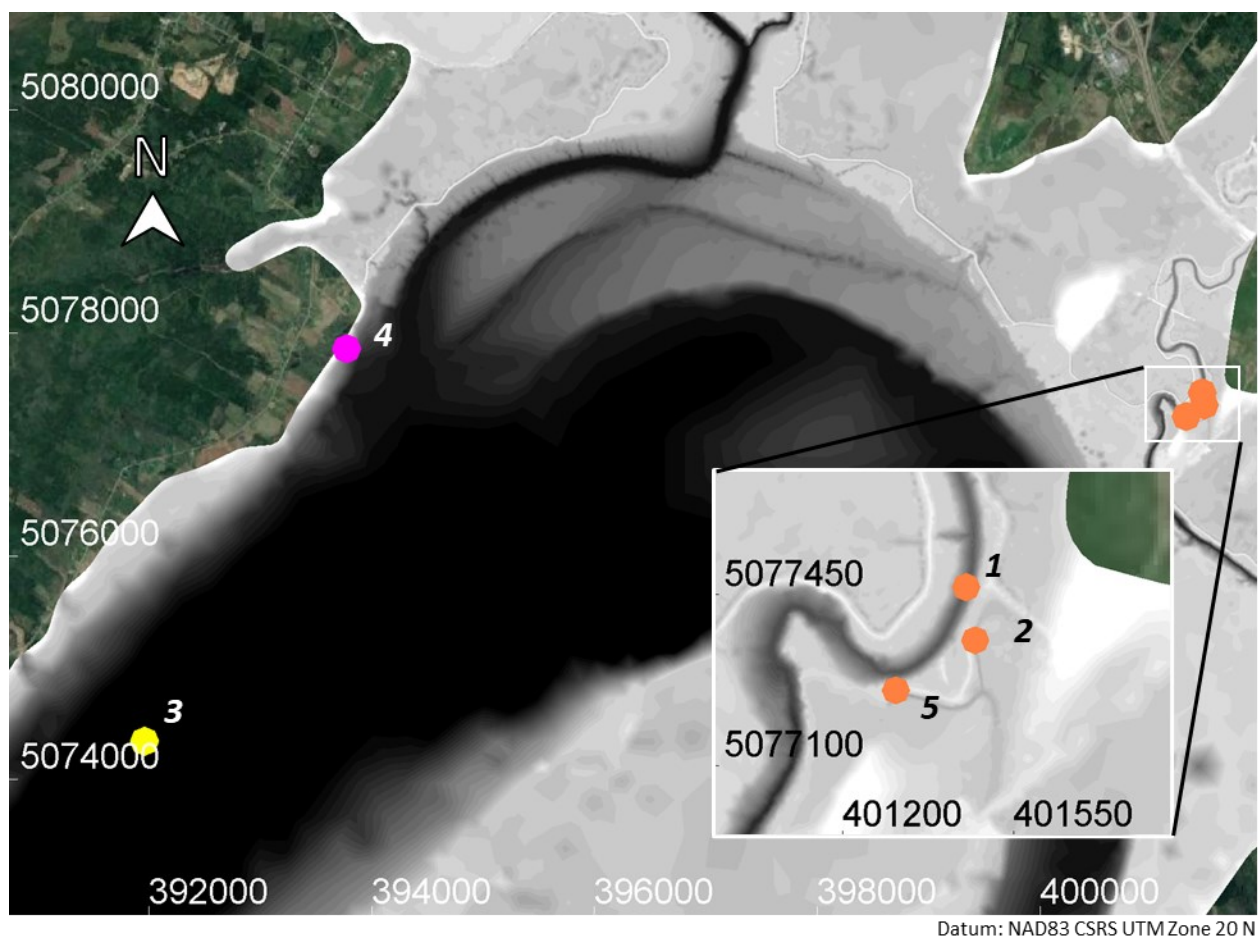


Figure 2.5 Year 2020 and 2021 field campaign sites provided by number in the figure and defined in Table 2.2.

Table 2.2 Overview of the year 2020 and 2021 field campaigns held in the Chignecto Isthmus relevant to the data used to develop the Cumberland Basin hydrodynamic model

Location	Date	Instrument	Parameter
(1) Missaguash River	June 29 – August 22, 2020	Wave logger	Water pressure
(2) Converse Marsh borrow pit	June 29 – August 22, 2020	Wave logger	Water pressure
(3) Allen Creek	September 10 – December 7, 2021	Wave logger	Water pressure
(4) Wood Point	July 16 – November 21, 2021	Water level gauge	Water depth
(5) Converse Marsh outlet	July 24 – July 26, 2021	Wave logger	Water pressure

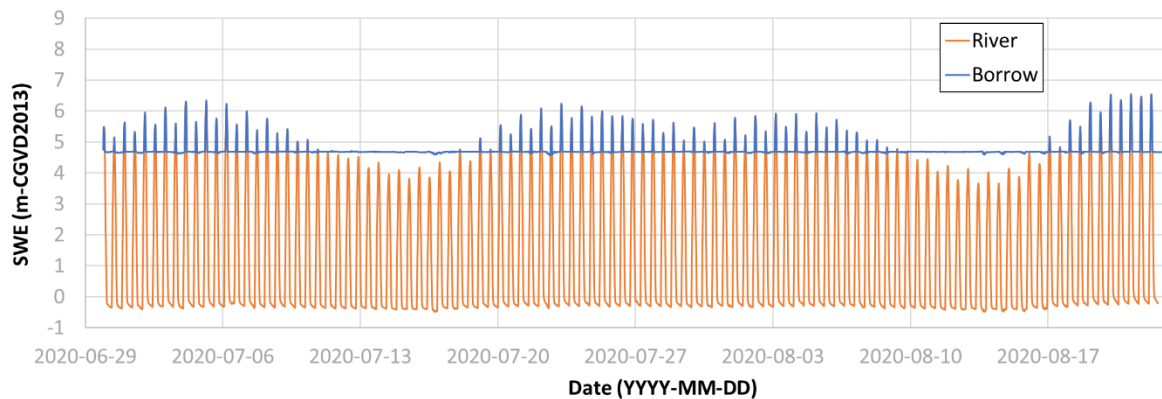


Figure 2.6 Observed water levels (or surface water elevation (SWE)) at Missaguash River (orange) and borrow pit in the Converse Marsh (blue) in 2020.

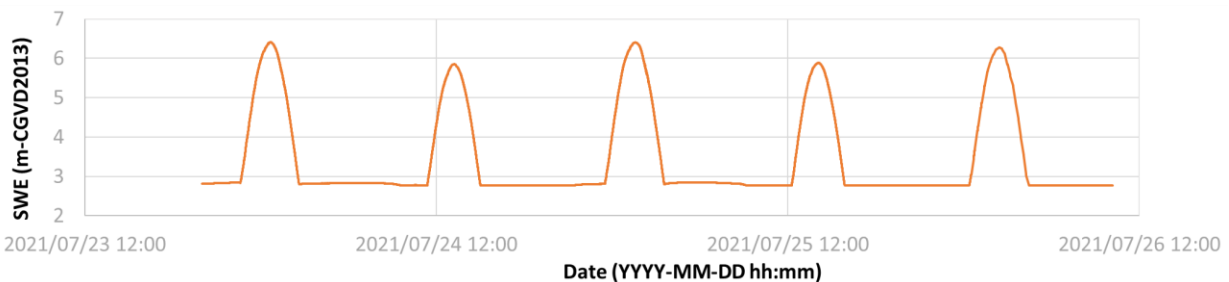


Figure 2.7 Observed water levels (or surface water elevation (SWE)) at Converse Marsh in 2021.

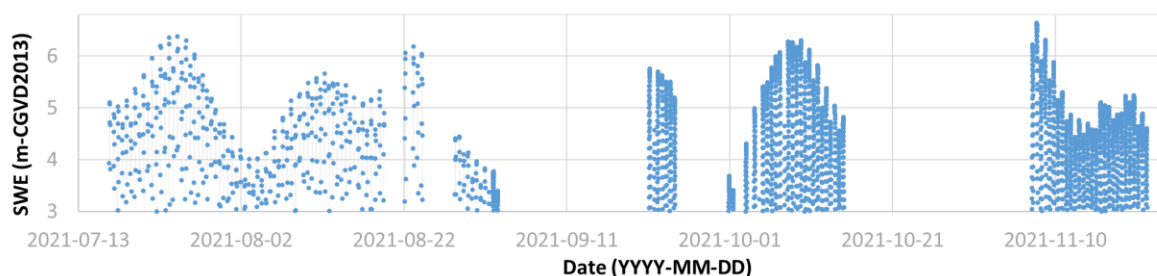


Figure 2.8 Observed water levels (or surface water elevation (SWE)) at Wood Point in 2021.

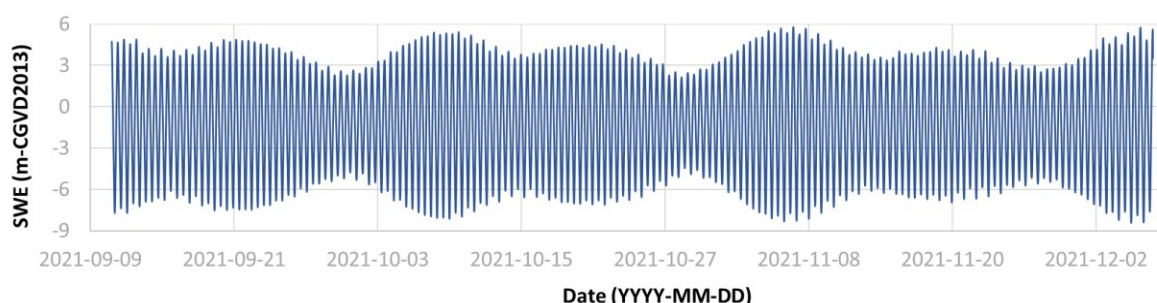


Figure 2.9 Observed water levels (or surface water elevation (SWE)) at Allen Creek in 2021.

The CHS manages over 700 tidal gauges across Canada (Fisheries and Oceans Canada, 2023). Observed (historic) water level data are available for many of these gauge locations for various durations. Predicted (astronomical) tides can also be generated for the tide gauge locations based on harmonic constituents published by CHS. The closest permanent tide gauge with both predicted tides and measured water level data to Cumberland Basin is gauge #65, located in the harbour of Saint John, New Brunswick, more than 100 km away. The Saint John gauge provides data at a 1-minute interval. The Wood Point water level gauge, managed by SMU, continues to record water levels to this day. Water levels from the Saint John tidal gauge #65 and the Wood Point water level gauge were used to validate the Cumberland Basin hydrodynamic model with storm surge. The locations of these gauges are provided in Table 2.3 and Figure 2.10, represented in the North American Datum of 1983 (NAD83) (CSRS) UTM Zone 20. Water levels for these two locations are provided in Figure 2.11 and Figure 2.12.

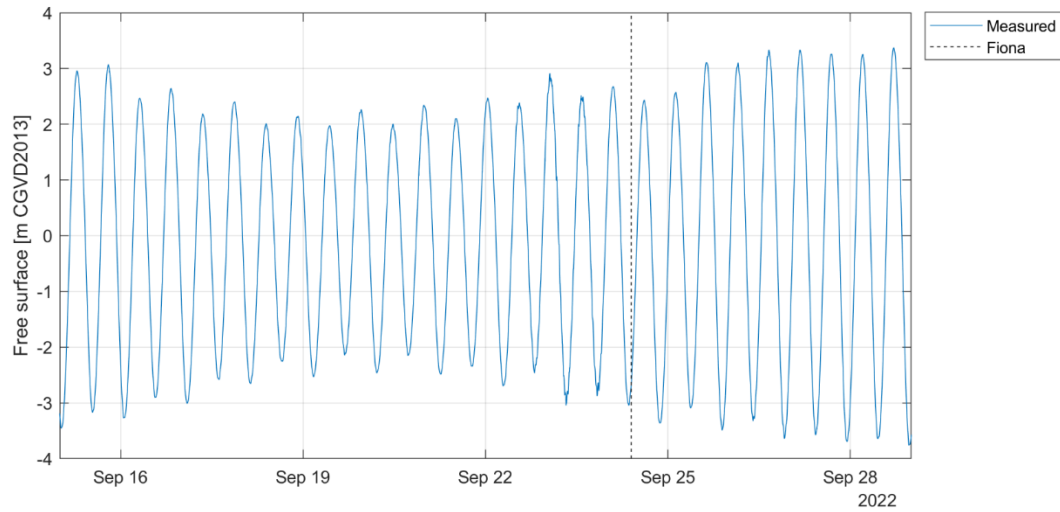
Table 2.3 Overview of water level stations with locations in NAD83 (CSRS) UTM Zone 20N.

Meteorological Station	Easting [m]	Northing [m]
Saint John	259912.1	5015792.5
Wood Point	393779.7	5077844.3



Figure 2.10. Location of water level stations in the Bay of Fundy, where tidal gauge #65 at Saint John is managed by the CHS and water level gauge at Wood Point is managed by SMU.

a) Time series of water level data



b) Time series specifically around Fiona of water level data

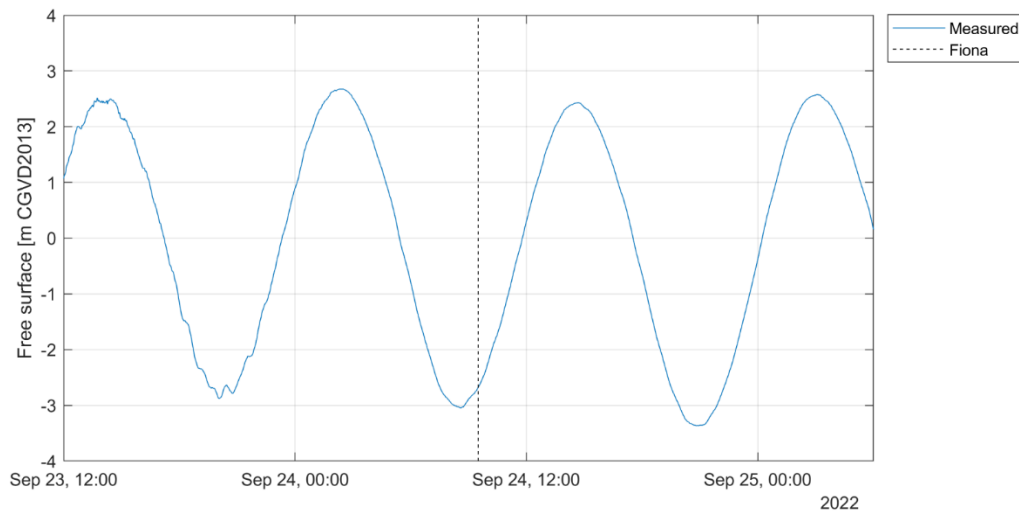
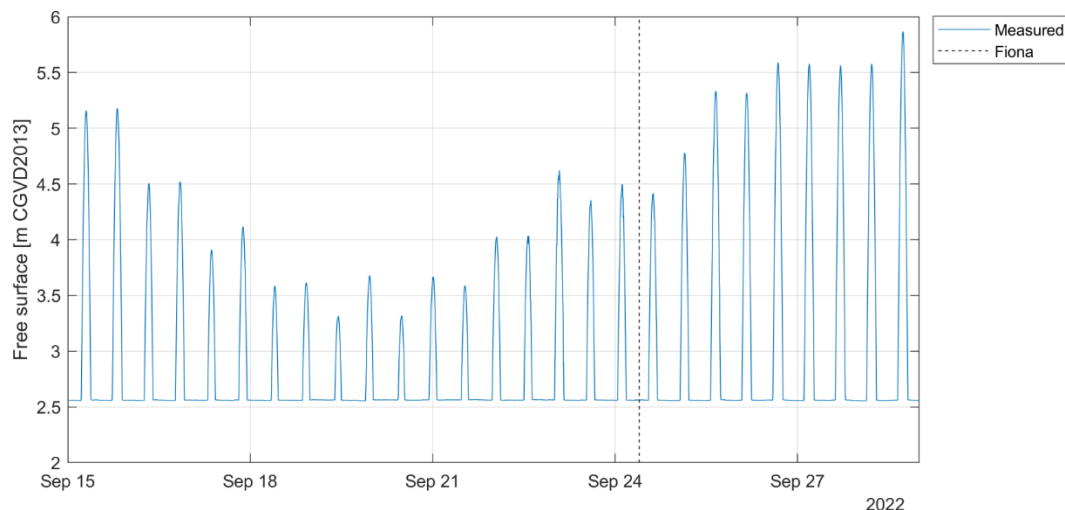


Figure 2.11. Time series (UTC) of water level data (Fisheries and Oceans Canada, 2024) at Saint John, a) time period September 15th to September 29th 2022; and b) time period September 23rd 12:00 UTC to September 26th 6:00 UTC 2022. Dashed black line indicates the time of ERA5 peak wind speed taken at an offshore point in the Cumberland Basin (point location provided in Table 4.2, Location 1) caused by the post-tropical storm Fiona.

a) Time series of water level data



b) Time series specifically around Fiona of water level data

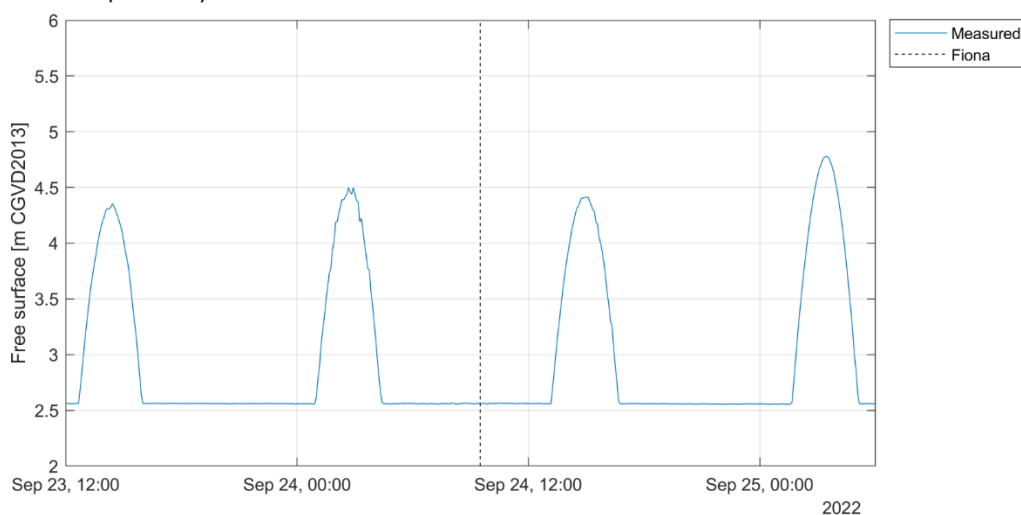


Figure 2.12. Time series (UTC) of water level data (Saint Mary's University) at Wood Point, a) time period September 15th to September 29th 2022; b) time period September 23rd 12:00 UTC to September 26th 6:00 UTC 2022. Dashed black line indicates the time of ERA5 peak wind speed taken at an offshore point in the Cumberland Basin (point location provided in Table 4.2, Location 1) caused by the post-tropical storm Fiona.

Permanent tidal gauge in the Cumberland Basin does not exist. The closest one available is the Saint John gauge, as described above. The establishment of a permanent tidal gauge in the Cumberland Basin would greatly enhance the calibration and validation of total water levels for the Chignecto Isthmus. This addition would not only enable more accurate modelling, but also significantly benefit future studies of this nature. Please refer to Section 7 point 1. for further discussion.

2.4.3. Tidal predictions

The lunar nodal cycle, spanning 18.6 years, causes variations in the range of tidal signals. As explained in Section 1.1.3, the Bay of Fundy functions as a natural funnel, intensifying these tidal signals. CHS has predicted the long-term tidal range variations at Burntcoat Head in the Bay of Fundy. Figure 2.13 shows this tidal variation provided by Environment and Climate Change Canada (ECCC) (personal communication, Bob Robichaud, April 9th 2024), which clearly indicates the large variations over the lunar nodal cycle.

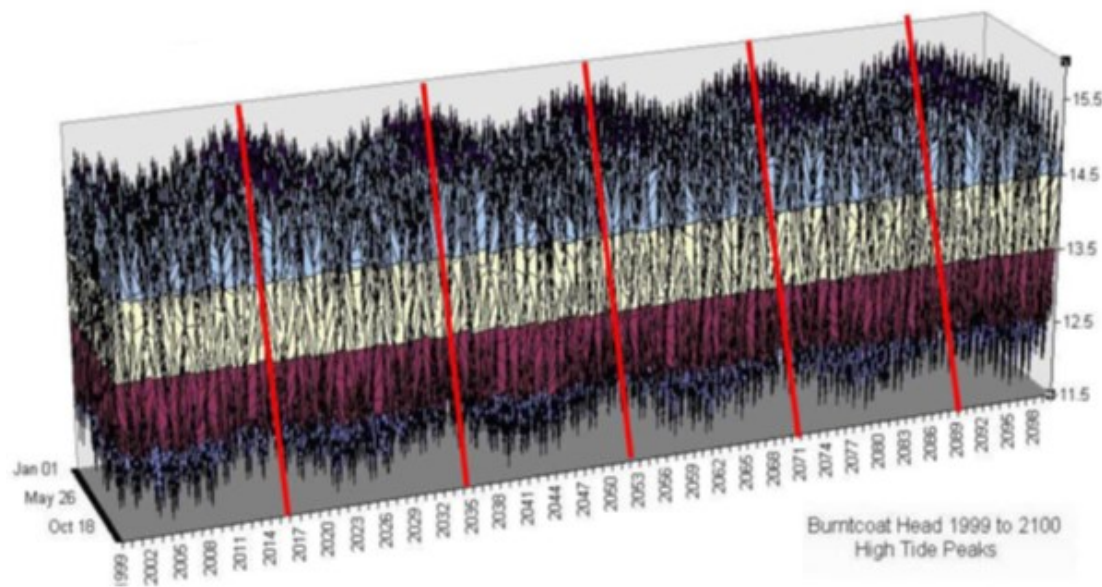


Figure 2.13. Tidal variations from 1999 to 2100 at Burntcoat Head. The red lines indicate peaks in the tide level based on the 18.6 years lunar nodal cycle (Figure obtained from Bob Robichaud (ECCC)).

2.5. Surface Wind and Pressure

Atmospheric (surface) wind and pressure data were used as boundary condition inputs to the Cumberland Basin hydrodynamic model, as the main drivers of storm surge. Storm surge is the combined effect of wind setup (or setdown) and atmospheric pressure setup (or setdown) resulting from the inverse barometer and dynamic effects, which manifests as a temporary increase (or decrease, in the case of negative surge) in water level during the passage of a storm (Kamphuis, 2010). For this study, the European Centre for Medium-Range Weather Forecasts fifth generation reanalysis for global climate and weather (ERA5) data (Hersbach et al., 2023) were used. The data are available at a spatial resolution of 0.25 degrees and a temporal resolution of one hour from 1940. Collected for this study were the wind speed (u- and v-components) at 10 m above mean sea level and mean sea level atmospheric pressure.

2.6. Relative Sea-Level Rise

Relative SLR refers to the change in water level relative to the land. While global sea-level change is driven by thermal expansion of water and meltwater from glaciers, ice caps, and ice sheets, relative SLR also considers the vertical motion of the land. This land movement is influenced by the loading and unloading of the Earth's surface due to ice sheets.

The dataset of relative SLR available from ClimateData.ca (2024a) provides gridded projections for 2006 and every decade from 2010 – 2100, relative to the baseline period of 1986 – 2005 (James et al., 2021). These projections account for several factors including the effect of changes in glacier and ice-sheet mass loss, thermal expansion of the oceans, changing ocean circulation conditions, and human-caused changes in land water storage, following the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5). Additionally, the dataset integrates a land motion model from the Canadian Geodetic Survey, enhancing accuracy along the Canadian coastline by incorporating more accurate land motion values (Canadian Geodetic Survey, 2019; Robin et al., 2020).

Projected relative SLR is available for three Representative Concentration Pathways (RCP), which loosely correspond to different global greenhouse gas emissions scenarios, and an enhanced scenario:

- **RCP 2.6** – low global emissions scenario.
- **RCP 4.5** – moderate global emissions scenario.
- **RCP 8.5** – high global emissions scenario.
- **Enhanced scenario** - Includes an additional 65 cm of global SLR beyond the RCP 8.5 median projection by 2100, reflecting potential additional contributions from the Antarctic Ice Sheet.

Each scenario is provided with lower, median and upper estimates, corresponding to the 5th, 50th, and 95th percentiles of the Global Climate Models. The projections are based on open ocean basin changes and then extrapolated to the coastline. For Canada's coastlines, these projections are available at a resolution of 0.1° (approximately 11 km latitude, 2-8 km longitude). Here, the projected relative SLR in Cumberland Basin, Nova Scotia is selected (Figure 2.14). Although it falls outside the scope of this work, it is worth noting that, in addition to the projected relative SLR discussed here, the Bay of Fundy experiences tidal amplification. This is caused by changes in resonance and greater alignment with the direct gravitational effect of the Moon on the tides (Greenberg et al., 2012).

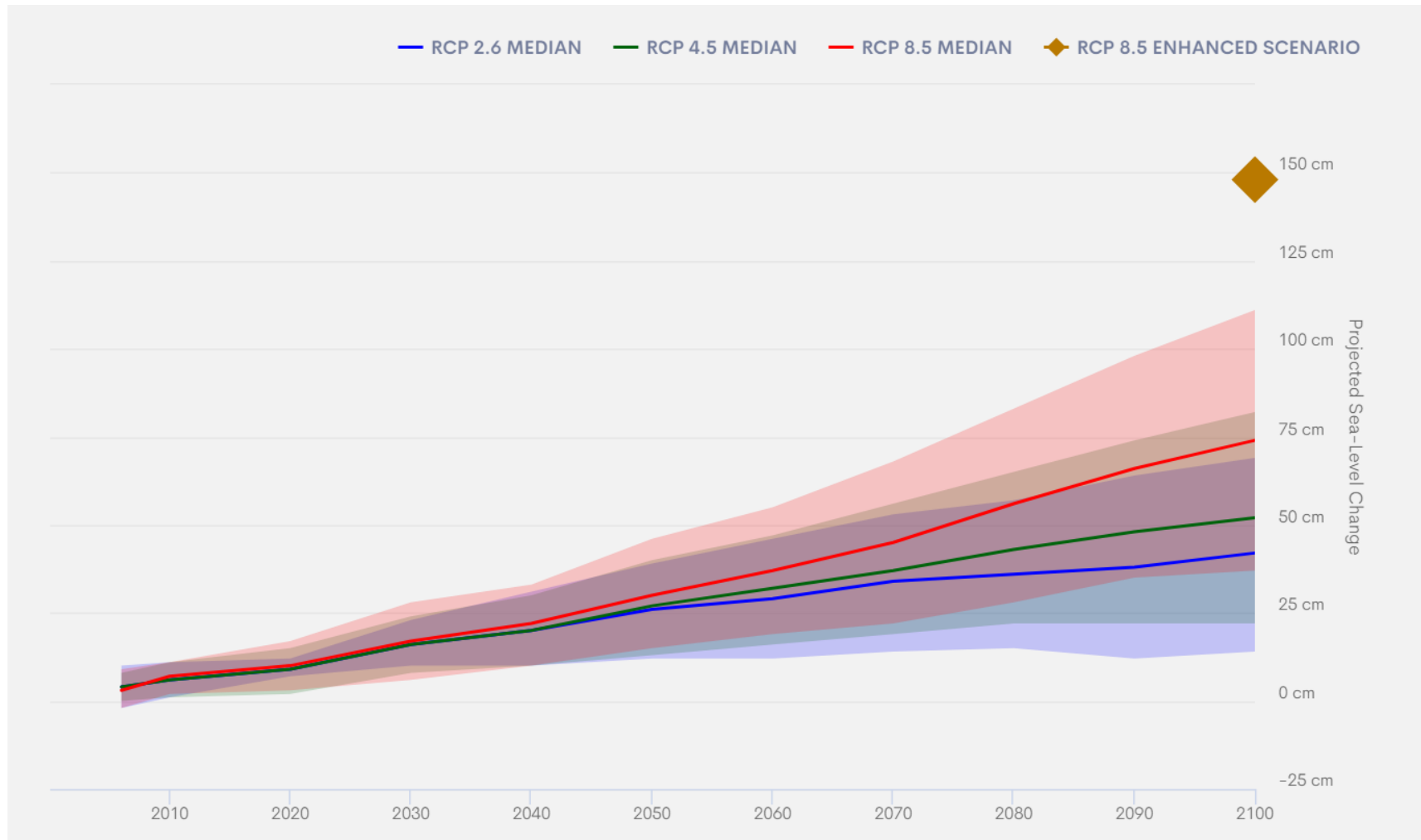


Figure 2.14. Projected relative SLR in the Cumberland Basin, Nova Scotia (ClimateData.ca, 2024b).

3. Historical Storm Analysis

3.1. Storms in the Chignecto Isthmus

The counter-clockwise rotation of storms in the northern hemisphere is a factor influencing how storms result in storm surges. Northerly tracking storms tend to result in highest storm surges (and waves) at the northeastern front of the storm. The shape of the Bay of Fundy significantly influences how winds translate to elevated water levels on the Chignecto Isthmus. Thus, a storm tracking slightly to the west of Cumberland Basin is likely to result in winds aligned with the longest fetches in the Bay of Fundy, resulting in higher storm surges at Chignecto Isthmus. The Chignecto Isthmus is prone to both post-tropical and winter storms. Conditions of the storm, including wind direction and timing of the storm, can significantly influence water levels and flooding on the Chignecto Isthmus.

Based on discussions with Bob Robichaud (ECCC), four potential storms in addition to post-tropical storm Fiona were selected covering either post-tropical storms or memorable winter storms impacting the Bay of Fundy (Table 3.1). Each of these storms resulted in high water levels and (potential) flooding on the Chignecto Isthmus. It is important to note that the 1869 Saxby Gale is excluded from this overview. The Saxby Gale, originally a hurricane, transitioned into a deep extratropical depression, generating an estimated storm surge of 1.7 to 2.1 m along the Bay of Fundy (Daigle, 2020; Ruffman, 1999). This study focuses on more recent storm surges in the region. In addition, the ERA5 data used to force the numerical model are available from the year 1940 onwards.

In Sections 3.1.1 to 3.1.5 storms are presented in chronological order, whose atmospheric pressure and magnitudes and direction of winds were extracted from the baseline ERA5 data. For each storm, data for the Cumberland Basin were extracted from a point as shown in Figure 3.1.

Table 3.1. Overview of storms with maximum wind speed and direction in the Cumberland Basin based on interpolated ERA5 data (Copernicus Climate Change Service, 2017).

Storm	Maximum wind speed [m/s]	Wind direction [°]
1976 Groundhog Day storm	15.2	195° / SW
2007 Post-tropical storm Noel	10.5	250° / SW
2008 Severe December storm	12.7	220° / SW
2019 Post-tropical storm Dorian	13.0	315° / NW
2022 Post-tropical storm Fiona	15.5	320° / NW

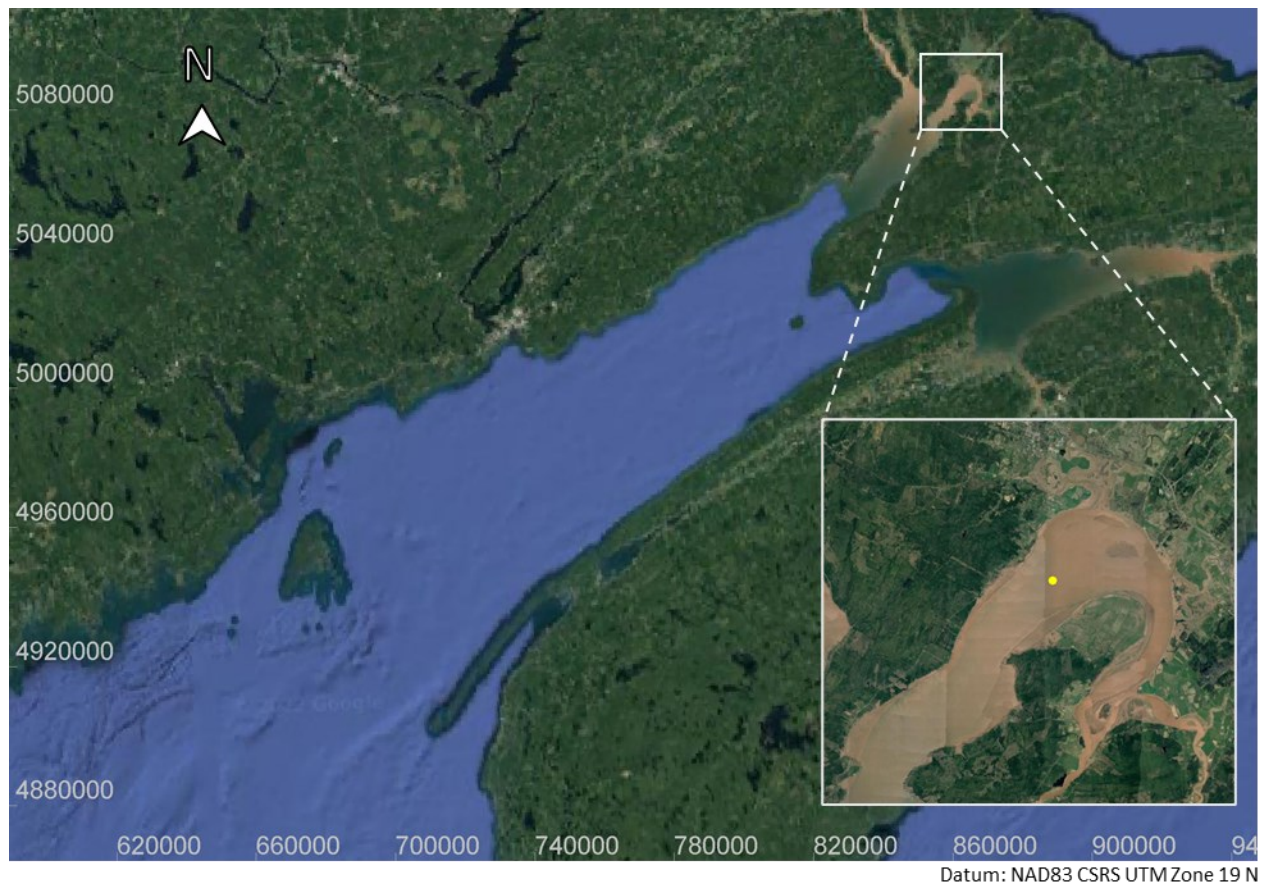


Figure 3.1 Map indicating the extraction location (yellow) of the peak wind in the Cumberland Basin from ERA5 data for each storm discussed in Sections 3.1.1 to 3.1.5.

3.1.1. 1976 Groundhog Day Storm

On February 2nd 1976 southwestern Nova Scotia was struck by a severe storm that caused significant damage across the province. The prolonged duration of the storm exacerbated its effects, particularly since the peak coincided with high tide (Council of Nova Scotia Archives, 2020). In the Cumberland Basin, wind speeds reached 15.2 m/s (55 km/h), blowing from the southwest (Figure 3.2, Figure 3.3 and Figure 3.4). These southwesterly winds, aligned with the orientation of the Bay of Fundy, allowed for a long fetch, amplifying the storm surge and resulting in considerable impact on coastal areas. In the Bay of Fundy, the winds peaked at 25.3 m/s (91 km/h) according to the ERA5 dataset.

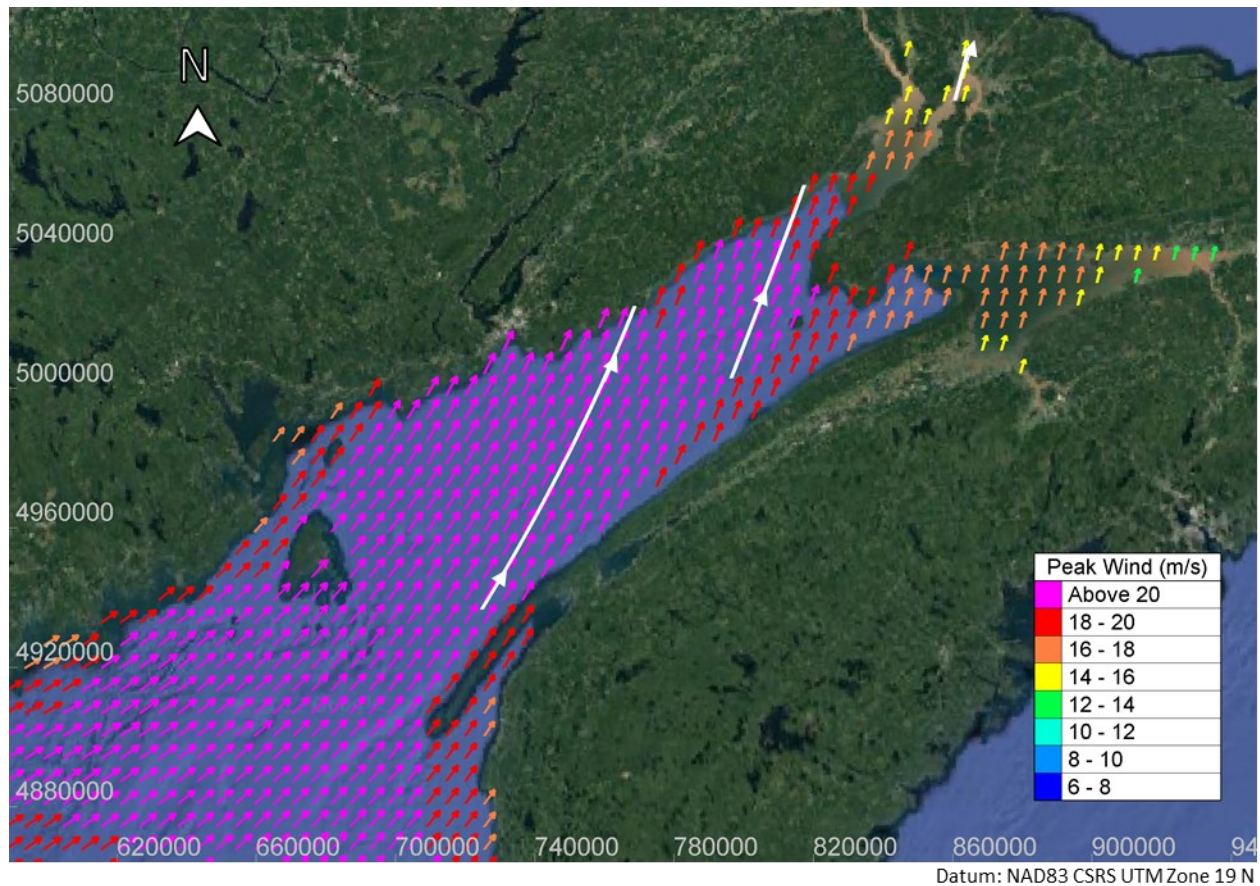


Figure 3.2. A snapshot of the surface wind field in the Bay of Fundy at the time of maximum wind speed in the Cumberland Basin during the 1976 Groundhog Day storm (Copernicus Climate Change Service, 2017). The wind vectors represent linearly interpolated ERA5 data to the regional model resolution and resampled to a 500 m x 500 m rectangular grid. Winds in the Cumberland Basin peaked at 15.2 m/s (55km/h).

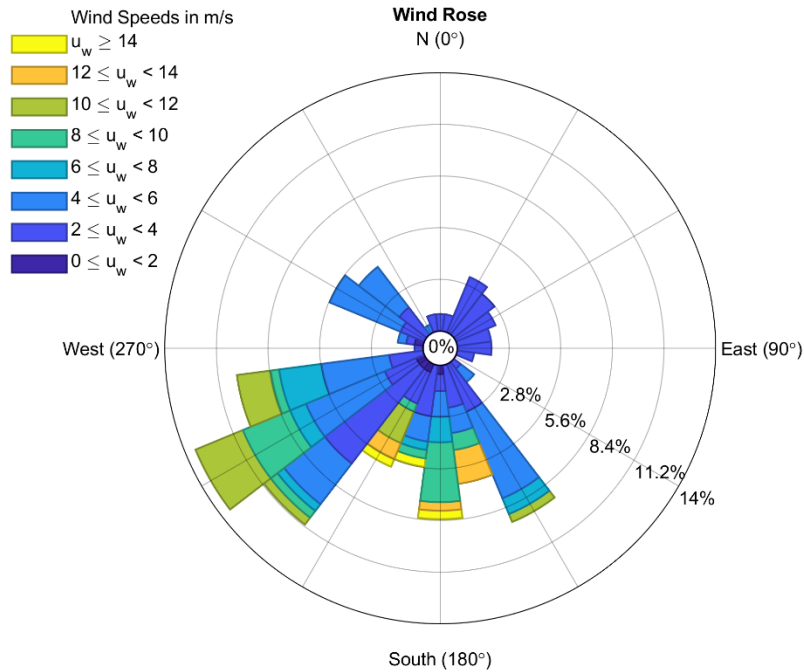


Figure 3.3. Wind rose based on ERA5 surface wind fields during the 1976 Groundhog Day storm in the Cumberland Basin from January 28th to February 6th 1976. Wind direction is presented according to the nautical convention, indicating the direction which the wind is coming from, measured in degrees clockwise from true north (Copernicus Climate Change Service, 2017).

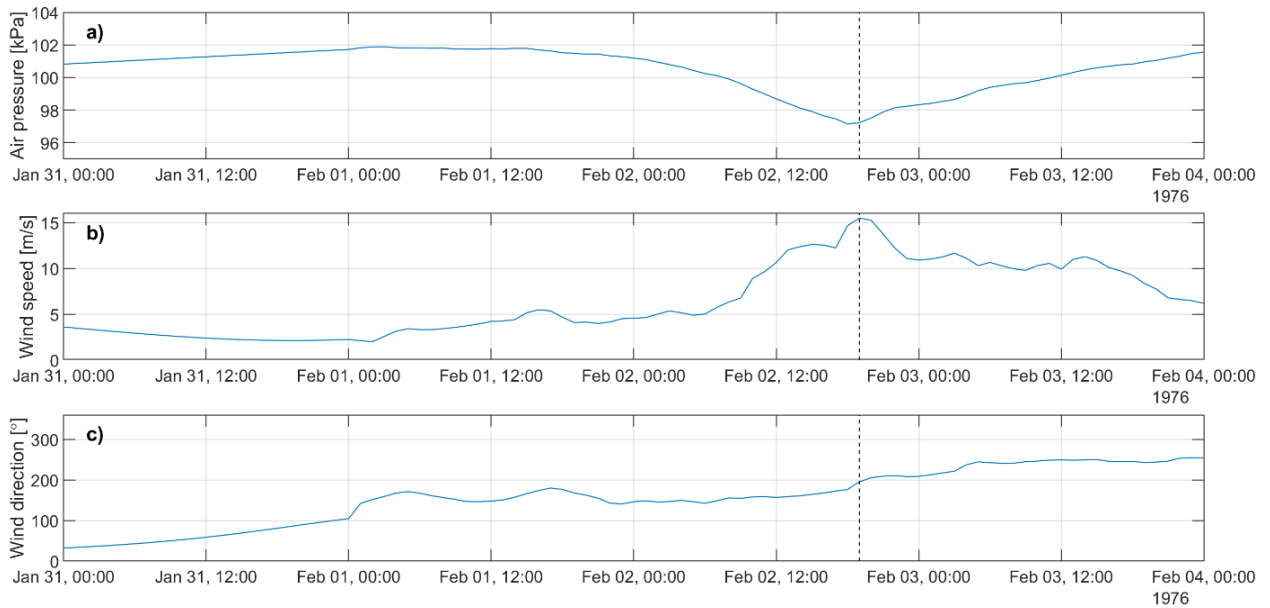


Figure 3.4. ERA5 data for the 1976 Groundhog Day storm in the Cumberland Basin including a) air pressure, b) wind speed, and c) wind direction. The dashed line indicates the approximate time of maximum wind speed in the Cumberland Basin (Copernicus Climate Change Service, 2017).

3.1.2. 2007 Post-Tropical Storm Noel

Post-tropical storm Noel passed over Hispaniola and Cuba as a tropical storm and continued as a hurricane causing torrential rainfall over the northwestern Bahamas (National Oceanic and Atmospheric Administration, 2024). Noel then evolved into a large and powerful extratropical cyclone that brought hurricane force wind gusts to portions of the northeastern United States and eastern Canada. On November 4th 2007 shortly after 2:00 Coordinated Universal Time (UTC), the centre of the low made landfall near Chebogue Point, Nova Scotia, just south of Yarmouth with maximum wind speeds of 18 m/s. The cyclone weakened after landfall in eastern Canada and exited the coast of Labrador about 18 h later (National Oceanic and Atmospheric Administration, 2024). In Nova Scotia, the coastal floods and significant wave action washed out sections of coastal roads and damaged waterfront buildings. In addition, 190,000 homes lost power during the storm (National Oceanic and Atmospheric Administration, 2024).

During post-tropical storm Noel, wind speeds in the Bay of Fundy peaked at 19.1 m/s (69 km/h) and reached 10.5 m/s (38 km/h) in the Cumberland Basin (Figure 3.5). During its peak, the wind direction in the Cumberland Basin was from the southwest. Although the wind direction in the Bay of Fundy was not directly towards the Chignecto Isthmus, the southwesterly wind in the Cumberland Basin still posed a significant threat due to its capacity to drive water towards the isthmus and enhance the local storm surge (Figure 3.6 and Figure 3.7).

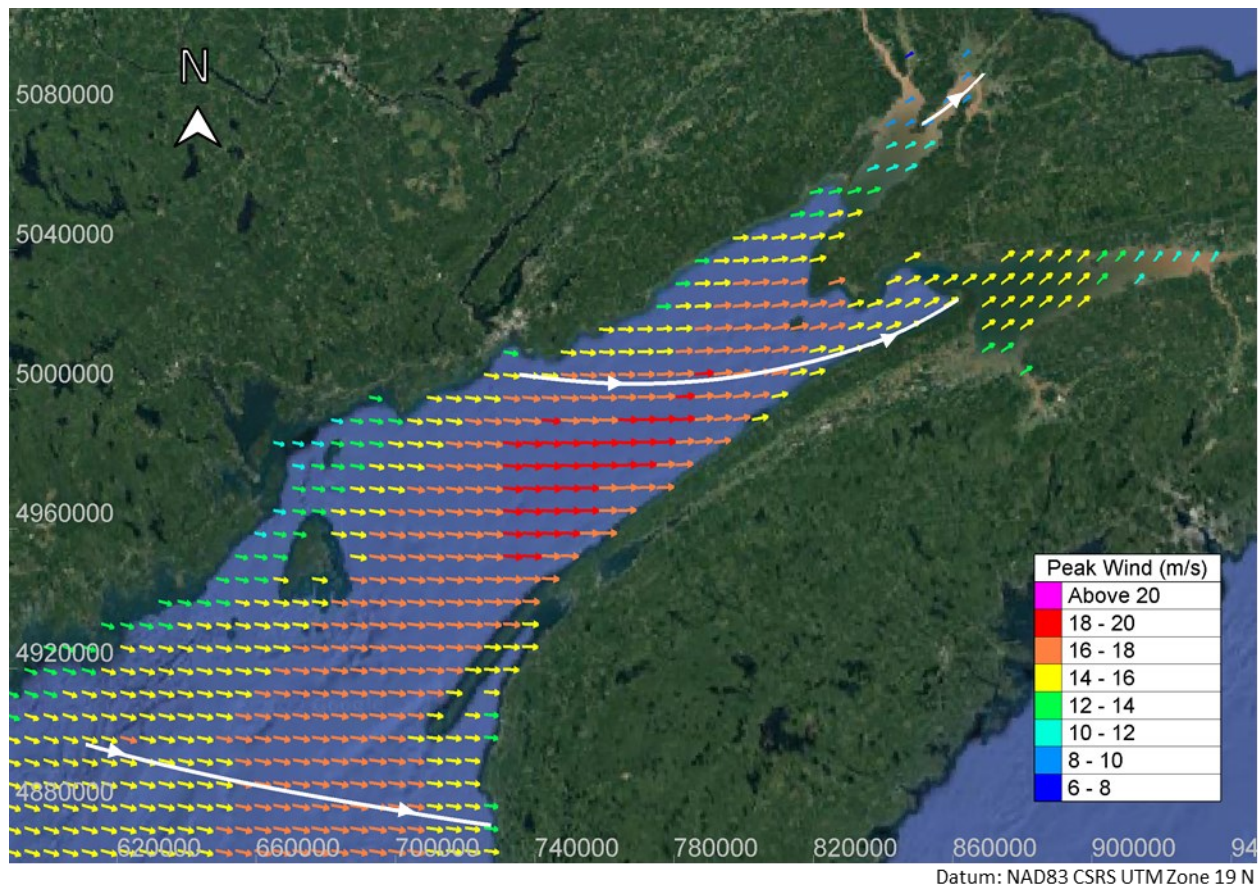


Figure 3.5. A snapshot of the surface wind field in the Bay of Fundy at the time of maximum wind speed in the Cumberland Basin during the 2007 post-tropical storm Noel (Copernicus Climate Change Service, 2017). The wind vectors represent linearly interpolated ERA5 data to the regional model resolution and resampled to a 500 m x 500 m rectangular grid. Winds in the Cumberland Basin peaked at 10.5 m/s (38 km/h).

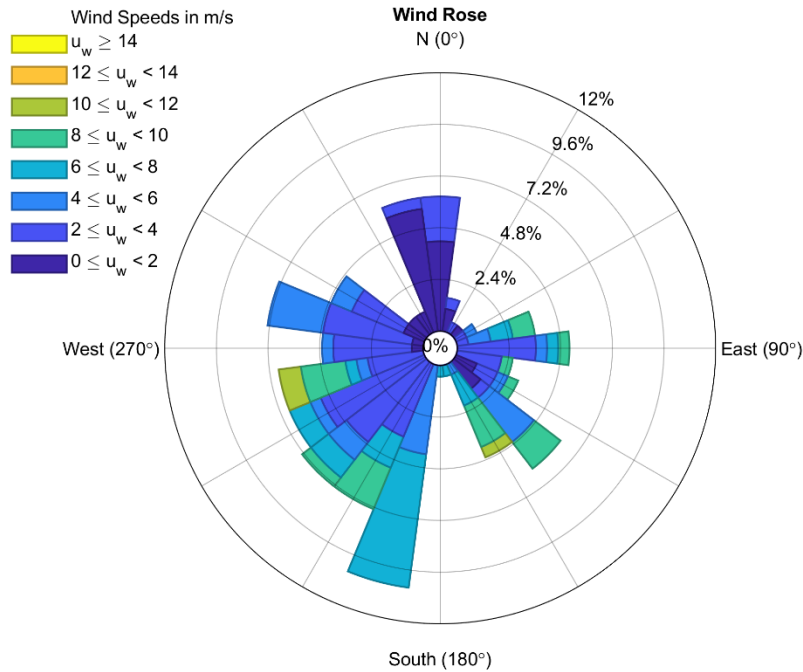


Figure 3.6. Wind rose covering ERA5 data for the 2007 post-tropical storm Noel in the Cumberland Basin from October 31st to November 7th 2007. Wind direction is presented according to the nautical convention, indicating the direction which the wind is coming from, measured in degrees clockwise from true north (Copernicus Climate Change Service, 2017).

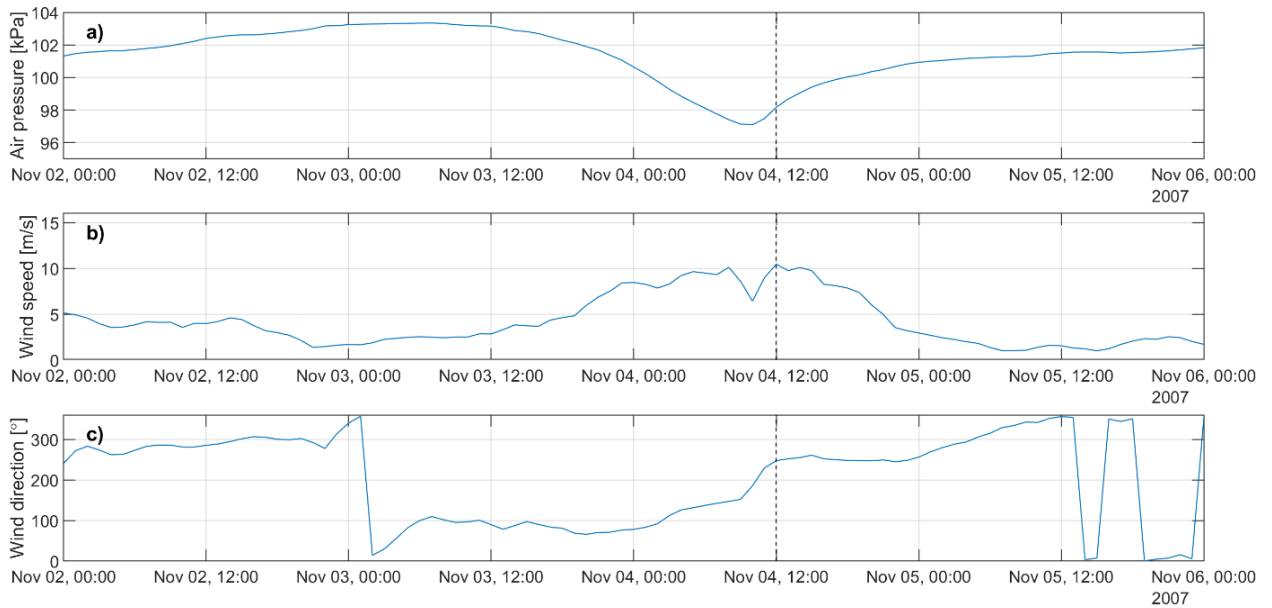


Figure 3.7. ERA5 data for the 2007 post-tropical storm Noel in the Cumberland Basin including a) air pressure, b) wind speed, and c) wind direction. The dashed line indicates the approximate time of maximum wind speed in the Cumberland Basin (Copernicus Climate Change Service, 2017).

3.1.3. 2008 Severe December Storm

In December 2008, Nova Scotia experienced a severe storm that caused considerable disruption and damage. Wind speeds reached up to 23 m/s (84 km/h) in the Bay of Fundy and 12.6 m/s (45 km/h) in the Cumberland Basin (Figure 3.8). During its peak, the southwesterly wind created significant potential for storm surge at the Chignecto Isthmus (Figure 3.9 and Figure 3.10).

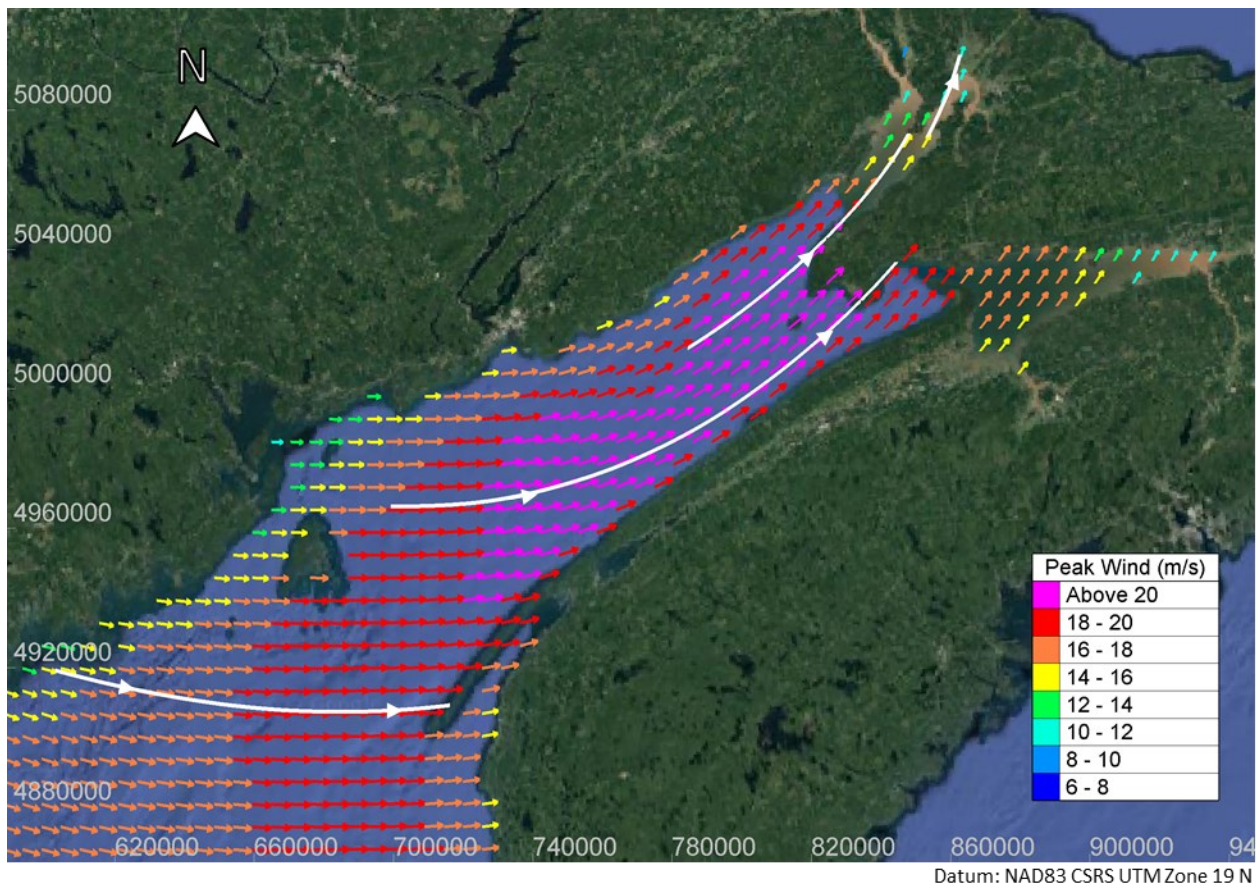


Figure 3.8. A snapshot of the surface wind field in the Bay of Fundy at the time of maximum wind speed in the Cumberland Basin during the 2008 severe December storm (Copernicus Climate Change Service, 2017). The wind vectors represent linearly interpolated ERA5 data to the regional model resolution and resampled to a 500 m x 500 m rectangular grid. Winds in the Cumberland Basin peaked at 12.6 m/s (45 km/h).

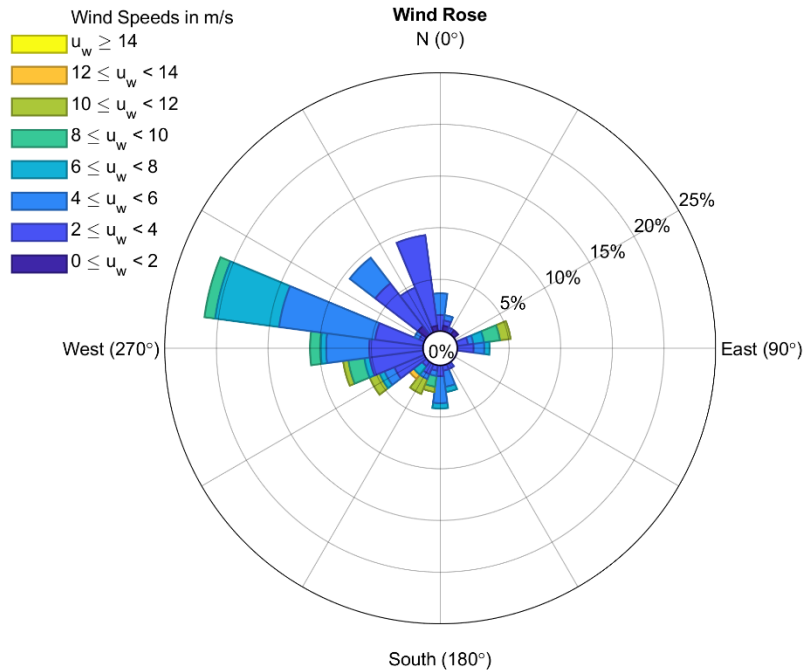


Figure 3.9. Wind rose covering ERA5 data for the 2008 severe December storm in the Cumberland Basin from December 18th to 25th 2008. Wind direction is presented according to the nautical convention, indicating the direction which the wind is coming from, measured in degrees clockwise from true north (Copernicus Climate Change Service, 2017).

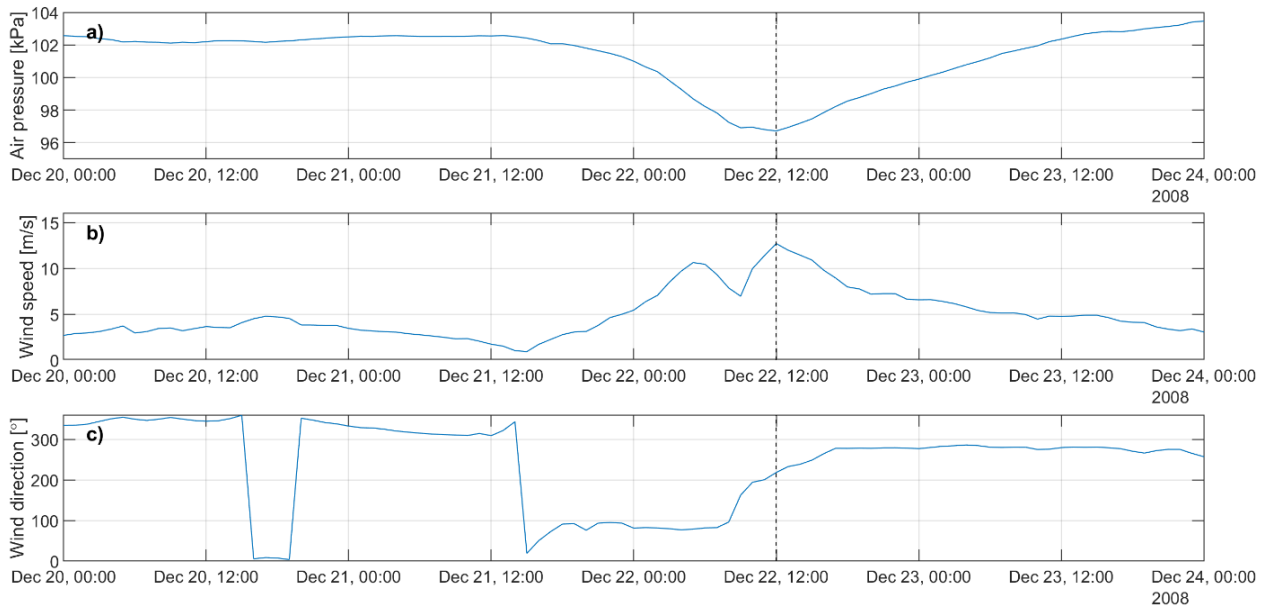


Figure 3.10. ERA5 data for the 2008 severe December storm in the Cumberland Basin including a) air pressure, b) wind speed, and c) wind direction. The dashed line indicates the approximate time of maximum wind speed in the Cumberland Basin (Copernicus Climate Change Service, 2017).

3.1.4. 2019 Post-Tropical Storm Dorian

Post-tropical storm Dorian started off as a tropical wave off the west coast of Africa on August 19th 2019 and developed into a tropical depression on August 24th as it reached Barbados (National Oceanic and Atmospheric Administration, 2024). Passing over America, Dorian became a strong post-tropical cyclone on September 7th before it reached Nova Scotia, Canada. It moved further over the Gulf of St. Lawrence and was finally absorbed by a larger extratropical low over the far northern Atlantic Ocean. A large portion of Atlantic Canada experienced hurricane-force wind gusts causing significant damage along the coast and across Nova Scotia (National Oceanic and Atmospheric Administration, 2024). The post-tropical storm Dorian resulted in a high storm surge almost 2 m above normal tide levels at Shediac, New Brunswick and 1.4 m in Halifax, which is above 1.5 m Higher High Water Large Tide (HHWLT) at Shediac and above 0.85 m in Halifax (National Oceanic and Atmospheric Administration, 2024). During the 2019 post-tropical storm Dorian, wind speeds in the Cumberland Basin remained elevated for an extended period. On the evening of September 7th, a northeasterly wind was observed at 20:00 UTC, which later shifted to a northwesterly wind (Figure 3.11, Figure 3.12 and Figure 3.13). The wind speed reached up to 19.8 m/s (71 km/h) in the Bay of Fundy (Figure 3.11(a)), while wind speeds in the Cumberland Basin were 12.2 m/s (44 km/h). Several hours later, when the wind shifted (Figure 3.11(b)), the peak wind speed reached 13.1 m/s (47 km/h) during the peak of the storm in the Cumberland Basin, while it decreased in the Bay of Fundy to 17.0 m/s (61 km/h).

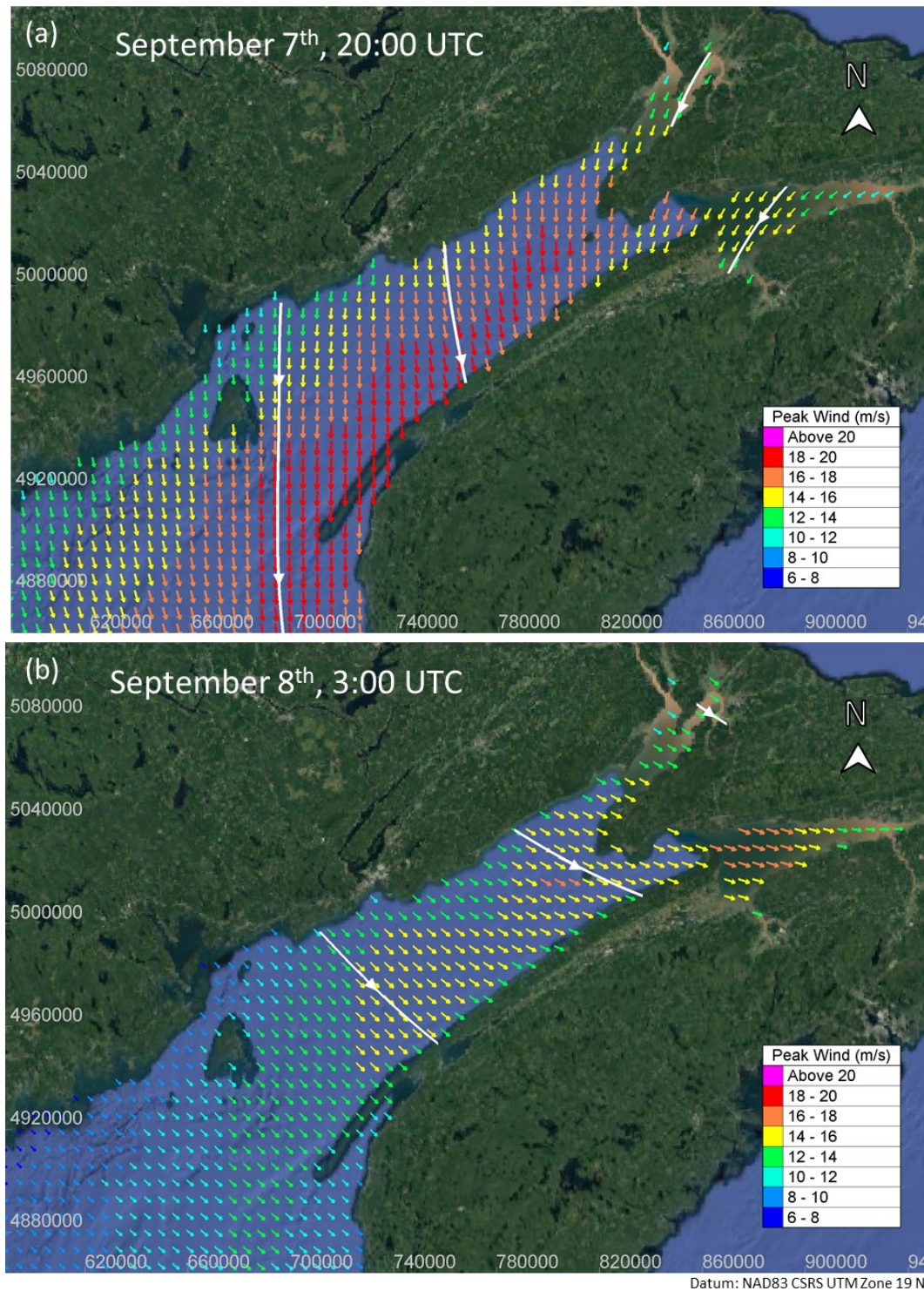


Figure 3.11. Snapshots of the surface wind field during the 2007 post-tropical storm Dorian (Copernicus Climate Change Service, 2017). The wind vectors represent linearly interpolated ERA5 data to the regional model resolution and resampled to a 500 m x 500 m rectangular grid. On September 7th at 20:00 UTC (a), peak wind in the Bay of Fundy reached up to 19.8 m/s (71 km/h). Several hours later (b), peak wind in the Cumberland Basin reached up to 13.1 m/s (47 km/h).

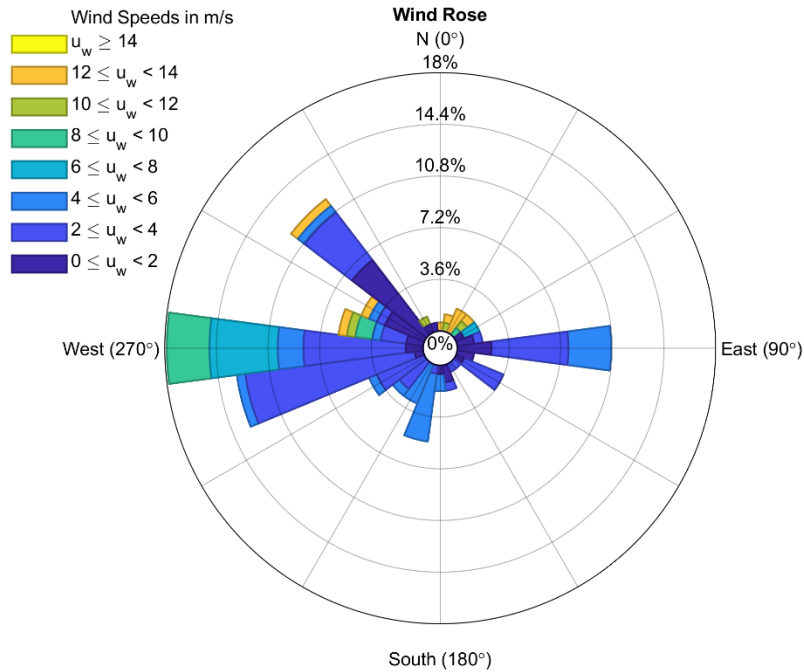


Figure 3.12. Wind rose covering ERA5 data for the 2019 post-tropical storm Dorian in the Cumberland Basin from September 4th to September 10th 2019. Wind direction is presented according to the nautical convention, indicating the direction which the wind is coming from, measured in degrees clockwise from true north (Copernicus Climate Change Service, 2017).

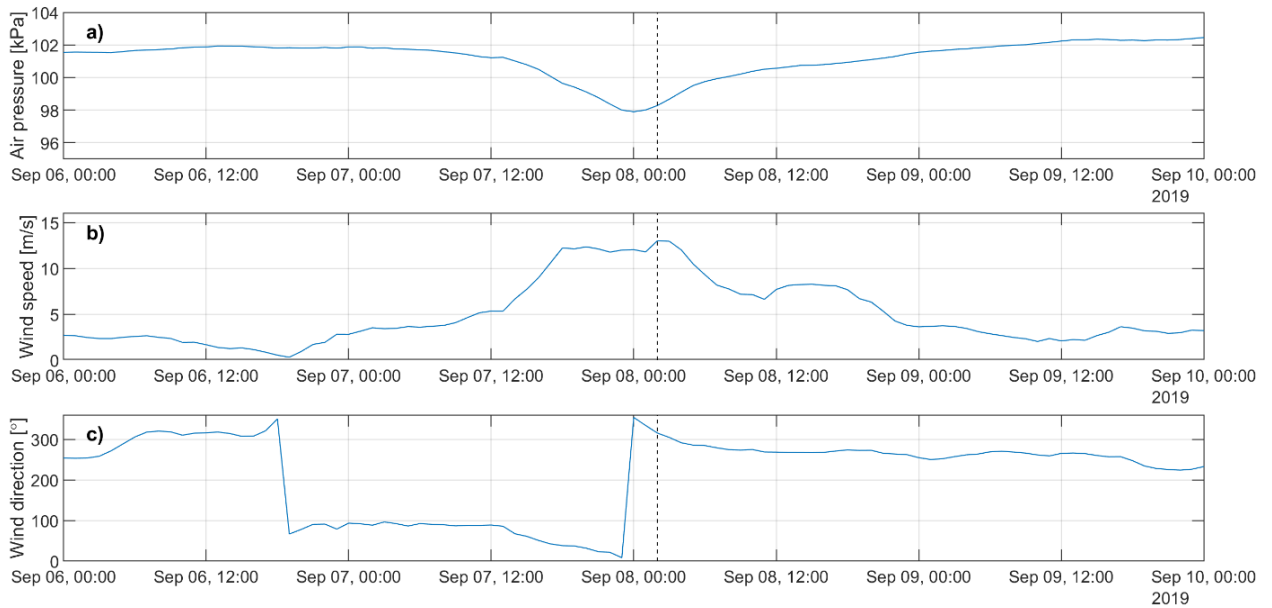


Figure 3.13. ERA5 data for the 2019 post-tropical storm Dorian in the Cumberland Basin including a) air pressure, b) wind speed, and c) wind direction. The dashed line indicates the approximate time of maximum wind speed in the Cumberland Basin (Copernicus Climate Change Service, 2017).

3.1.5. 2022 Post-Tropical Storm Fiona

Post-tropical storm Fiona originated from a tropical wave that moved off the African coast on September 7th 2022. By September 14th, it had developed into a tropical depression east of Guadeloupe. Fiona made landfall as a hurricane on September 18th in Puerto Rico, and a short while later, the Dominican Republic. Passing through the Caribbean, Fiona gradually turned northwards and made landfall on Cape Breton on September 24th as a very strong extratropical cyclone (National Oceanic and Atmospheric Administration, 2024). The track of the storm passed more than 200 km to the east of the Cumberland Basin, leading to significantly lower peak winds in the Cumberland Basin compared to regions nearer to the centre of the storm whose winds reached up to 30 m/s (Figure 1.1), demonstrating a potential “near miss” for the Chignecto Isthmus.

In the Cumberland Basin, the northwesterly wind (generated from the northwest) reached maximum speed of 15.8 m/s (Figure 3.14, Figure 3.15 and Figure 3.16). At the time, wind speeds in the Bay of Fundy peaked at 18.6 m/s (Figure 3.14).

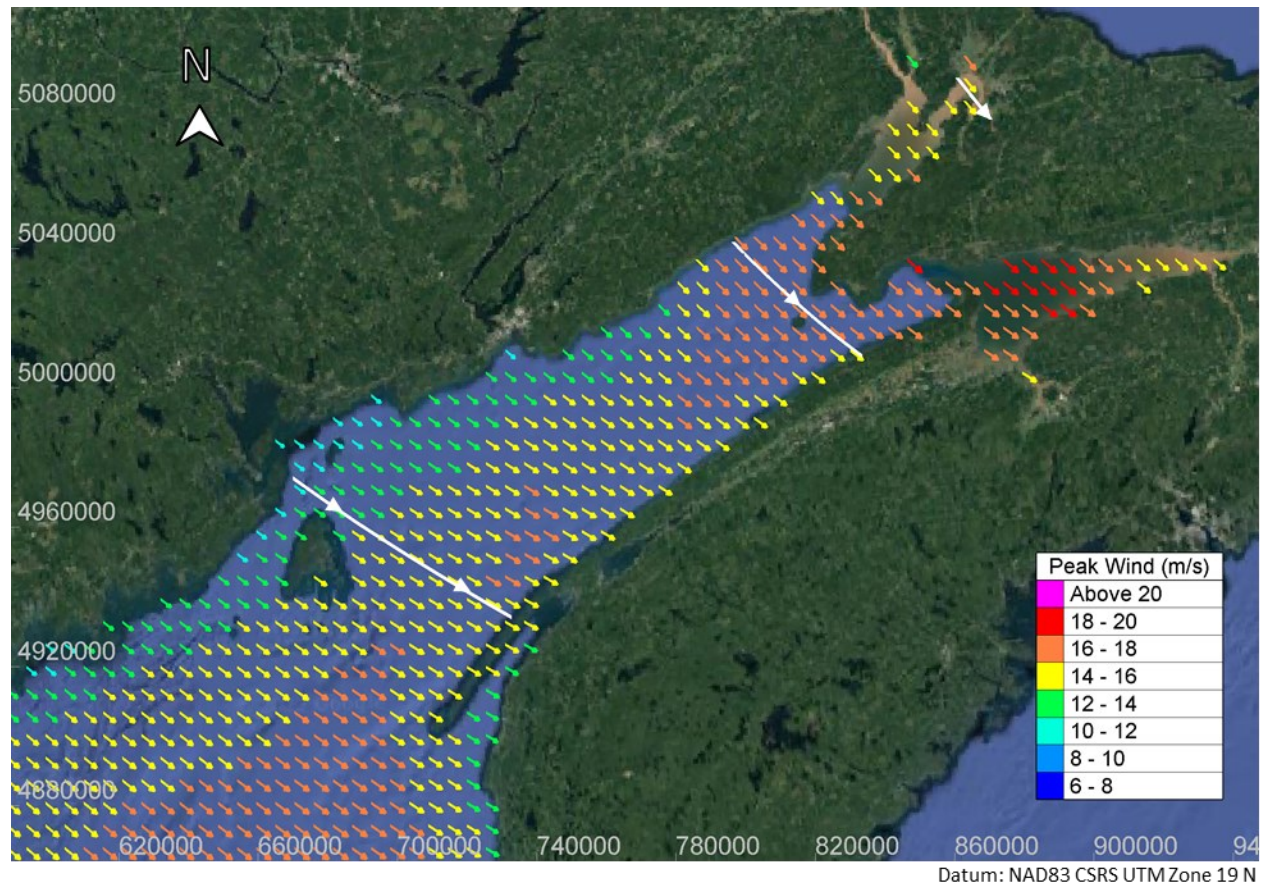


Figure 3.14. A snapshot of the wind field in the Bay of Fundy at the time of peak wind values in the Cumberland Basin during the 2022 post-tropical storm Fiona (Copernicus Climate Change Service, 2017). The wind vectors represent linearly interpolated ERA5 data to the regional model resolution and resampled to a 500 m x 500 m rectangular grid.

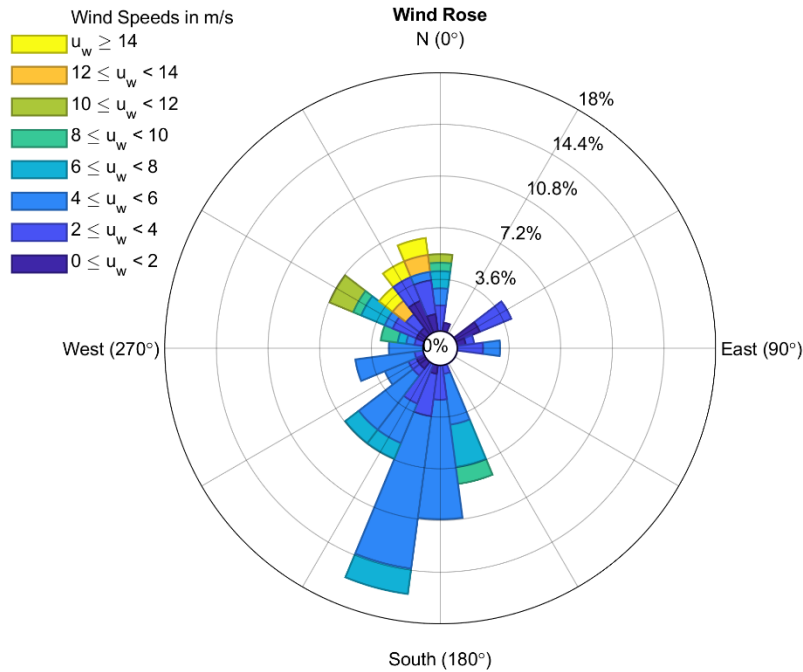


Figure 3.15. Surface wind rose based on ERA5 data for the 2022 post-tropical storm Fiona in the Cumberland Basin from September 21st to 27th 2022. Wind direction is presented according to the nautical convention, indicating the direction which the wind is coming from, measured in degrees clockwise from true north (Copernicus Climate Change Service, 2017).

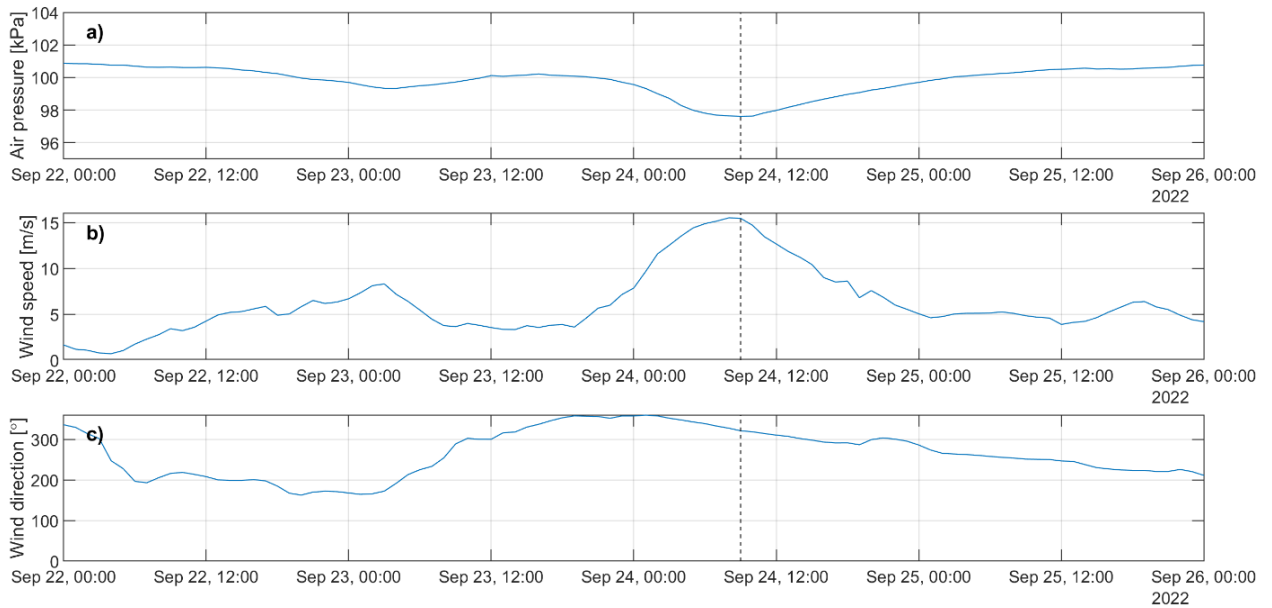


Figure 3.16. ERA5 data for the 2022 post-tropical storm Fiona in the Cumberland Basin including a) air pressure, b) wind speed, and c) wind direction. The dashed line indicates the approximate time of maximum wind speed in the Cumberland Basin (Copernicus Climate Change Service, 2017)

3.2. ERA5 Validation

Previous studies have demonstrated a strong correlation between local observations and ERA5 data in Atlantic Canada (Ferguson et al., 2022; Provan et al., 2022). To further establish the reliability of ERA5 as a source of atmospheric data for storm surge modelling at the Chignecto Isthmus additional validation was conducted. This validation involved comparing ERA5 pressure and wind data with measurements from meteorological stations located on the Chignecto isthmus and surrounding areas, ensuring its suitability as a driving force in the numerical storm surge model. Two meteorological stations, Nappan and Parrsboro, available via ECCC's Meteorological Survey of Canada (MSC) and an additional station, Aulac, via Saint Mary's University (SMU) in Halifax, Nova Scotia, were used (Table 3.2 and Figure 3.17). Measurements from these meteorological stations were compared with collocated ERA5 data over a period from September 10th to October 1st 2022. ERA5 data were linearly interpolated to the locations of the meteorological stations. Figure 3.18, Figure 3.19 and Figure 3.20 show the comparison between ERA5 data and local measurements for Aulac, Nappan and Parrsboro, respectively. These figures include time series of air pressure, wind speed and wind direction, as well as quantile-quantile (qq) plots, which provide a graphical method to evaluate the differences between the measured data and ERA5 reanalysis data. In the qq-plots, if the data points form a straight line with equal values on the x- and y-axes, the two datasets are in agreement. Deviations from a straight line indicate that one dataset overestimates or underestimates values compared to the other. Table 3.3 provides a summary of maximum wind speeds recorded at the meteorological stations and the corresponding ERA5 data at these locations. Additionally, the Root Mean Square Error (RMSE) of the wind speed over the period from September 10th to October 1st 2022 is included.

The data from the Aulac station were interpolated to a 60-minute interval to match the frequency of the ERA5 data. The results indicate that locally measured air pressure is consistently lower than the ERA5 data, though the overall trend is comparable (Figure 3.18a). ERA5 data underpredict the peak wind speed of the storm by 19% (Table 3.3). Due to the relatively coarse spatial resolution, ERA5 data often underpredict the maximum wind speed during the passage of a storm and cannot capture local variations in the wind field (Section 2.5) or topographic steering of winds, which are reflected in measurements at local meteorological stations. These differences are evident in the time series of both wind speed and wind direction (Figure 3.18c and Figure 3.18e). Despite the differences, the overall trend of the data is captured, and the storm is clearly identified in the ERA5 data, indicating ERA5 data suitability for forcing storm surge in the numerical model.

At Nappan and Parrsboro, ERA5 data consistently overpredict air pressure but capture the overall trend (Figure 3.19a and Figure 3.20a). Similar to Aulac, ERA5 data at Nappan do not capture local variations in wind speed and direction and underpredict storm peak wind speeds, here by 12% (Table 3.3), although the overall trend is well represented (Figure 3.19c and Figure 3.19e) with RMSE ranging from 1.98 m/s at Aulac and 1.25 m/s at Nappan. Larger differences are noted between ERA5 data and local measurements at Parrsboro (Figure 3.20c and Figure 3.20e), where the RMSE is 3.33 m/s (Table 3.3). However, data from Nappan and Aulac are comparable with the ERA5 data and fall within the main geographic region of interest, whereas Parrsboro is further away and outside the Chignecto Isthmus. The comparability of data at both Nappan and Aulac indicates that ERA5 data are suitable for use in this study.

Table 3.2. Overview of meteorological stations with locations in NAD83 (CSRS) UTM zone 20N and elevation above the ground of the measurements and measurement frequency.

Meteorological Station	Easting [m]	Northing [m]	Elevation [m]	Frequency [min]
1 – Aulac	398763.5	5079194.3	3	30
2 – Nappan	403569.8	5068130.0	10	60
3 – Parrsboro	394361.0	5029384.2	10	60

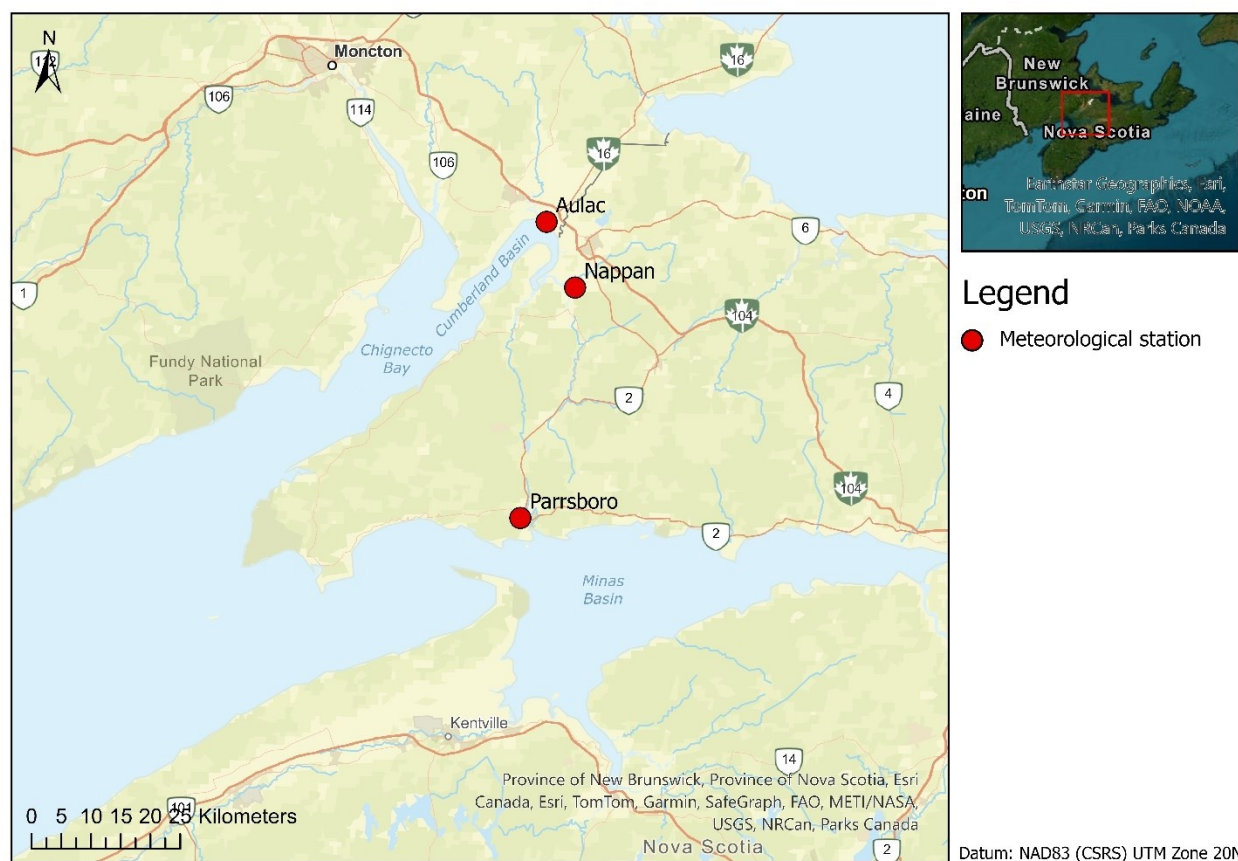


Figure 3.17. Location of meteorological stations on the Chignecto Isthmus and surrounding regions, where the meteorological stations at Nappan and Parrsboro were retrieved from MSC and the meteorological station at Aulac were made available by SMU.

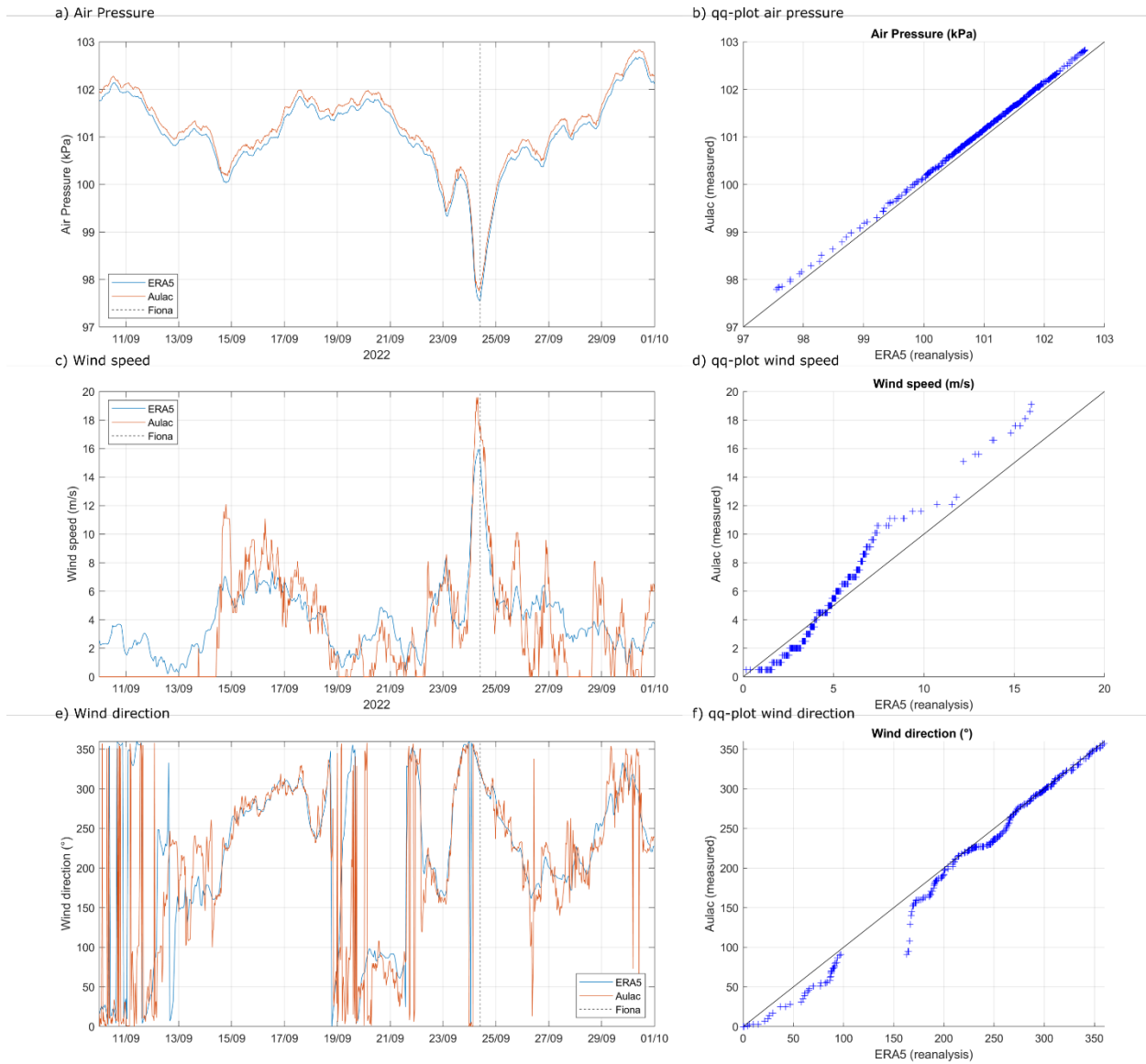


Figure 3.18. Comparison of meteorological data collected by SMU at Aulac with ERA5 data: a) time series of air pressure (UTC); b) qq-plot of air pressure; c) time series of wind speed (UTC); d) qq-plot of wind speed; e) time series of wind direction (UTC); f) qq-plot of wind direction. The dashed vertical line indicates the approximate time of maximum wind speed in the Cumberland Basin (Copernicus Climate Change Service, 2017).

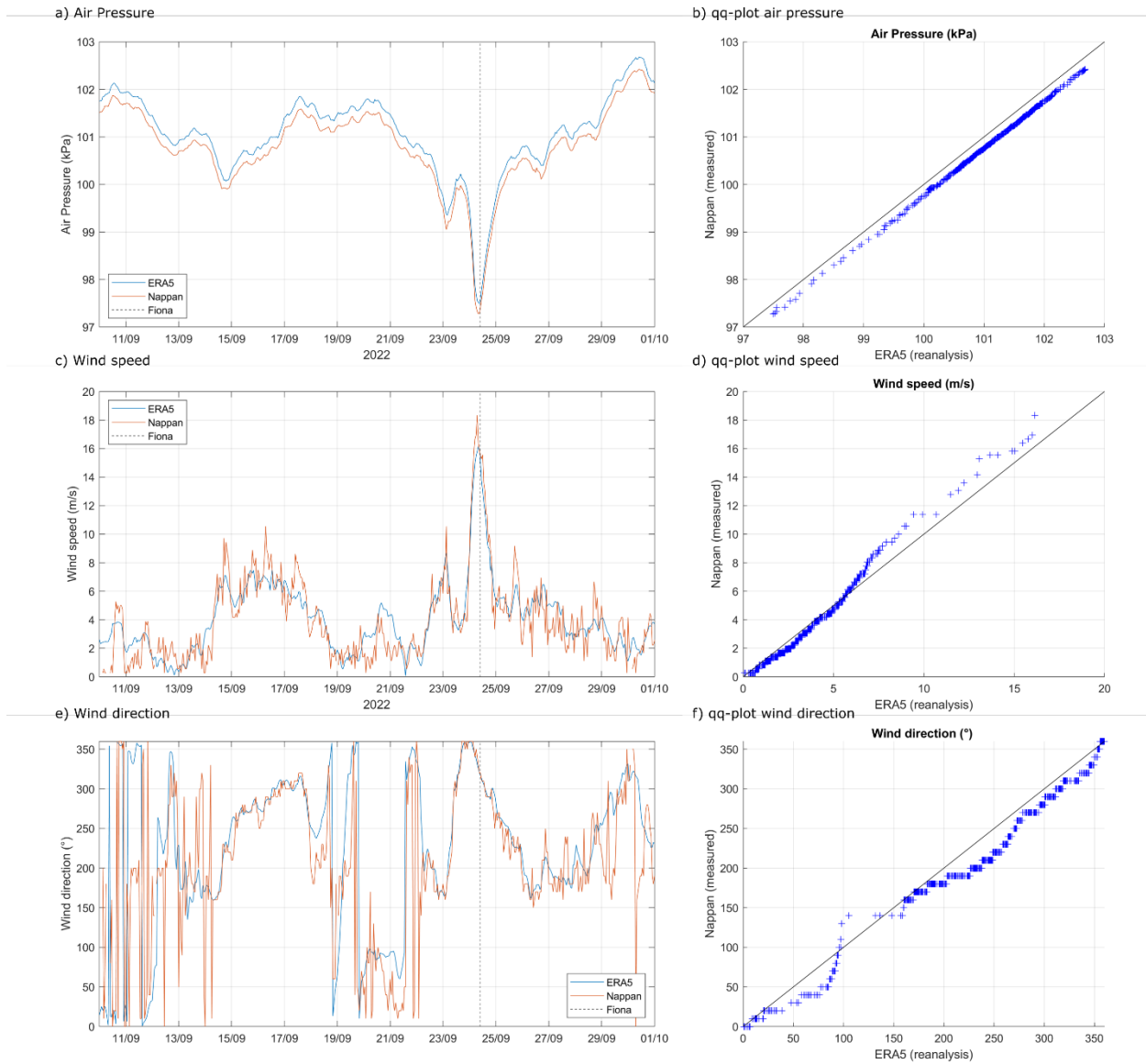


Figure 3.19. Comparison of meteorological data from MSC at Nappan with ERA5 data: a) time series of air pressure (UTC); b) qq-plot of air pressure; c) time series of wind speed (UTC); d) qq-plot of wind speed; e) time series of wind speed (UTC).

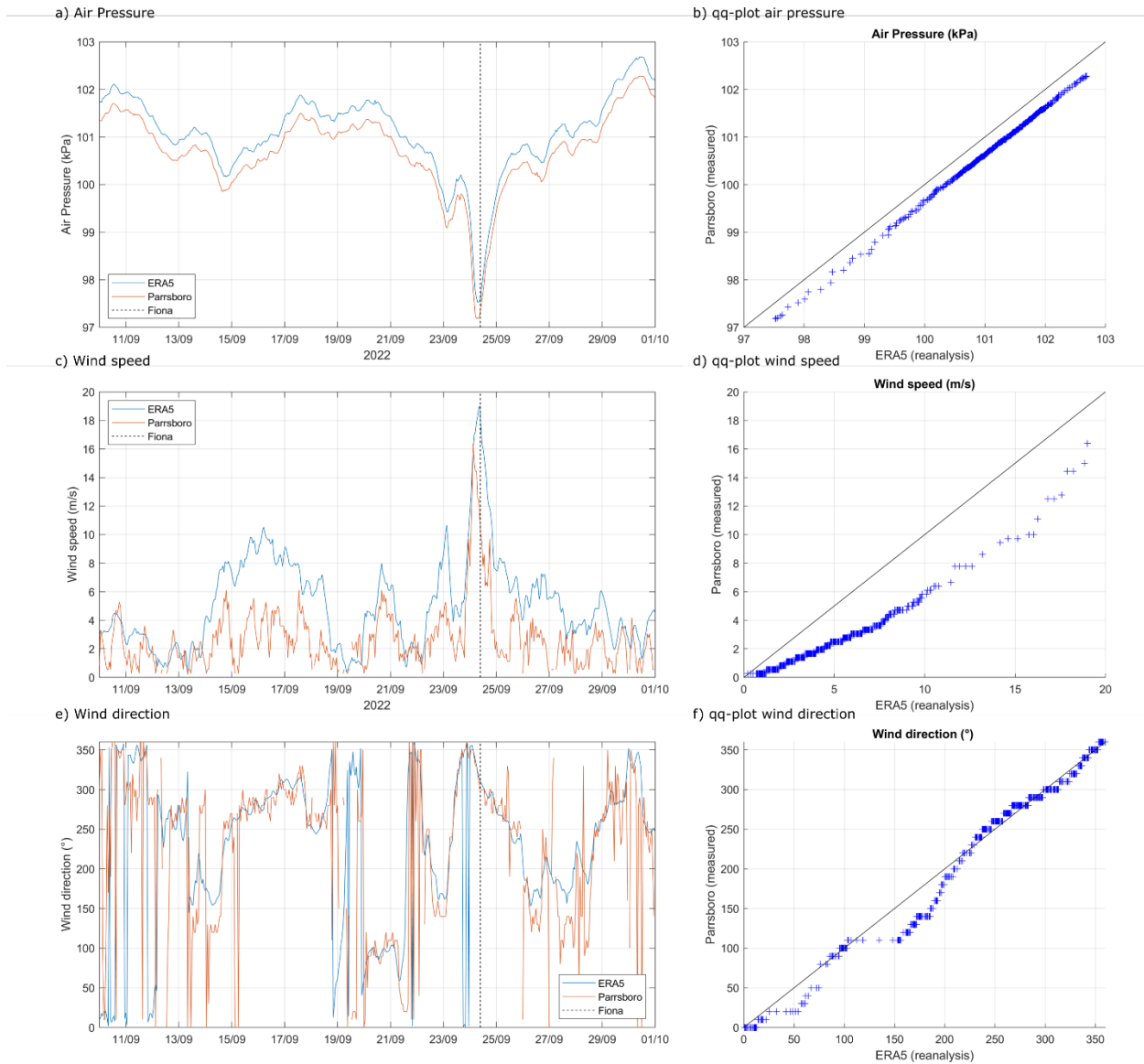


Figure 3.20. Comparison of meteorological data from MSC at Parrsboro with ERA5 data: a) time series of air pressure (UTC); b) qq-plot of air pressure; c) time series of wind speed (UTC); d) qq-plot of wind speed; e) time series of wind speed (UTC).

Table 3.3. Overview of peak wind speeds of the meteorological and ERA5 data with percentual difference. RMSE of the wind speed covering the period from September 10th to October 1st 2022.

Meteorological Station	Peak wind speed meteorological station [m/s]	Peak wind speed ERA5 data [m/s]	Percentage difference between measured wind speed and ERA5 data	RMSE wind speed [m/s]
1 – Aulac	19.6	15.9	-19%	1.98
2 – Nappan	18.3	16.1	-12%	1.25
3 – Parrsboro	16.4	19.0	16%	3.33

4. Methodology

The hydrodynamic model of the Cumberland Basin was created as a research tool to explore the feasibility of managed dyke realignment in a hypertidal environment characterised by dykes and highly erosive forces on coastal mud flats. The motivation for such a study was to investigate Nature-based Solutions in areas with significant tidal activity and highly mobile sediment. The Bay of Fundy, renowned for having one of the highest tidal ranges in the world (Archer, 2013), and specifically the Chignecto Isthmus, known for its low land elevations, was identified as the ideal location for this research. This section describes the development of the model.

4.1. Modelling Software

The Cumberland Basin numerical hydrodynamic model was developed using TELEMAC-2D (Open Telemac-Mascaret, 2022), which is part of the open TELEMAC-MASCARET suite of hydro-environmental modelling tools. The tools were originally developed by the Studies and Research Division of *Electricité de France* (EDF) to support environmental assessments for EDF's power plants. The tools are now managed by a consortium of users and developers in France, Germany and the UK; and developed under a collaborative open-source framework. Its numerical schemes and high-performance solvers are continuously improved upon by developers across the world in conformance to EDF's quality assurance.

TELEMAC-2D is a finite element-based (or optionally, finite volume-based) modelling system, as described by Hervouet (2007), used for coastal and riverine applications. It simulates two-dimensional free surface flows across a spatial domain by calculating water depths and two-dimensional velocities. TELEMAC-2D performs simulations using the shallow water (i.e. Saint Venant) equations, which are two-dimensional, unsteady flow calculations that allow parameters such as flow to change with time. TELEMAC-2D is based on an unstructured triangular mesh, which allows for increased computational mesh resolution in areas of interest, or where there are strong gradients in topography/bathymetry or hydrodynamic fields. TELEMAC-2D includes the capability to simulate the wetting and drying of computational cells, enabling the simulation of intertidal flats and floodplains. It also supports spatially and temporally varying wind and atmospheric pressure forcing to simulate storm surge. One of the system's key advantages is its open-source framework, which allows users to develop new modules or modify existing ones to address a variety of customised needs.

4.2. Model Setup

4.2.1. Model Domain

The extent of the Cumberland Basin hydrodynamic model computational domain (shown in Figure 2.1) was developed reflecting available data and to simulate tides and flow circulation in Cumberland Basin. Prior to the start of this study, the model was initially developed by the NRC-OCRE as a research tool to assess the extent of overland flooding and changes in the flow field resulting from a series of possible managed dyke realignment options in the Chignecto Isthmus. As such, the model's domain encompasses Cumberland Basin and its major tributaries, including the Tantramar, Aulac, Missaguash, Hebert and Maccan rivers. The overland computational domain of the numerical model extends into the low-lying

regions of the Chignecto Isthmus, incorporating the existing dyke infrastructure and surrounding coastal floodplains. An 8 m contour line was extracted from available DEMs (see Section 2.1) to help delineate the model's domain within this low-lying region of the Chignecto Isthmus.

4.2.2. Model Mesh

The initial basis for developing the hydrodynamic model's mesh was the CHC model (see Section 2.1) created for the Petitcodiac River study (AMEC Earth and Environmental, 2005). The original mesh within the boundaries of Shepody Bay and the Petitcodiac River was preserved, while the remainder of the mesh was modified to meet the requirements for modelling of the Cumberland Basin. Specific areas of the mesh in the upper Cumberland Basin, including the shoreline and intertidal zones, were refined. This refinement encompassed the dykes from Westcock to Converse marshes, the TransCanada Highway, and the tributaries flowing into the Cumberland Basin (i.e. Tantramar, Aulac and Missaguash rivers). Dyke centrelines were used from available data or digitized from the CHS Chart 4130 where dyke data were not available (refer to Section 2.2 for more details). The model mesh resolution ranges from 1 km at the open water boundary near Cape Enrage to 5 m in specific locations within the Chignecto Isthmus including the dykes, shorelines and tributaries to Cumberland Basin as illustrated in the inset of Figure 4.1.



Figure 4.1 Model mesh and boundary with a detailed inset of upper Cumberland Basin

4.2.3. Model Bathymetry

The Cumberland Basin model was created using the NAD83 (CSRS) UTM Zone 20N spatial projection and the Canadian Geodetic Vertical Datum 2013 (CGVD2013), to which all topography and bathymetry datasets (as outlined in Section 2.1 and depicted in Figure 2.1) were merged and transformed, generating a continuous DEM covering the Cumberland Basin and surrounding coastal areas. Spatial re-projections, where required, were performed using a combination of QGIS software (QGIS.org, 2021) and NRC-OCRE's Blue Kenue™ (Barton, 2019) pre-processing, post-processing and visualisation tool. Vertical

transformations were carried out using Blue Kenue™. The final model bathymetry is illustrated in Figure 4.2. It should be noted, however, that the bathymetry in the subtidal and offshore regions of the model would benefit from more up-to-date data as suggested in Section 2.1. Section 7 point 1. provides further discussions and recommendations.

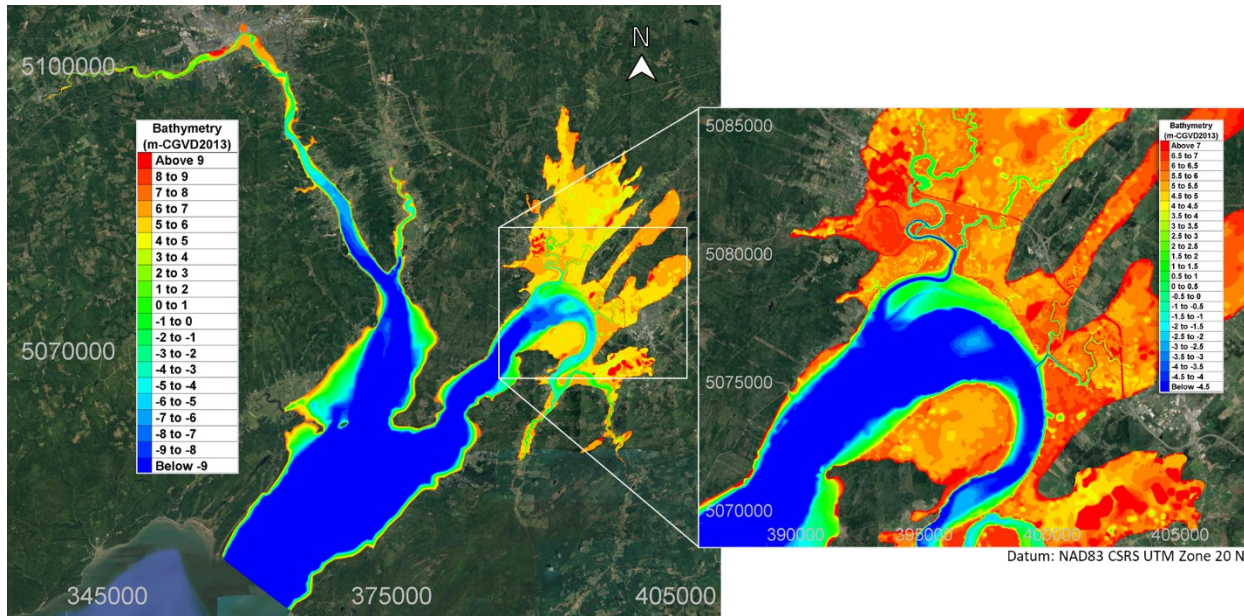


Figure 4.2 Model bathymetry with a detailed inset of upper Cumberland Basin

4.2.4. Model Forcing

Model forcing refers to the incorporation of external data and boundary conditions into a numerical model to drive the model's simulations.

Regional Model

The open-water boundary of the regional model was driven by the TPXO 7.2 database available in Telemac (Open Telemac-Mascaret, 2022) as described in Section 2.4.1. These simulations generated tide only boundary conditions for the Cumberland Basin Model. To incorporate storm surge, the regional model was forced by spatiotemporal ERA5 surface wind and mean sea level pressures (Copernicus Climate Change Service, 2017). These two data layers were linearly interpolated to the regional model's mesh. With the inclusion of ERA5 to the simulations, the simulations produced tide and storm surge boundary conditions for the Cumberland Basin Model.

Cumberland Basin Model

The open-water boundary of the Cumberland Basin hydrodynamic model was driven by spatiotemporally varying water levels output from the regional model. The water levels were linearly interpolated along the "open water boundary" segment shown in Figure 4.1, converted from NAD83 (CSRS) UTM Zone 19 to Zone 20, and applied to the model. Two boundary conditions were established: tide only, and tide combined with storm surge. For the storm surge scenario, similar to the regional model, the Cumberland Basin model was forced by spatiotemporal ERA5 surface wind and mean sea level pressure, which were linearly interpolated to fit the model's mesh.

4.2.5. Model configuration

A constant model time step of 30 seconds for both the regional and Cumberland Basin hydrodynamic models was selected to satisfy Courant stability criteria. Model output was saved at 5-minute increments for both models, to temporally resolve the changing hydrodynamic conditions in response to tides and storm surge. Roughness coefficients described in Section 2.3 were used to describe the flow resistance in the model. Model simulations included a spin-up period necessary to resolve transient effects from the initial conditions.

4.2.6. Definitions of Model Output Parameters

Water depth is defined as the difference in elevation between the water surface (often referred to as the free surface) and the bed (based on the local topography or bathymetry). Elevations are referenced relative to the CGVD2013 datum (Figure 4.3a), whereas water depth is a scalar (always positive or zero, and with no datum reference). When water is present at a model grid cell, this value represents the water level or the surface water elevation; when no water is present (i.e. water depth equal to zero), the free surface elevation represents the elevation of the local topography or bathymetry. In the Bay of Fundy, the large tidal range causes extensive areas to be covered by water only during high tide, with the bed exposed during low tide. In free surface results, this is indicated by a constant bed value at low tide. For instance, in Figure 4.3b, the bed is at -1.6 m CGVD2013 and is regularly exposed during low tide.

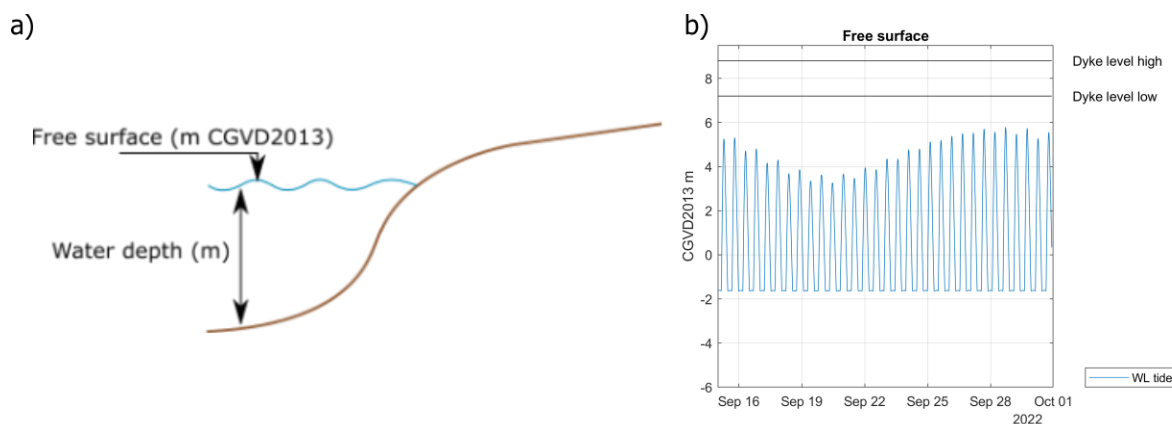


Figure 4.3. a) Definitions of free surface and water depth; b) Example result of free surface (m CGVD2013) on a mudflat in the Cumberland Basin.

4.3. Modelling Scenarios

The criteria for selecting modelling scenarios were based on post-tropical storm Fiona and two other hypothetical agreed-upon extreme events, in consultation with the Technical Advisory Committee. An additional fourth scenario is included as it was essential to assess the relative timing of the highest storm surge to the astronomical high tide. The criteria considered historic storm events in the Cumberland Basin and the Bay of Fundy (see Section 3), adjustments to the tidal phase coinciding with high tides based on the 18.6-year lunar nodal cycle (see Section 1.1.3), and predicted relative SLR scenarios (see Section 2.6).

4.3.1. Criteria

Storm

Among all of the storms presented in Section 3.1, the 1976 Groundhog Day storm appears to present the potential for largest storm surge in the Chignecto Isthmus. Aligned with the orientation of the Bay of Fundy, the storm generated southwesterly winds allowing for a long fetch and thereby amplifying storm surge. In Cumberland Basin, the Groundhog Day storm generated maximum wind speeds comparable to those of post-tropical storm Fiona (Table 3.1). While Fiona was a more recent significant event in Atlantic Canada, its northwesterly winds did not generate a significant surge. For this reason, the 1976 Groundhog Day storm was selected to represent a storm for hypothetical Scenarios 2, 3 and 4.

Tides

Tidal variations are relatively well predicted based on the motions of the Moon, the Sun and the Earth (Section 1.1.3). The peak of the lunar nodal cycle (having an 18.6-year period) is predicted to occur in the Cumberland Basin on October 10th 2033, creating the highest high tide, according to discussions with Bob Robichaud (ECCC) and confirmed with long-term simulations of the regional model. This tidal event will be referred to as the “peak tide 2033,” which was selected to represent the tides for hypothetical Scenarios 2, 3 and 4.

Relative SLR

In agreement with the Technical Advisory Committee, the RCP8.5 median predictions, which represent a high-emissions pathway as discussed in Section 2.6, were selected to represent projected relative SLR for the study. Thus, the projected relative SLR for year 2033 was selected for simulating Scenario 2, coinciding with the peak tide 2033. For Scenario 3, the projected relative SLR for year 2100 was selected exploring a more extreme but plausible future scenario. These projections are crucial for understanding the potential impacts on the Cumberland Basin over both the medium and long term. ClimateData.ca (2024b) indicates a relative SLR of +0.19 m for 2033 and +0.74 m for 2100 in the Cumberland Basin relative to 1986-2005 conditions.

As discussed in Section 2.1, NSCC-AGRG collected and processed LiDAR data in 2021, which were used, among other data, to create the Cumberland Basin model's bathymetry. The surface area that the NSCC-AGRG data cover is also the region of primary interest for this study. Since the relative SLR projections account for vertical land movement, it is necessary to establish a baseline reference date for the land elevations used in the model. Therefore, the year 2021 was selected as the reference year for considering relative SLR projections. ClimateData.ca (2024b) indicates a relative SLR of 0.11 m for 2021 in the Cumberland Basin relative to 1986-2005 conditions. Therefore, the relative SLR in the Cumberland Basin under RCP8.5, compared to 2021, is projected to be +0.08 m for 2033 and +0.63 m for 2100. Henceforth in this report, the year 2021 will serve, and be referenced to, as the “baseline year” for simulations.

4.3.2. Selected Scenarios

Four scenarios were examined, each with two simulations: one focusing solely on tides and the other incorporating both tides and storm surges (Table 4.1). Tides-only simulations were performed to isolate the relative contribution of storm surge to total water levels on the Chignecto Isthmus, and to determine the

phasing of tides and peak storm surge for the post-tropical storm Fiona scenario. All scenarios included time for model spin-up and to capture the evolution of hydrodynamics and water levels caused by the storms being simulated. A fourth scenario was conducted to determine the most likely alignment of storms coinciding with peak tides.

Table 4.1. Overview scenarios

Scenario	Sub-Scenario	Storm	Date of storm in TELEMAC-2D model	Relative SLR [m]
1	1A – Tide only	-	-	0.00
	1B – Tide + Surge	Fiona	September 24 th , 2022	
2	2A – Tide only	-	-	0.08
	2B – Tide + Surge	Groundhog Day	October 10 th , 2033	
3	3A – Tide only	-	-	0.63
	3B – Tide + Surge	Groundhog Day	October 10 th , 2033	
4 – Sensitivity of storm timing	4A – Tide only	-	-	0.00
	4B – Tide + Surge (multiple scenarios where timing of the peak wind speed is shifted – by -1, -2, -2.5 and -3 h – relative to the high astronomical tide)	Groundhog Day	October 10 th , 2033	

Scenario 1 – Post-Tropical Storm Fiona

Scenario 1 simulations encompass the period from September 1st to October 1st 2022.

- **Scenario 1A – Tides only:** The model simulated astronomical tides only (i.e. no atmospheric forcing) during the Fiona event.
- **Scenario 1B – Tides and storm surges:** The model simulated both tides and storm surges during the Fiona event by forcing ERA5 air pressure and wind data to both the regional and local models.

Scenario 2 – Groundhog Day Storm-Type Event with Peak Tide 2033 and Predicted Relative SLR for Year 2033

Scenario 2 simulations cover the tidal range predicted for the future period between September 7th and October 17th 2033, coinciding with the peak lunar nodal cycle on October 10th.

- **Scenario 2A – Tides only:** The model simulated predicted astronomical tides for peak tide 2033, including a 0.08 m increase in water levels caused by relative SLR predicted for year 2033.
- **Scenario 2B – Tides and storm surges:** The model built on Scenario 2A by adding ERA5 air pressure and wind data to simulate the Groundhog Day storm. This forcing was applied to both the regional and local models, with timing adjusted so that the peak wind speed of the Groundhog Day storm-type in the Cumberland Basin occurred 2.5 hours before peak tide on October 10th 2033, to achieve the highest expected water levels near the Chignecto Isthmus.

Scenario 3 – Groundhog Day Storm-Type Event with Peak Tide 2033 and Predicted Relative SLR for Year 2100

Scenario 3 simulations cover the tidal range predicted for the period between September 7th and October 17th 2033.

- **Scenario 3A – Tides only:** The model simulated predicted astronomical tides for peak tide 2033, including a 0.63 m increase in water level caused by relative SLR predicted for year 2100.
- **Scenario 3B – Tides and surges:** The model built on Scenario 3A by forcing ERA5 air pressure and wind data to simulate a Groundhog Day-type storm. This forcing was applied to both the regional and local models, with the timing adjusted so that the peak wind speed of the Groundhog Day storm-type in the Cumberland Basin occurred 2.5 hours before peak tide on October 10th 2033, to achieve the highest expected total water levels near the Chignecto Isthmus.

Scenario 4 – Groundhog Day Storm-Type Event with Peak Tide 2033 and

Scenario 4 simulations cover the tidal range predicted for the period between September 7th and October 17th 2033.

- **Scenario 4A – Tides only:** The model simulated predicted astronomical tides for peak tide 2033.
- **Scenario 4B – Tides and surges:** The model built on Scenario 4A by forcing ERA5 air pressure and wind data to simulate a Groundhog Day-type storm. Unlike the above three scenarios, Scenario 4 required conducting a number of simulations. In Scenarios 2 and 3, the timing of the ERA5 data, specifically the peak wind speeds of the Groundhog Day storm-type, were adjusted to align with the highest expected water levels near the Chignecto Isthmus, coinciding with the peak tide of the lunar nodal cycle predicted for October 10th 2033. A sensitivity analysis was performed in Scenario 4 to evaluate the alignment of the storm's timing relative to the peak tide 2033. Multiple simulations were conducted until the greatest difference in water levels was achieved, creating the most extreme scenario possible given the conditions. Simulations were conducted with the

maximum wind speed shifted earlier in time relative to high tide, including shifts of -1 h, -2 h, -2.5 h and -3 h.

4.3.3. Model Scenario Extraction Locations

For each of the scenario simulations, maps showing the spatial distribution of water depth values in meters were prepared, to indicate the maximum extent of inundation and one factor influencing flood hazard. Additionally, free surface elevation time series were extracted at seven specific locations (Table 4.2, Figure 4.4) and named based on their nearby landmarks. The first six locations were used to assess tide and storm surge levels in the Cumberland Basin and in the vicinity of dykes (Sections 5.1, 5.2, 5.3). In addition, locations 1 and 7 were used to assess the timing of the storm relative to high tide (Section 5.4). To provide reference elevations for comparison to the simulated free surface elevation, dyke elevation ranges in the vicinity are included in the free surface extraction figures (Figure 4.3b). The elevation of the dykes in the area varies along their extent (see Figure 2.2). In the free surface extraction figures, the high dyke level refers to the maximum dyke elevation at Aulac, which is +8.8 m CGVD2013, while the low dyke level refers to the minimum dyke elevation at Aulac, which is +7.2 m CGVD2013 (Table 4.3).

Table 4.2. Extraction-point locations of free surface model results (NAD83 (CSRS) UTM Zone 20N)

Extraction Point	Easting [m]	Northing [m]
1 – Cumberland Basin Offshore	394700.6	5076032.8
2 – Tantramar River	395657.1	5083181.5
3 – Aulac River	399215.6	5081779.8
4 – Cumberland Basin Nearshore	399276.7	5078766.4
5 – Missaguash River	401141.5	5078205.7
6 – LaPlanche River	402575.2	5075868.0
7 – Cumberland Basin Mid-shore	398813.8	5077795.0

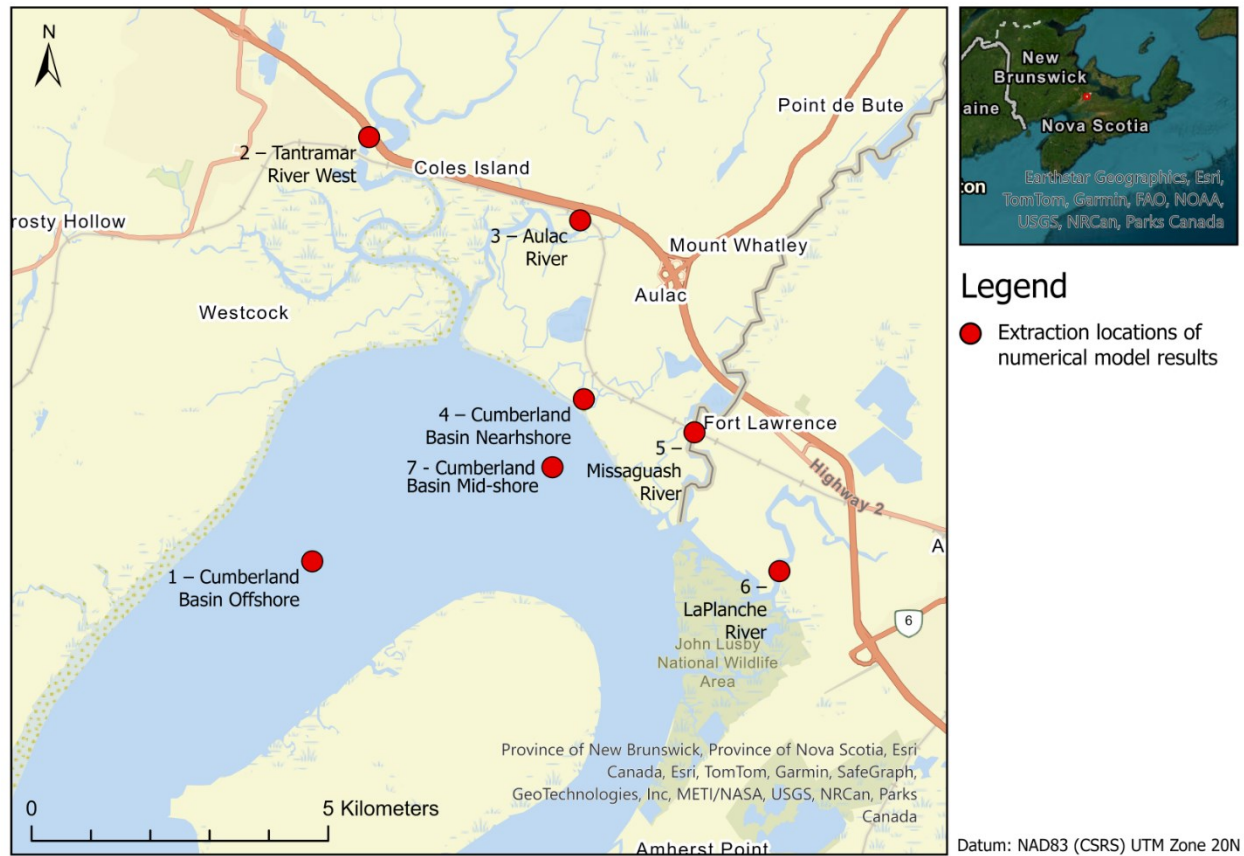


Figure 4.4. Location of seven identified extraction points for free surface model results.

Table 4.3. Minimum, maximum and mean height of dyke elevations.

Dyke	Min [m CGVD2013]	Max [m CGVD2013]	Mean [m CGVD2013]
Sackville	8.0	8.7	8.3
Westcock	7.4	8.6	8.0
Aulac	7.2	8.8	7.8

4.4. Hydrodynamic Modelling

Model calibration and validation are essential steps in the model development to ensure confidence in the results produced by a numerical model, and to quantify model uncertainty. In a standard split-sample model calibration and validation procedure, a historical time period with available field (observed) data is identified and selected for calibration. Through an iterative process, the numerical model and its parameters are adjusted until modelled (simulated) data are in close agreement to observed (measured) data. The validation phase then assesses how well the calibrated model can independently simulate hydrodynamic conditions for a time period outside of the calibration period, based on comparisons to a distinct set of observations not used in calibration. This validation phase involves evaluating the model's ability to accurately represent the system and processes it was designed for, without making further adjustments to the model.

4.4.1. Model Calibration (tides-only)

During the development stages of the model, the primary focus was to study Managed Dyke Realignment. Therefore, the Cumberland Basin hydrodynamic model was calibrated to match the observed water levels at sites along the northeast shores of Cumberland Basin, near the Missaguash River. The model was calibrated using roughness coefficients which consider existing land use types using land cover described in Section 2.3. The model was calibrated using year 2021 field data discussed in Section 2.4.2 of this report. This calibration was completed with tidal forcing only during (relatively) calm periods where storm surges were limited.

The tidal elevation for the calibrated model (tides-only) are compared to observed water levels at three different locations (Figure 2.5). Figure 4.5, Figure 4.6 and Figure 4.7 provide these comparisons, with model results shown in orange and field data in blue.

At the Wood Point gauging site (Figure 2.5, location point 4), field observations were intermittent between July and October 2021, as illustrated by blue markers in Figure 4.5. Here, the modelled high tides demonstrate a correlation of 0.96 with the observed. The RMSE between the two datasets (modelled and observed high tides) is 0.26 m. On average, the modelled tidal phase leads (is ahead of) the observed tides by 30 min at this site.

At the Allen Creek gauging site (Figure 2.5, location point 3), the modelled peak tidal elevations for the period from September to December 2021 show a correlation of 0.97 with the field observations (Figure 4.6). The RMSE between the modelled and observed high tides is 0.27 m, with the model leading in phase by an average of 26 min.

At Missaguash River field site (Figure 2.5, location point 5), the correlation is 0.94 between modelled tidal elevations and the observed water levels, and an RMSE of 0.28 m (Figure 4.7). On average, the modelled peaks lead the observed peaks by 17 min.

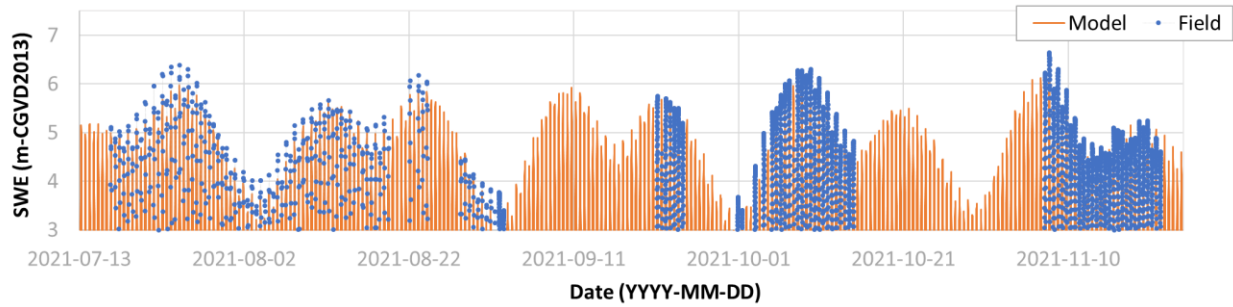


Figure 4.5 Modelled/simulated (orange) tidal elevations and observed/field (blue markers) water levels (surface water elevations (SWE)) at Wood Point in 2021.

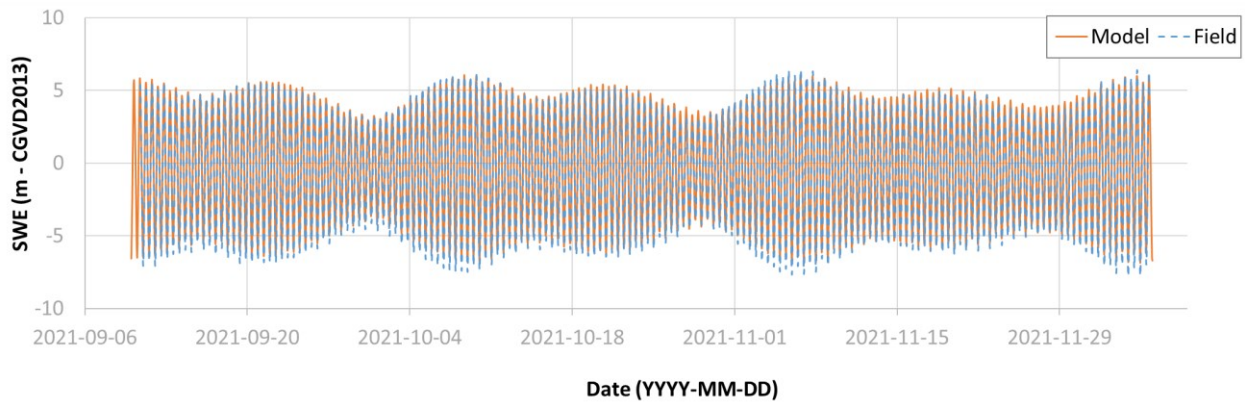


Figure 4.6 Modelled/simulated (orange) tidal elevations and observed/field (blue) water levels (or SWE) for Allen Creek in 2021.

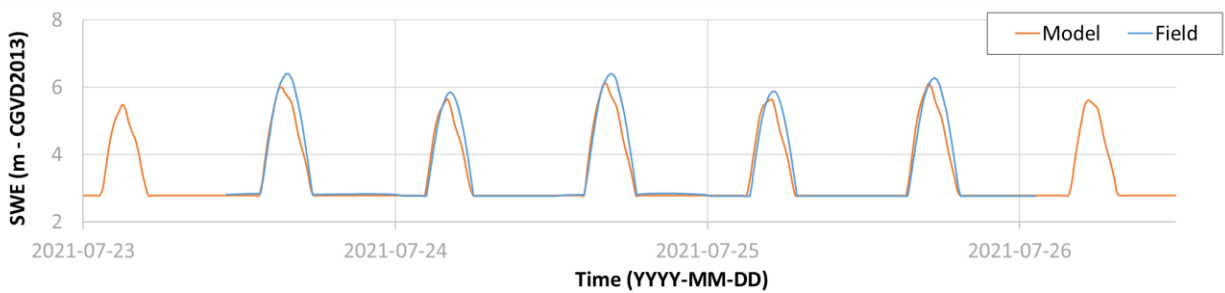
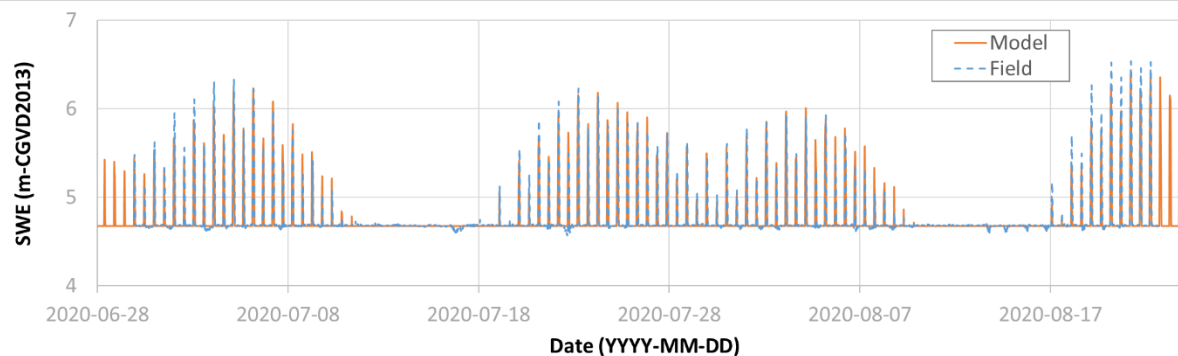


Figure 4.7 Modelled/simulated (orange) tidal elevations and observed/field (blue) water levels (or SWE) for year 2021 at Missaguash River.

4.4.2. Model Validation (tides-only)

The tides-only model was validated using observed water level data from June 29th to August 22nd 2020, as detailed in Section 2.4.2. The modelled tidal elevations and water level observations at the borrow pit location (Figure 2.5, location point 2) are shown in Figure 4.8a). The correlation between the modelled tidal elevations and observed field measurements is 0.93, with an RMSE of 0.13 m. At this site, the modelled high tide leads the observed high tide by an average of 22 min. For the location in the Missaguash River (Figure 2.5, location point 1), the results are shown in Figure 4.8b). Here, the correlation is 0.94, with an RMSE of 0.14 m. The modelled high tides at this river location lead the observed high tides by an average of 30 min.

a) Borrow pit



b) River

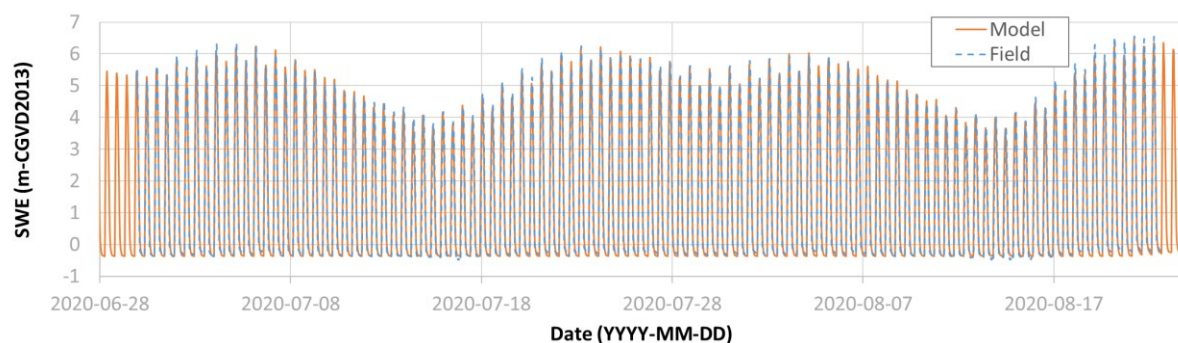


Figure 4.8 Validation of the Cumberland Basin hydrodynamic model using summer 2020 field campaign observations in a) the borrow pit and b) Missaguash River, with modelled/simulated tidal elevations in orange and observed/field water levels (SWE) in blue.

4.4.3. Model Validation (tides and surges)

The implementation of storm surge by forcing of ERA5 pressure and wind data in the model was validated using observed water levels at Saint John and Wood Point (Table 2.3, Figure 2.10). The time period here spans from September 15th to September 29th 2022, to focus on the period around post-tropical storm Fiona. Two variations of numerical input are assessed to best validate the model results:

- **Baseline ERA5**

Baseline (unmodified) ERA5 data with default wind stress parameters in TELEMAC-2D (Open Telemac-Mascaret, 2022).

- **Adjusted wind drag coefficient (wind drag)**

The default wind drag coefficients (which vary as a function of wind speed) used in TELEMAC-2D were modified to simulate and test model sensitivity to enhanced wind-sea momentum transfer during storm conditions (Figure 4.9). The default wind drag coefficients in TELEMAC-2D are based on methods developed by Flather (1976).

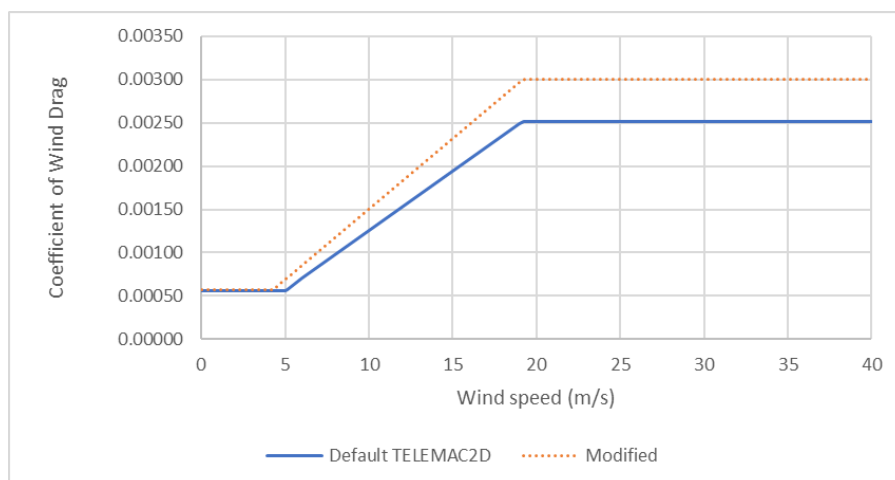


Figure 4.9. Default wind drag coefficient in TELEMAC-2D (blue) and modified wind drag coefficient to enhance the impact of high wind speeds (orange).

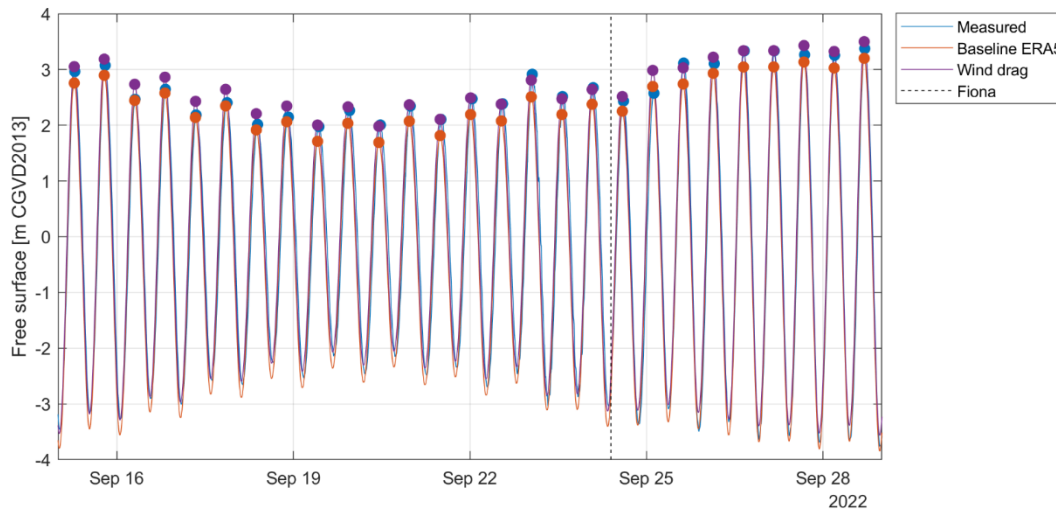
The numerical model results were compared with water level measurements. Figure 4.10 and Figure 4.11 show the comparison between measured water levels and numerical model results for Saint John and Wood Point, respectively. Table 4.4 provides an overview of the RMSE between the water level measurements and the numerical model results, with a focus on the peaks of the water level as these are critical for determining overflowing over the dykes on the Chignecto Isthmus.

Comparison of the measurements with the baseline ERA5 numerical results indicates that the model results tend to underpredict the peak water levels. At Saint John, the wind drag option shows a reduction in RMSE, which is not noticeable at Wood Point. This reduction could be due to local effects within the harbour that are not captured in detail by the regional numerical model, as it falls outside the scope of the project. Wood Point, being closer to the area of interest, does not show a noticeable reduction in RMSE with the wind drag option. Therefore, the baseline (unaltered) ERA5 data provides the most comparable model results to the available dataset and is selected as the most suitable option for this study. In addition to this validation of the numerical model, Section 4.5 investigates the sensitivity of the ERA5 data implemented in the numerical model.

Table 4.4. Sensitivity analysis RMSE results of the peak free surface at Saint John and Wood Point for the various numerical inputs over the time period September 15th to September 29th 2022.

Numerical input	RMSE peak free surface Saint John [m]	RMSE peak free surface Wood Point [m]
Baseline ERA5	0.23	0.14
Wind drag	0.15	0.15

a) Time series of water level data and numerical model results



b) Time series specifically around Fiona of water level data and numerical model results

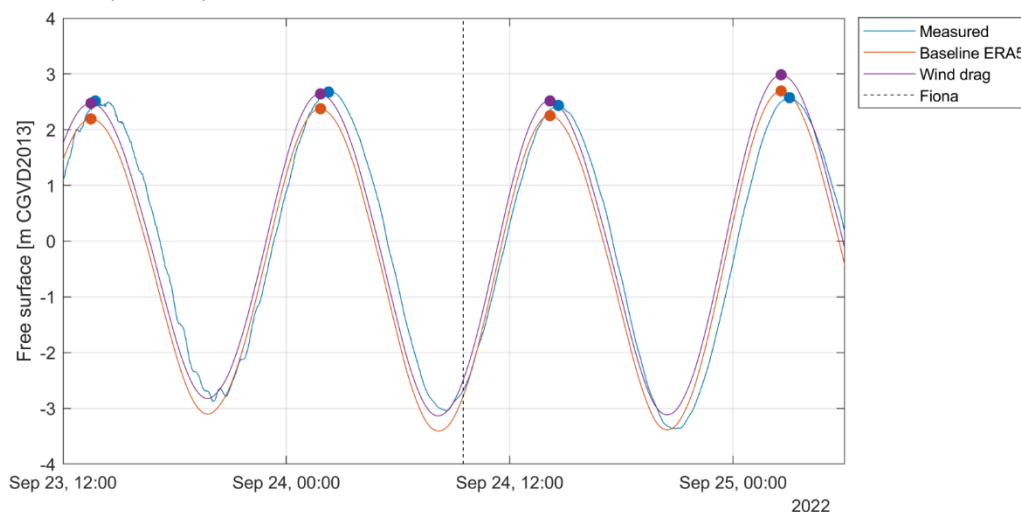
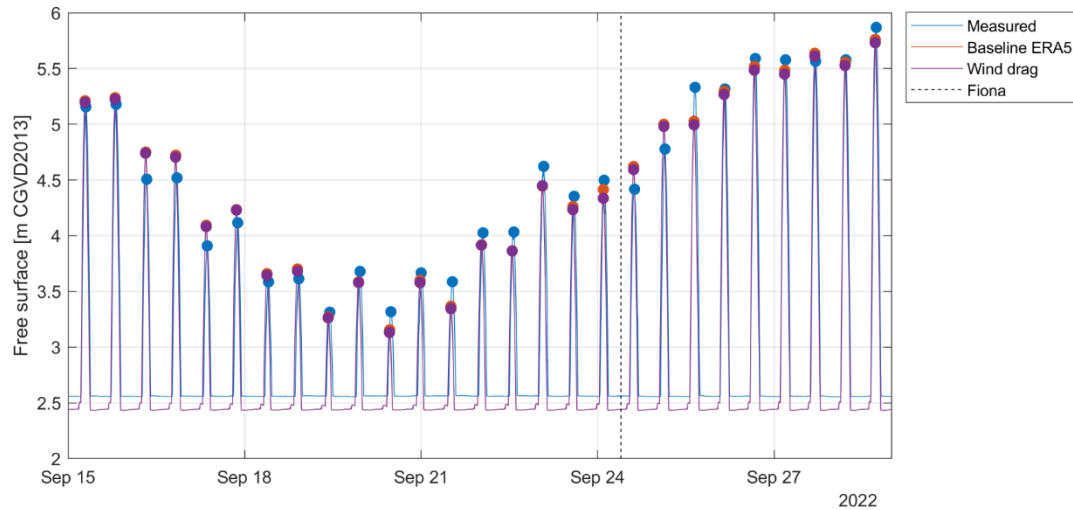


Figure 4.10. Time series (UTC) of water level data (Fisheries and Oceans Canada, 2024) and numerical model results at Saint John, a) time period September 15th to September 29th 2022; b) time period September 23rd 12:00 UTC to September 26th 6:00 UTC 2022. The dots indicate high water level and the dashed line indicated the timing of the peak of storm Fiona, based on peak wind speed in the Cumberland Basin Offshore (Location 1, Table 4.2).

a) Time series of water level data and numerical model results



b) Time series specifically around Fiona of water level data and numerical model results

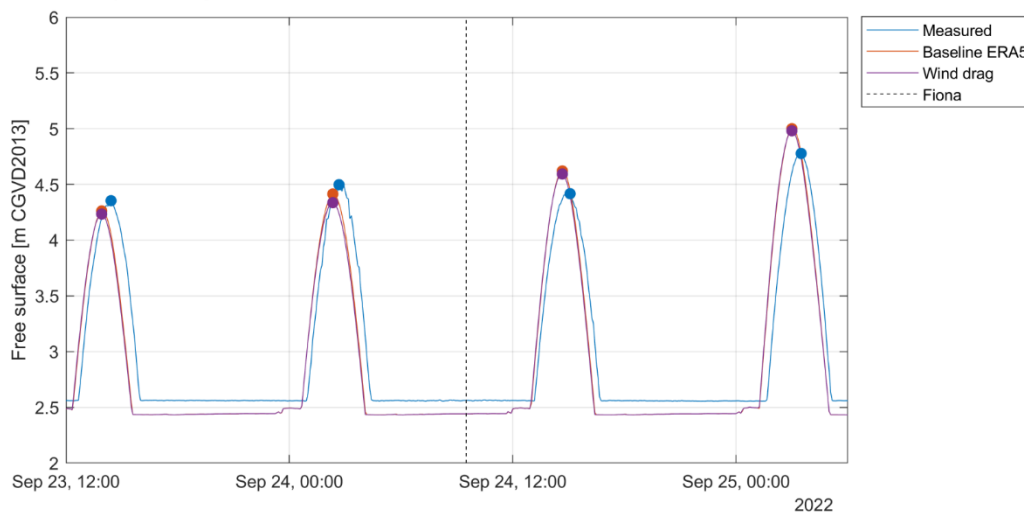


Figure 4.11. Time series (UTC) of water level data (Saint Mary's University) and numerical model results at Wood Point, a) time period September 15th to September 29th 2022; b) time period September 23rd 12:00 UTC to September 26th 6:00 UTC 2022. The dots indicate high water level and the dashed line indicated the timing of the peak of storm Fiona, based on peak wind speed in the Cumberland Basin Offshore (Location 1, Table 4.2).

4.5. ERA5 Sensitivity

Due to its relatively coarse resolution, ERA5 has a tendency to underpredict peak wind speeds during storms, as evidenced in this study by comparisons with local meteorological data (Section 3.2). A sensitivity analysis using ERA5 forcing in TELEMAC-2D was conducted to assess modelling uncertainty and identify the most suitable setup for capturing accurate results during extreme events. For further analysis, measured meteorological data from Aulac, the closest station to the study area, were used as a reference due to the station's proximity to the area of interest. Several variations of numerical input are assessed to determine the model's sensitivity:

- **Delta bias correction - increased ERA5 wind speeds by 25%**

Wind speeds across the model domain were adjusted (increased) by 25% to better capture storm peak wind speeds (i.e. “delta” bias correction method). This bias correction was based on the observation that the peak measured wind speed of post-tropical storm Fiona at Aulac was 19.6 m/s, compared to 15.9 m/s in the ERA5 data, corresponding to a 25% underprediction by ERA5 (Section 3.2). While the delta bias correction method also results in increases in wind speeds during relatively calm (i.e. non-storm) conditions, the influence on resulting water levels is minimal during these periods.

- **Quantile-Quantile Bias Correction of ERA5 data based on the local meteorological station data.**

These analyses involved two steps. First, wind speed measurements at Aulac were adjusted from 3 m to 10 m elevation to enable a consistent comparison with 10 m elevation ERA5 wind velocity data, following the method provided in the US Army Corps of Engineers (2002). Second, ERA5 wind speeds were bias-corrected based on the elevation-adjusted Aulac data, using the quantile-quantile method (Figure 3.18) (Maraun, 2013), which in this case resulted in higher wind speeds receiving a larger adjustment (Figure 4.12). These bias corrections, developed based on comparisons at Aulac, were uniformly applied to ERA5 wind fields across the model domain. The influence of dataset length on bias correction was assessed by comparing corrected factors derived from a comparison of the full meteorological station dataset (2021-2022) with those from the period specifically around post-tropical storm Fiona (September 10th to October 1st 2022). Minimal differences were observed and therefore only the Fiona-specific dataset is presented here.

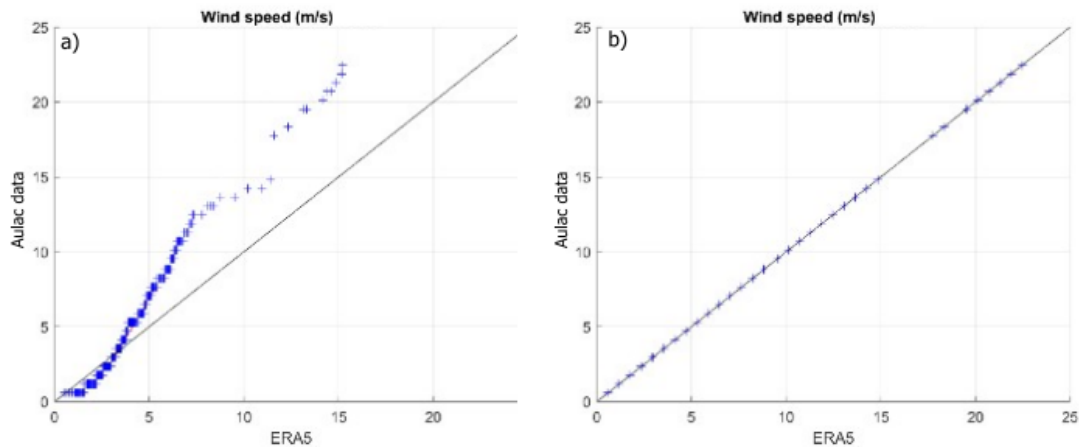


Figure 4.12. a) qq-plot of wind speed from meteorological station at Aulac and ERA5 data; b) qq-plot of wind speed data after bias correction.

The numerical model results were compared with water level measurements at Saint John and Wood Point (Table 2.3, Figure 2.10). Figure 4.13 and Figure 4.14 show the comparison between measured water levels and numerical model results for Saint John and Wood Point, respectively. Table 4.5 provides an overview of the RMSE between the water level measurements and the numerical model results, with a focus on the peaks of the water level as these are critical for determining if free surface elevations would exceed the

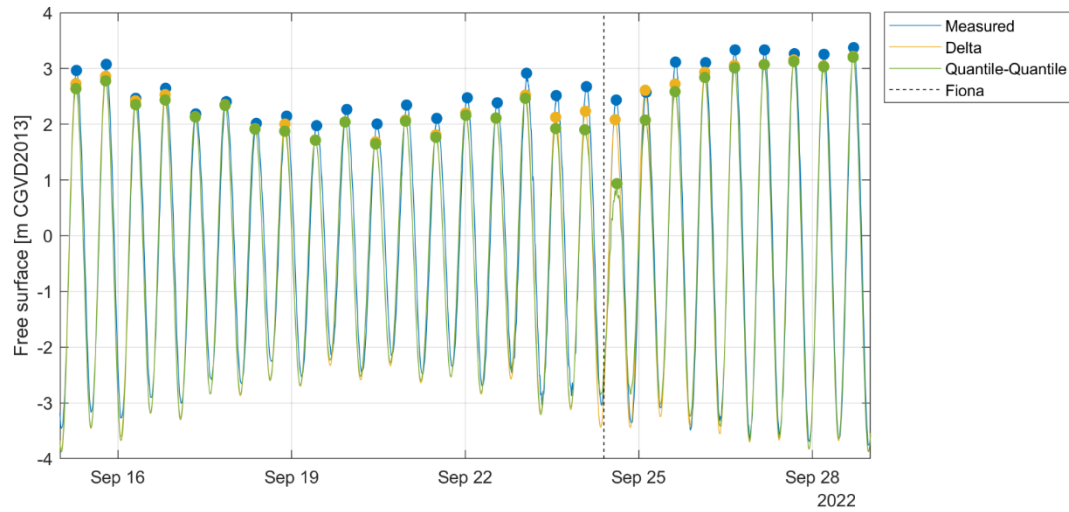
crest elevations of the dykes, resulting in seawater flowing over the top of the dykes on the Chignecto Isthmus.

At both Saint John and Wood Point, the RMSE between the measurements and the numerical model results is lower with the delta bias correction than with the quantile – quantile bias correction. However, when these results are compared with the Baseline ERA5 data (4.4.3), the RMSE for the corrected ERA5 conditions, whether using the delta or quantile-quantile bias correction, is higher than that of the uncorrected baseline ERA5. Therefore, the baseline (unaltered) ERA5 data provide the most comparable model results to the available dataset and are selected as the most suitable option for this study.

Table 4.5. Sensitivity analysis RMSE results of the peak free surface at Saint John and Wood Point for the various numerical inputs over the time period September 15th to September 29th 2022.

Numerical input	RMSE peak free surface	
	Saint John [m]	Wood Point [m]
Delta bias correction	0.25	0.16
Quantile – Quantile bias correction	0.43	0.38

a) Time series of water level data and numerical model results



b) Time series specifically around Fiona of water level data and numerical model results

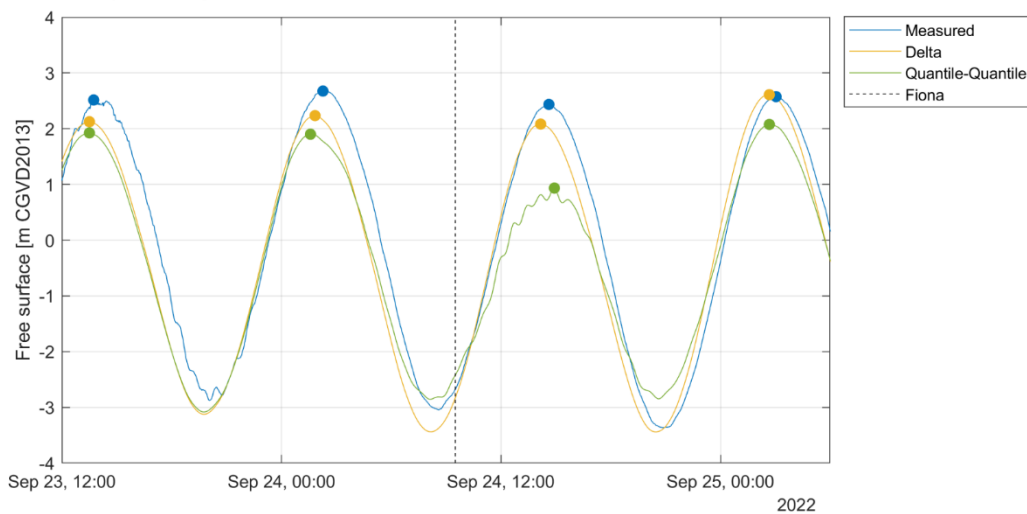
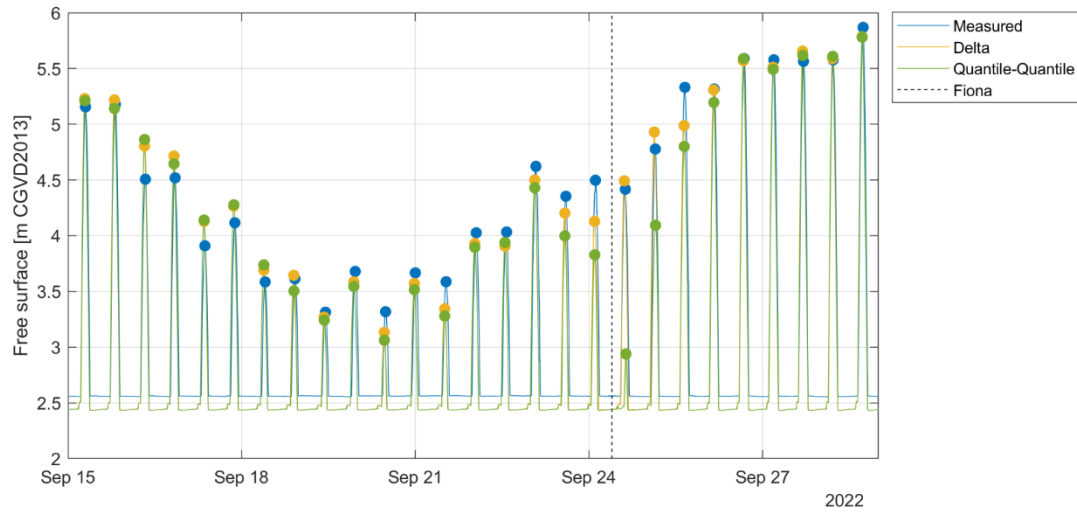


Figure 4.13. Time series (UTC) of water level data (Fisheries and Oceans Canada, 2024) and numerical model results at Saint John, a) time period September 15th to September 29th 2022; b) time period September 23rd 12:00 UTC to September 26th 6:00 UTC 2022. The dots indicate high water level and the dashed line indicate the approximate timing of the peak of storm Fiona, based on peak wind speed in the Cumberland Basin Offshore (Location 1, Table 4.2).

a) Time series of water level data and numerical model results



b) Time series specifically around Fiona of water level data and numerical model results

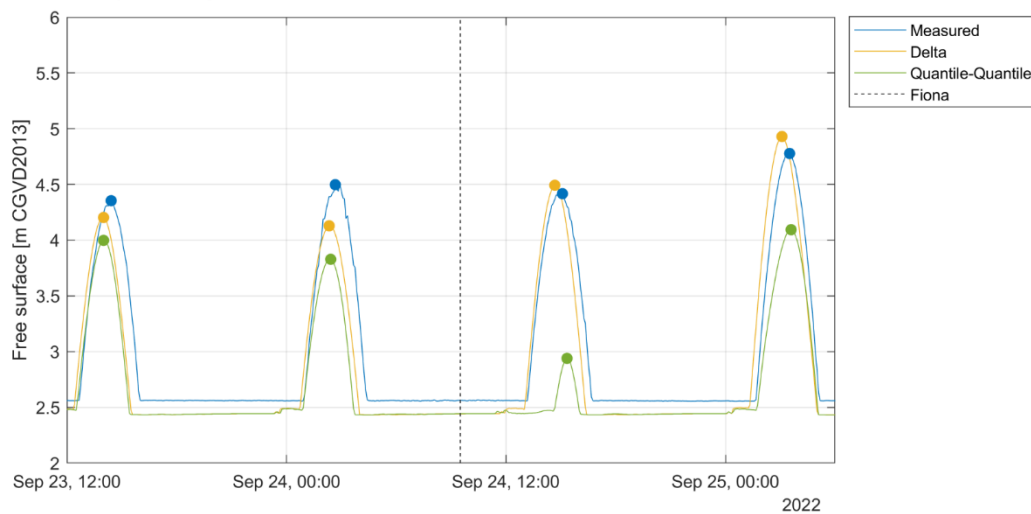


Figure 4.14. Time series (UTC) of water level data (Saint Mary's University) and numerical model results at Wood Point, a) time period September 15th to September 29th 2022; b) time period September 23rd 12:00 UTC to September 26th 6:00 UTC 2022. The dots indicate high water level and the dashed line indicate the approximate timing of the peak of storm Fiona, based on peak wind speed in the Cumberland Basin Offshore (Location 1, Table 4.2).

5. Results and Discussion

For a detailed description of the scenario selections and definitions refer to Section 4.3. For point-source locations 1 through 6 described here, see Table 4.2 and Figure 4.4.

5.1. Scenario 1 - Post-Tropical Storm Fiona

Figure 5.1 shows the extracted free surface level at location 1 (Cumberland Basin Offshore) for the period from September 15th to September 29th 2022, during the post-tropical storm Fiona. Additionally, Figure 5.2 shows snapshots of the results at the timing of maximum wind speed at location 1, on September 24th 2022 09:30 UTC, for both scenario 1A (tides-only) and 1B (tides + surges) and six locations identified in Table 4.2 and Figure 4.4. These maps include water depth results to illustrate the extent of water in the area. Figure 5.3 shows the extracted free surface elevations at the six locations, in comparison to the low and high dyke elevations (Section 4.3.3), with a focus on the period of maximum wind speed on September 24th. The increase in water levels shown in Figure 5.3 represents the difference in free surface elevation between Scenario 1B minus Scenario 1A at high tide ahead of maximum wind speeds reached during post-tropical storm Fiona, which occurred around 3:00 UTC on September 24th.

The results indicate that the storm surge resulting from the passage of post-tropical storm Fiona in the Cumberland Basin has a relatively minor effect on the water level, which is primarily dominated by the astronomical tide. This is evident from the plots showing that Scenarios 1A and 1B yield nearly identical results (Figure 5.2). The extracted free surface elevations in Figure 5.3 show a reduction in free surface elevation at high tide, ahead of maximum wind speeds, ranging from -0.28 m at location 2, Tantramar River, to -0.34 m at location 3, Aulac River, caused by the passage of the storm. At the time of maximum wind speeds, September 24th 2022 09:30 UTC, locations 3 through 6, further inland, remain unaffected, as they are not inundated during low tide. At location 1, an increase of +0.15 m in free surface elevation was observed at maximum wind speed. However, this occurred approximately 30 minutes after astronomical low tide, when the free surface elevation was approximately -4.9 m CGVD 2013. Therefore, the free surface elevation in Scenario 1B did not exceed maximum water levels produced by the astronomical tides. In addition, the maximum water levels did not exceed local dyke crest elevations (+7.2 – +8.8 m CGVD 2013). This underscores the importance of the timing of storm surges relative to astronomical tides in determining the potential for flooding.

Post-tropical storm Fiona made landfall in eastern Nova Scotia near Cape Breton and resulted in northwesterly winds over the Cumberland Basin (Section 3.1.5). Moreover, the maximum wind speed in the Cumberland Basin (15.8 m/s) was significantly lower than the wind speed passing over Cape Breton (30.0 m/s). For a storm surge to substantially affect water levels in the Chignecto Isthmus, winds generated from the southwest, along the longest open-water fetch from the Bay of Fundy are required. In the case of post-tropical storm Fiona, the wind direction was not well enough aligned with the longer fetch to generate a significant positive storm surge at the Chignecto Isthmus. Consequently, the offshore winds associated with Fiona did not lead to a notable increase in water levels. Additionally, the maximum positive storm surge associated with the passage of Fiona occurred just after low tide (Figure 5.3), so even with a southwesterly wind, the storm surge would have had a limited impact on the water levels.

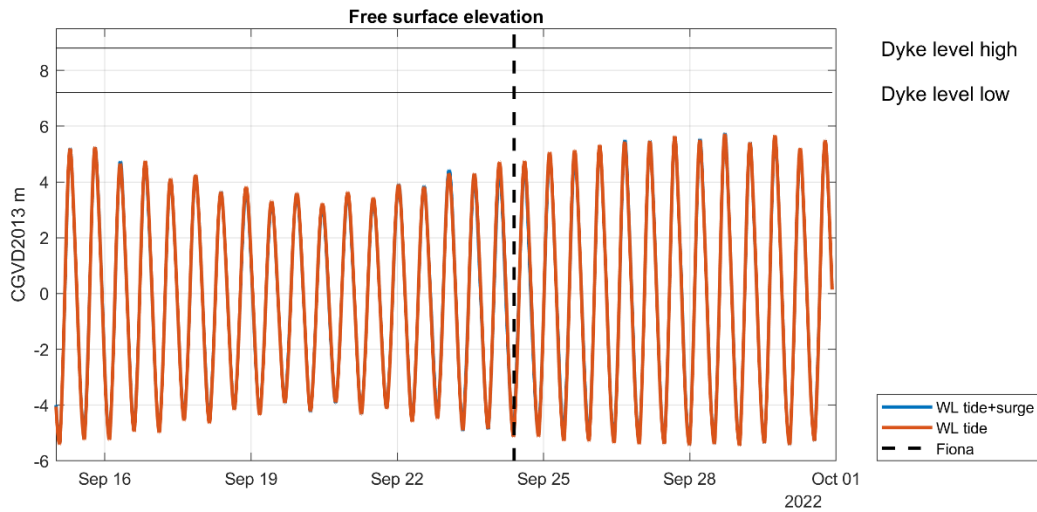


Figure 5.1. Time series of simulated free surface elevations at location 1 (Table 4.2 and Figure 4.4) during Scenario 1 – Fiona (baseline year sea level). The dashed line indicates the ERA5 maximum wind speed at location 1. The blue line represents model results of Scenario 1B (tides + surges), while the orange line represents Scenario 1A (tides-only). Horizontal black lines indicate the high and low dyke elevations (+7.2 – +8.8 m CGVD2013) as discussed in Section 4.3.3.

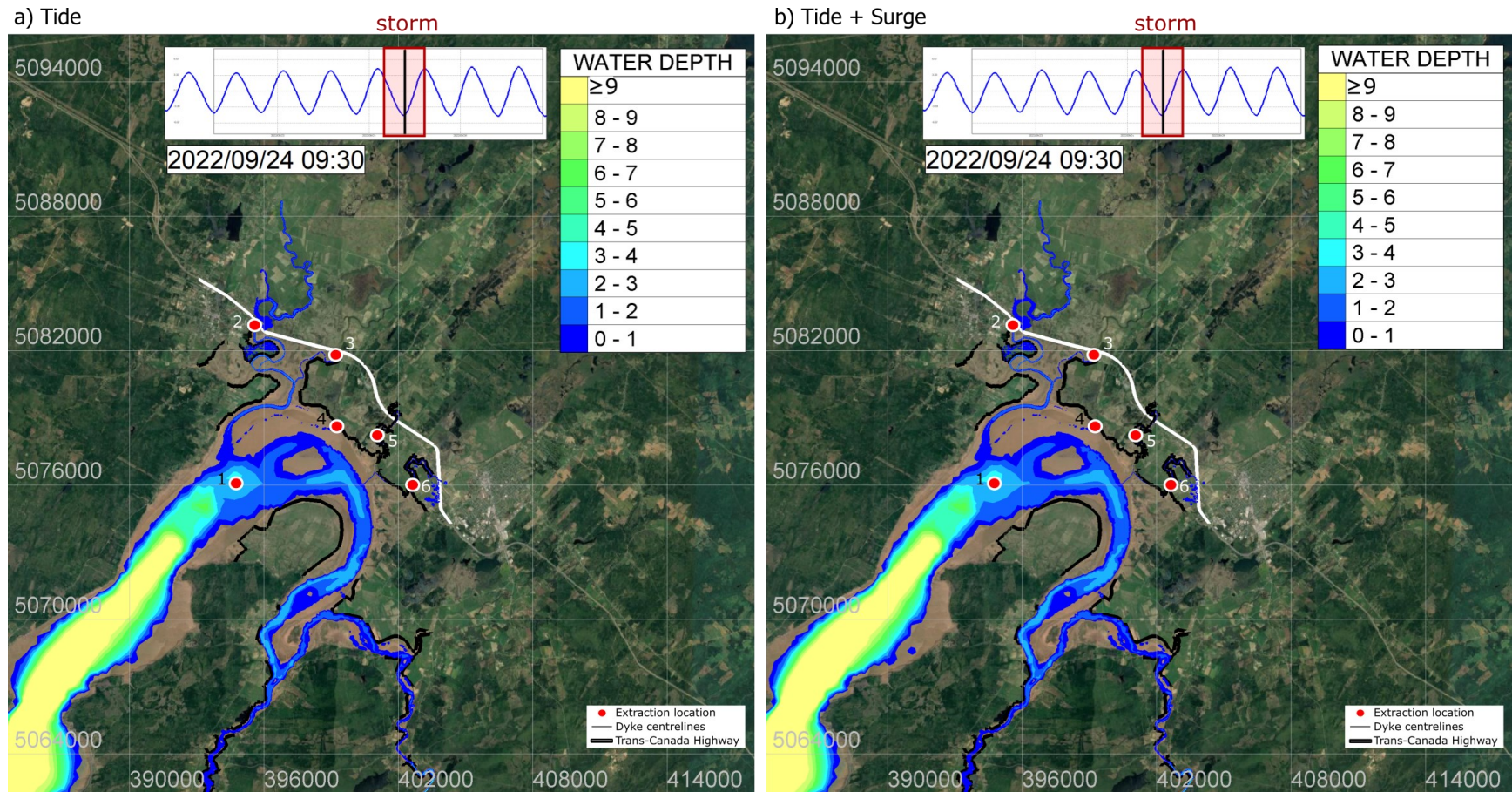


Figure 5.2. Snapshot of simulated water depth (m) for Scenario 1 (baseline year sea level) based on ERA5 maximum wind speed at location 1 (September 24th 2022 09:30 UTC) for a) Scenario 1A (tides-only) and b) Scenario 1B (tides + surges). The maps are overlaid with six identified locations for extraction of free surface elevation (Table 4.2): 1 - Cumberland Basin Offshore, 2 - Tantramar River, 3 - Aulac River, 4 - Cumberland Basin Nearshore, 5 - Missaguash River, and 6 - LaPlanche River.

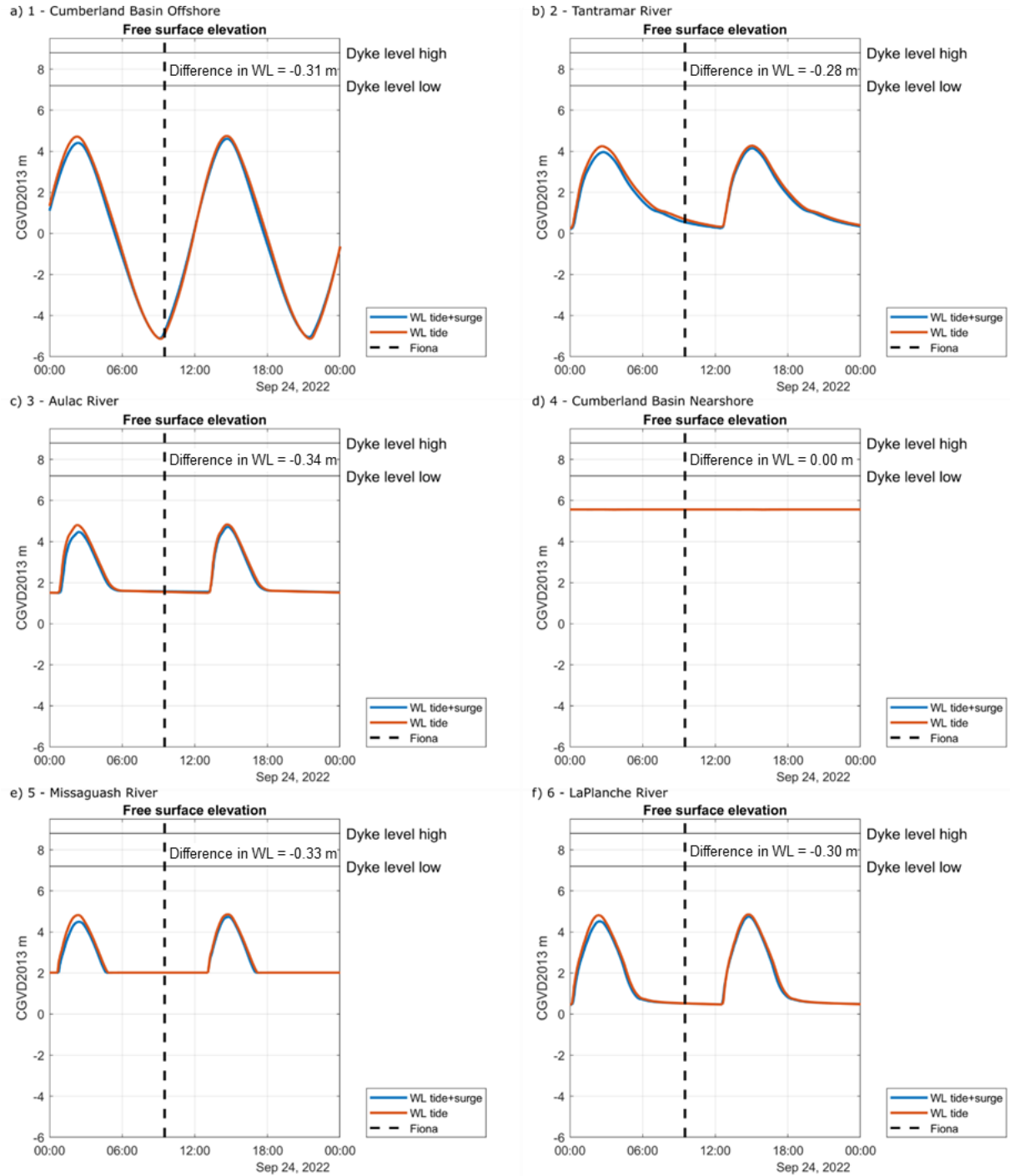


Figure 5.3. Model extraction of Scenario 1 – Fiona (baseline year sea level) of free surface at six locations (shown in Table 4.2) at a) 1 - Cumberland Basin Offshore, b) 2 - Tantramar River, c) 3 - Aulac River, d) 4 - Cumberland Basin Nearshore, e) 5 - Missaguash River and f) 6 - LaPlanche River. The dashed line indicates the time of ERA5 maximum wind speed at location 1 on September 24th 2022 09:30 UTC. The blue line represents model results of Scenario 1B (tides + surges), while the orange line represents Scenario 1A (tides-only). Horizontal black lines indicate the high and low dyke elevations (+7.2 – +8.8 m CGVD2013) as discussed in Section 4.3.3. The difference in water level represents the negative storm surge (decrease in water level), calculated as Scenario 1B (tides + surges) minus Scenario 1A (tides-only) during high tide, which occurred around 03:00 on September 24, ahead of the maximum wind speed.

5.2. Scenario 2 – Groundhog Day Storm-Type with SLR 2033

Figure 5.4 shows the extracted free surface water elevations at location 1 (Cumberland Basin Offshore) for the hypothetical scenario using the Groundhog Day storm that occurs during a peak tidal range of the lunar nodal cycle with a relative SLR of year 2033 (Scenario 2). This peak occurs during the simulated period from September 23rd to October 10th 2033. Additionally, Figure 5.5 shows snapshots of the results at peak tide 2033 on October 10th 2033 17:00 UTC, for both Scenario 2A (tides-only) and 2B (tides + surges). Figure 5.6 presents snapshots of the results after peak tide 2033 on October 11th 2033 04:00 UTC, for both Scenario 2A and Scenario 2B. These maps include water depth results to illustrate the extent of water in the area. Figure 5.7 shows extracted free surface levels at the six locations identified in Table 4.2 and Figure 4.4 in comparison to the low and high dyke elevations (Section 4.3.3), focusing on the period encompassing peak tide 2033 on October 10th. The increase in water levels shown in the figure represents the difference in free surface elevation between Scenario 2B minus Scenario 2A at peak tide 2033, which for the simulated event occurs at approximately 17:00 UTC on October 10th.

Scenario 2A results indicate that in the absence of a storm, the water level remains below the low dyke elevations (Figure 5.7). However, the resulting map at high tide indicates that water can be found behind the dykes (Figure 5.5a). This water tends to travel around the existing dykes. At Tantramar River (location 2), the water reaches up to the Trans-Canada Highway and then flows east along the northern part of the dyke. At LaPlanche River (location 6), the water moves southward around the dyke at the most eastern point (Figure 5.5a). Since drainage is not included in the model (Section 2.1) water found landward of the dykes remains in the area.

The map of Scenario 2B, where the Groundhog Day storm-type is simulated, indicates that the maximum water level exceeds the crest elevations of the dykes, resulting in seawater flowing over the top of the dykes and a larger area of inundation (Figure 5.5b). The dyke height varies across the Chignecto Isthmus, and in this scenario, parts of the crest elevations are below free surface elevations resulting in overflowing of the dyke crests. Owing to the relatively flat terrain behind the dykes, the water spreads over a large area, as shown in Figure 5.6b, which illustrates the results for the hypothetical scenario occurring on October 11th 2033 04:00 UTC. This time is after the peak tide 2033, when the water has overflowed the dykes and spread out.

In the offshore region in the Cumberland Basin (location 1), the Groundhog Day storm-type results in a +1.17 m increase in water level (storm surge) above the astronomical tide (Figure 5.7a). Nearer to the shore, at location 4 (Figure 5.7d), the positive storm surge (increase in water level) reaches +1.22 m. Once the storm surge starts propagating up the shallower waters into the rivers, it dissipates, ranging between +0.70 m at Aulac River (location 3, Figure 5.7c) and +1.08 m at LaPlanche River (location 6, Figure 5.7e). These free surface elevation time series results indicate that the maximum water levels during a storm like the Groundhog Day storm-type occurring at the peak of the lunar nodal cycle with SLR of +0.08 m would exceed the lowest dyke crest elevations on the Chignecto Isthmus (+7.2 m CGVD 2013), resulting in direct inundation (flooding) of areas landward of the dykes.

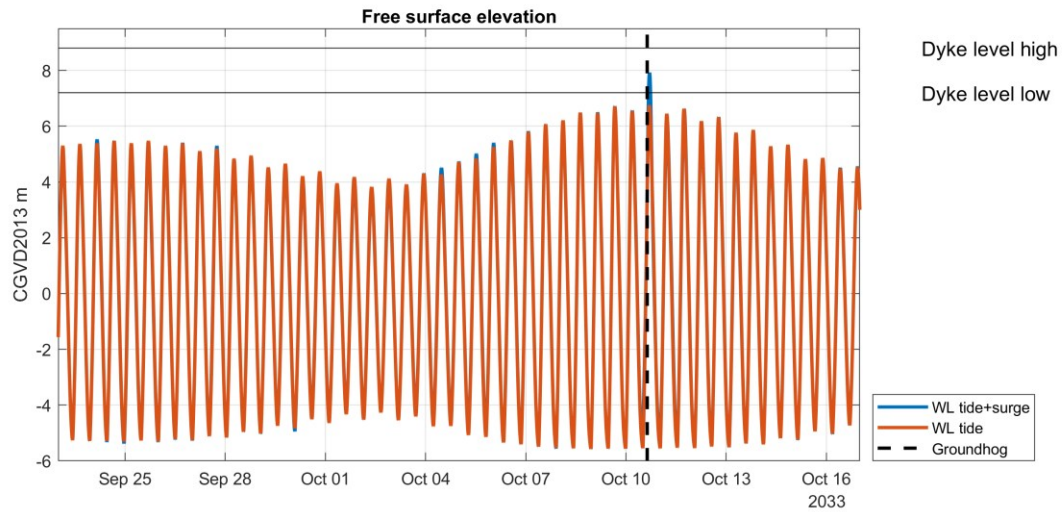


Figure 5.4. Time series of simulated free surface elevations at location 1 (Table 4.2 and Figure 4.4) during Scenario 2 – Groundhog Day storm-type with peak tide 2033. The dashed line indicates the ERA5 maximum wind speed at location 1. The blue line represents model results of Scenario 2B (tides + surges), while the orange line represents Scenario 2A (tides-only). Horizontal black lines indicate the high and low dyke elevations (+7.2 – +8.8 m CGVD2013) as discussed in Section 4.3.3.

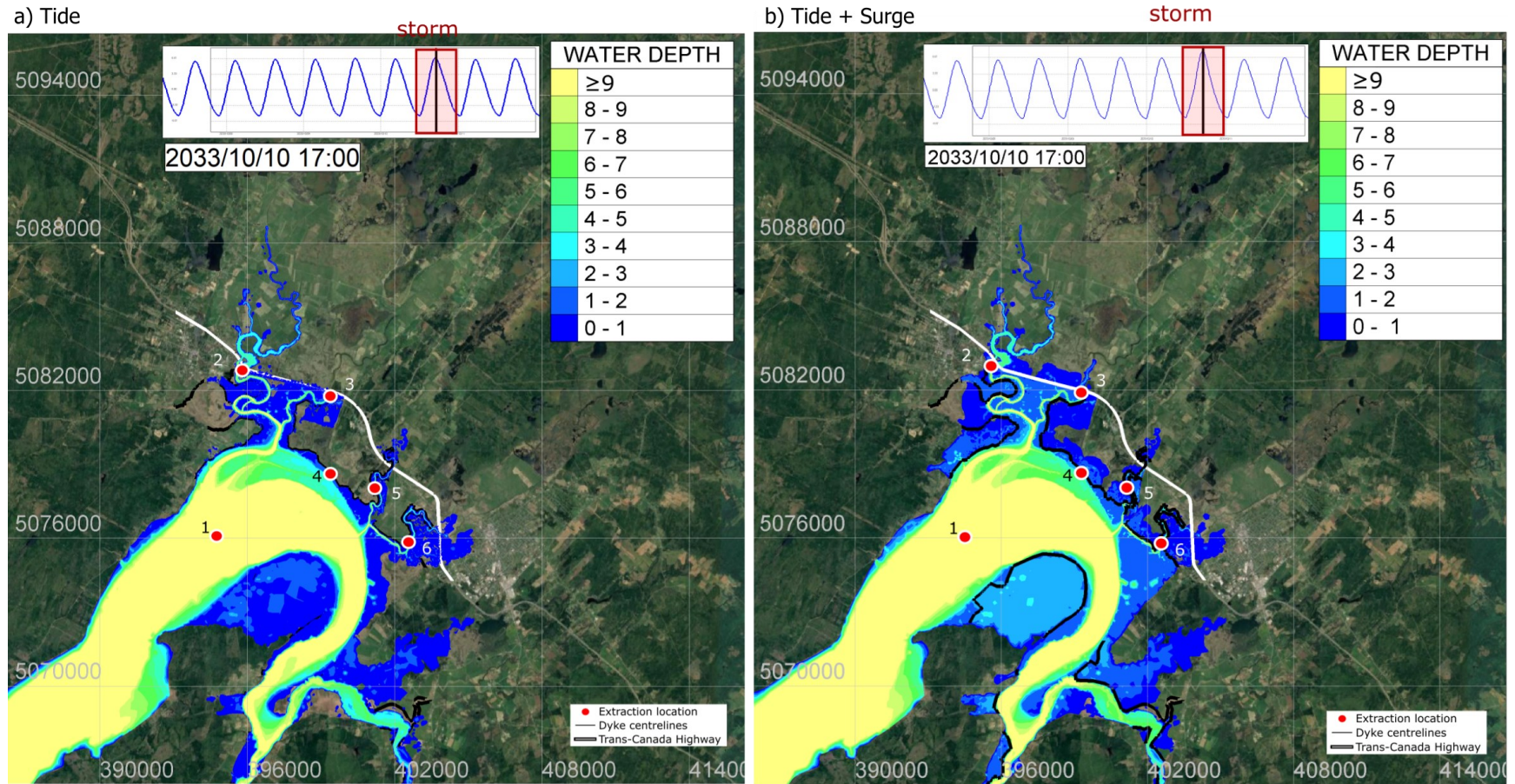


Figure 5.5. Snapshot of simulated water depth (m) for Scenario 2 – Groundhog Day storm-type at peak tide 2033 (October 10th 2033 17:00 UTC) for a) Scenario 2A (tides-only) and b) Scenario 2B (tides + surges). The maps are overlaid with six identified locations for extraction of free surface elevation (Table 4.2): 1 - Cumberland Basin Offshore, 2 - Tantramar River, 3 - Aulac River, 4 - Cumberland Basin Nearshore, 5 - Missaguash River, and 6 - LaPlanche River.

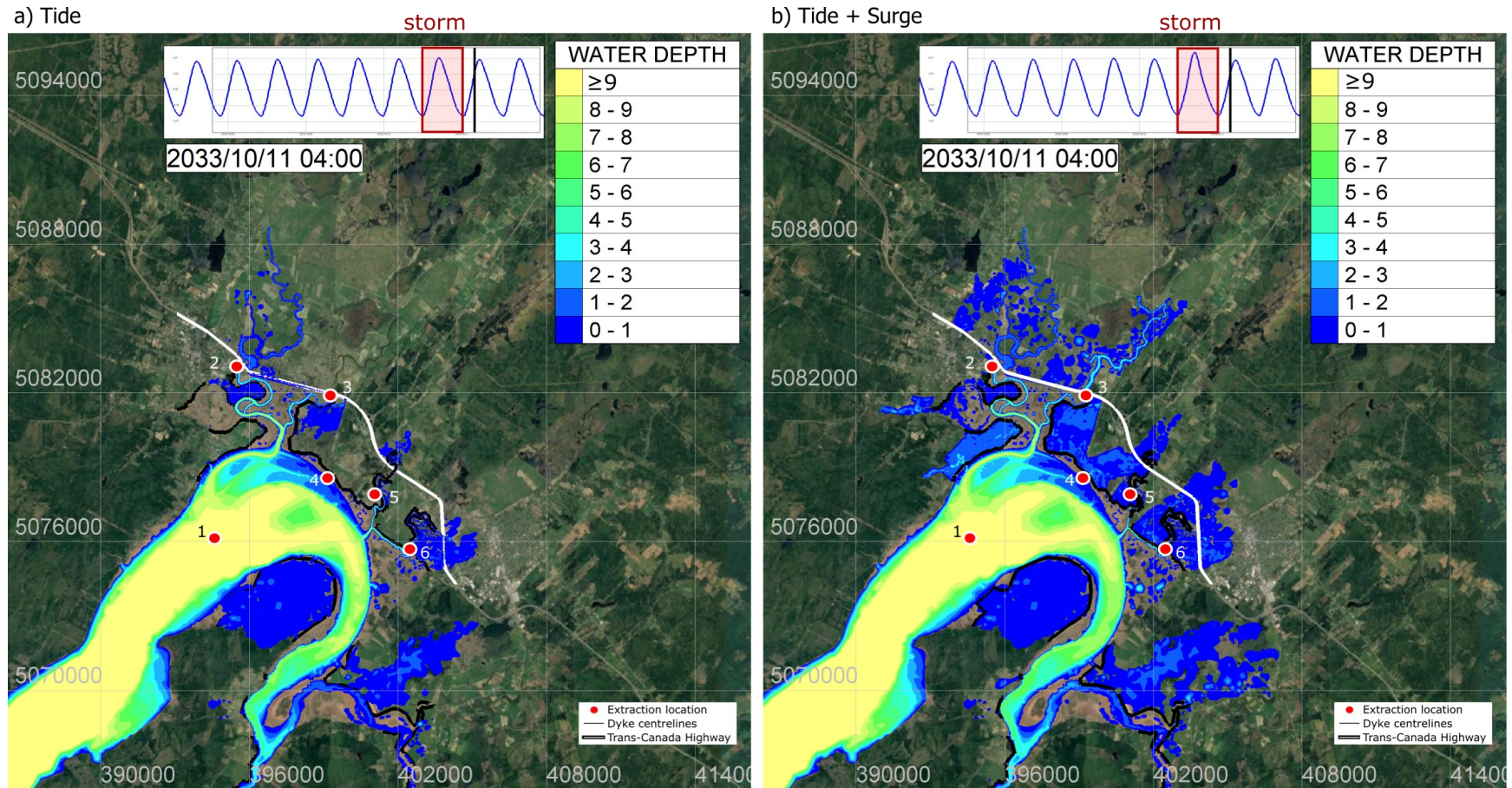


Figure 5.6. Snapshot of simulated water depth (m) for Scenario 2 – Groundhog Day storm-type at peak tide 2033 (October 11th 2033 04:00 UTC) for a) Scenario 2A (tides-only); b) Scenario 2B (tides + surges). The maps are overlaid with six identified locations for extraction of free surface elevation (Table 4.2): 1 - Cumberland Basin Offshore, 2 - Tantramar River, 3 - Aulac River, 4 - Cumberland Basin Nearshore, 5 - Missaguash River, and 6 - LaPlanche River.

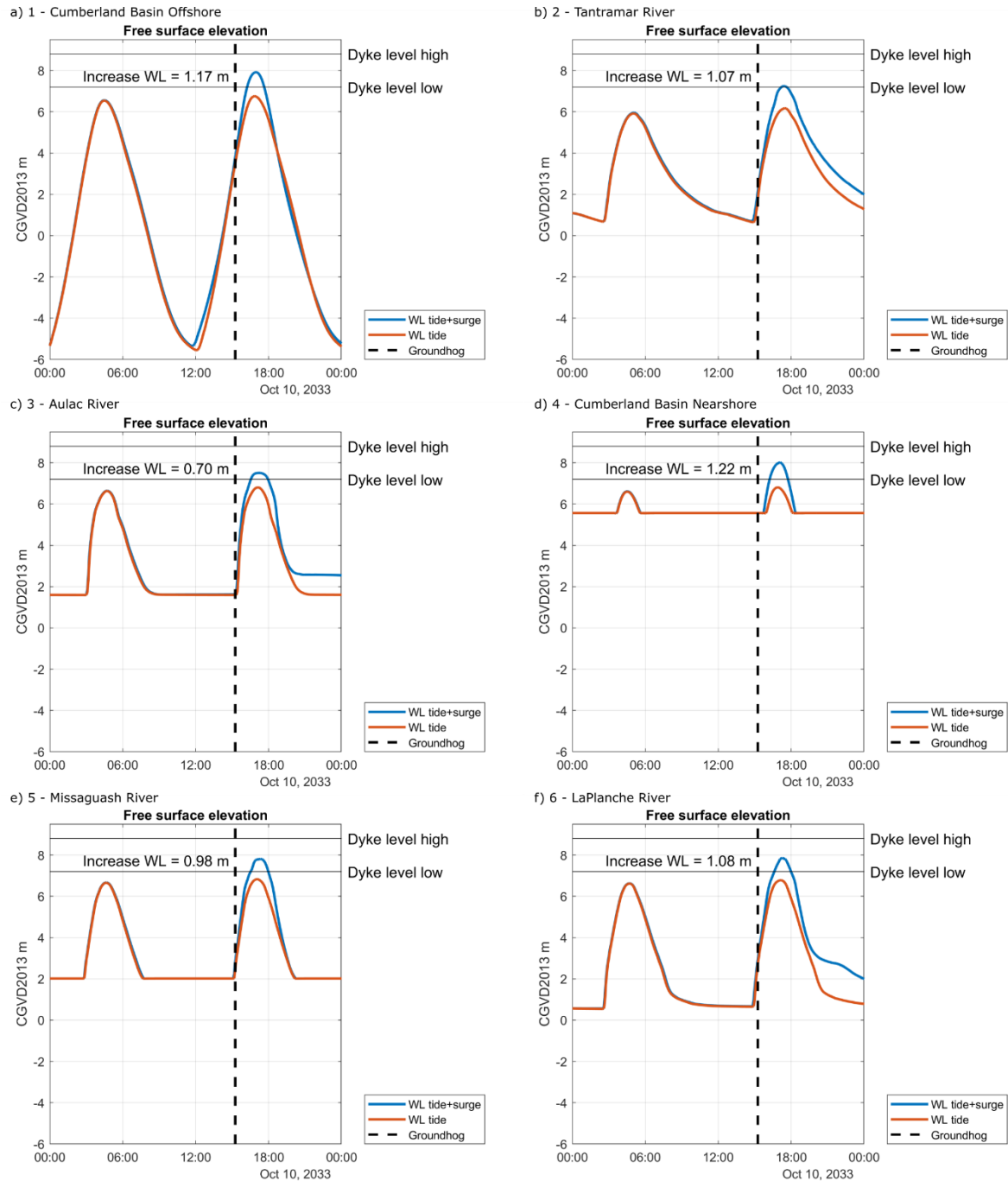


Figure 5.7. Model extraction of Scenario 2 – Groundhog Day storm-type with peak tide 2033, of free surface at six locations (Table 4.2Figure 4.4) at a) 1 - Cumberland Basin Offshore, b) 2 - Tantramar R., c) 3 - Aulac R., d) 4 - Cumberland Basin Nearshore, e) 5 - Missaguash R. and f) 6 - LaPlanche R. The dashed line indicates the ERA5 maximum wind speed at location 1. The blue line represents model results of Scenario 2B (tides + surges), while the orange line represents Scenario 2A (tides-only). Horizontal black lines indicate the high and low dyke elevations (+7.2 – +8.8 m CGVD2013) as discussed in Section 4.3.3. The increase in water level represents the difference between Scenario 2B (tides + surges) minus Scenario 2A (tides-only) at high tide after the maximum wind speed of the Groundhog Day storm-type, which (in the simulation) occurred around 17:00 UTC on October 10th.

5.3. Scenario 3 – Groundhog Day Storm-Type with SLR 2100

Figure 5.8 shows the extracted free surface elevation at location 1 (Cumberland Basin Offshore) for the hypothetical scenario using the Groundhog Day storm that occurs during a peak tidal range of the lunar nodal cycle with a relative SLR of year 2100 (Scenario 3). This peak occurs during the simulated period from September 23rd to October 10th 2033. Additionally, Figure 5.9 shows snapshots of the results at peak tide 2033 on October 10th 2033 17:00 (UTC) with projected relative SLR for year 2100, for both Scenario 3A (tides-only) and Scenario 3B (tides + surges). Figure 5.10 presents snapshots of the results after peak tide 2033 on October 11th 04:00 (UTC), for both Scenarios 3A and 3B. These maps include water depth results to illustrate the extent of water in the area. Figure 5.11 shows the extracted free surface levels at the six locations identified in Table 4.2 and Figure 4.4, in comparison to the low and high dyke elevations (Section 4.3.3), with a focus on the period around peak tide 2033 on October 10th. The increase in water levels shown in the figure represents the difference in free surface elevation between Scenario 3B minus Scenario 3A at the peak tide 2033, which for the simulated event occurs at approximately 17:00 on October 10th.

Scenario 3A results indicate that, in the absence of a storm, water levels at various locations already reach or exceed low dyke elevation, resulting in a larger area of inundation compared to other scenarios. This is evident in the map at high tide (Figure 5.9a), where water can be identified over a large area behind the dykes. Similar to scenario 2, water tends to travel around existing dykes. At Tantram River (location 2), water reaches up to the Trans-Canada Highway and then flows east along the northern part of the dyke. At LaPlanche River (location 6), water moves southward around the dyke at the easternmost point. In Scenario 3, the water levels are higher compared to Scenario 2. Consequently, water flows around the dykes and covers a larger area, especially because the terrain landward of the dykes is relatively flat. Graphs of Figure 5.11 indicate that peak water levels in many locations, during the tide-only event, are at the cusp of, if not overpassing, the existing low dyke elevations.

Scenario 3B, where the Groundhog Day storm-type is simulated, results in increased water levels compared with Scenario 3A and consequently larger volumes of water are able to flow over the top of the dykes, resulting in a larger area of inundation (Figure 5.9b). While the peak water level does not reach the highest dyke elevations (as evident in Figure 5.11), it exceeds the top of lower dyke elevations in various areas. The relatively flat terrain landward of the dykes allows the water to spread over a large area, as shown in Figure 5.10b. This figure shows the conditions on October 11th 2033 04:00 UTC, a time after peak tide 2033, when the water levels exceed the highest dyke elevations.

Offshore in the Cumberland Basin (location 1), the Groundhog Day storm-type results in a +1.11 m increase in water level (storm surge) above the astronomical tide (Figure 5.11a). Nearer to the shore, at location 4 (Figure 5.11d), the positive storm surge (increase in water level) reaches +1.14 m. As the storm surge propagates up the shallower waters into the rivers, it dissipates, ranging between +0.80 m at location 3, Aulac River (Figure 5.11c) and +1.09 m at location 5, Missaguash River (Figure 5.11e). These free surface elevations suggest that during a storm similar to the Groundhog Day storm-type, occurring at the peak of the lunar nodal cycle with a relative SLR of +0.63 meters, maximum water levels surpass low dyke elevations resulting in flooding landward of the dykes.

Although the absolute water levels in Scenario 3 are higher than in Scenario 2, the relative increase in the water level between Scenarios A and B is smaller for Scenario 3. The increased relative SLR leads to higher

total water levels causing more frequent dyke elevation exceedances. Free surface elevations surpass the crest elevations of lower dykes during high tides, even before the peak tide of 2033 is reached. Consequently, water spreads over a larger area and thus the relative increase in water level compared to the tides-only scenario is reduced compared to Scenario 2.

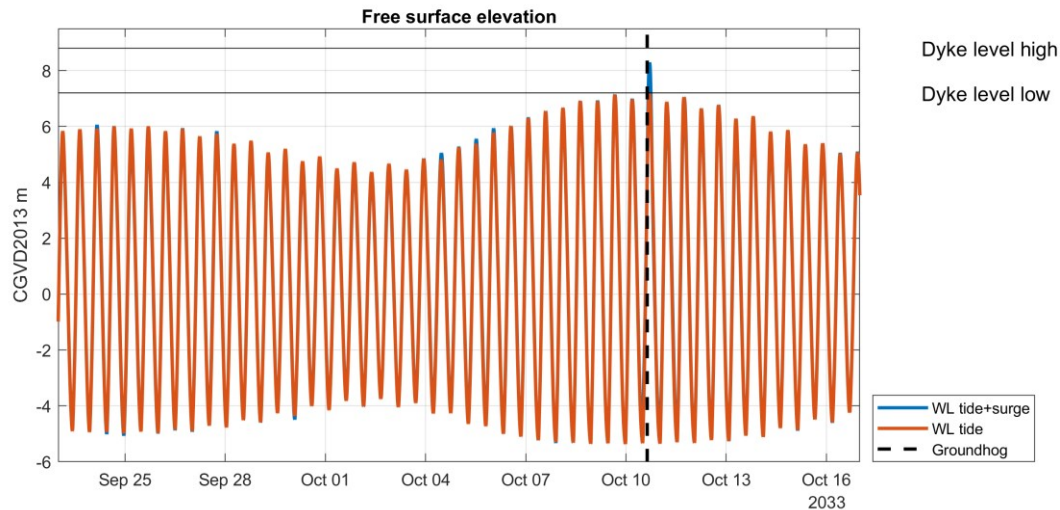


Figure 5.8. Time series of simulated free surface elevations at location 1 (Table 4.2 and Figure 4.4) during Scenario 3 – Groundhog Day storm-type with 2100 SLR. The dashed line indicates the ERA5 maximum wind speed at location 1. The blue line represents model results of Scenario 3B (tides + surges), while the orange line represents Scenario 2A (tides-only). Horizontal black lines indicate the high and low dyke elevations (+7.2 – +8.8 m CGVD2013) as discussed in Section 4.3.3.

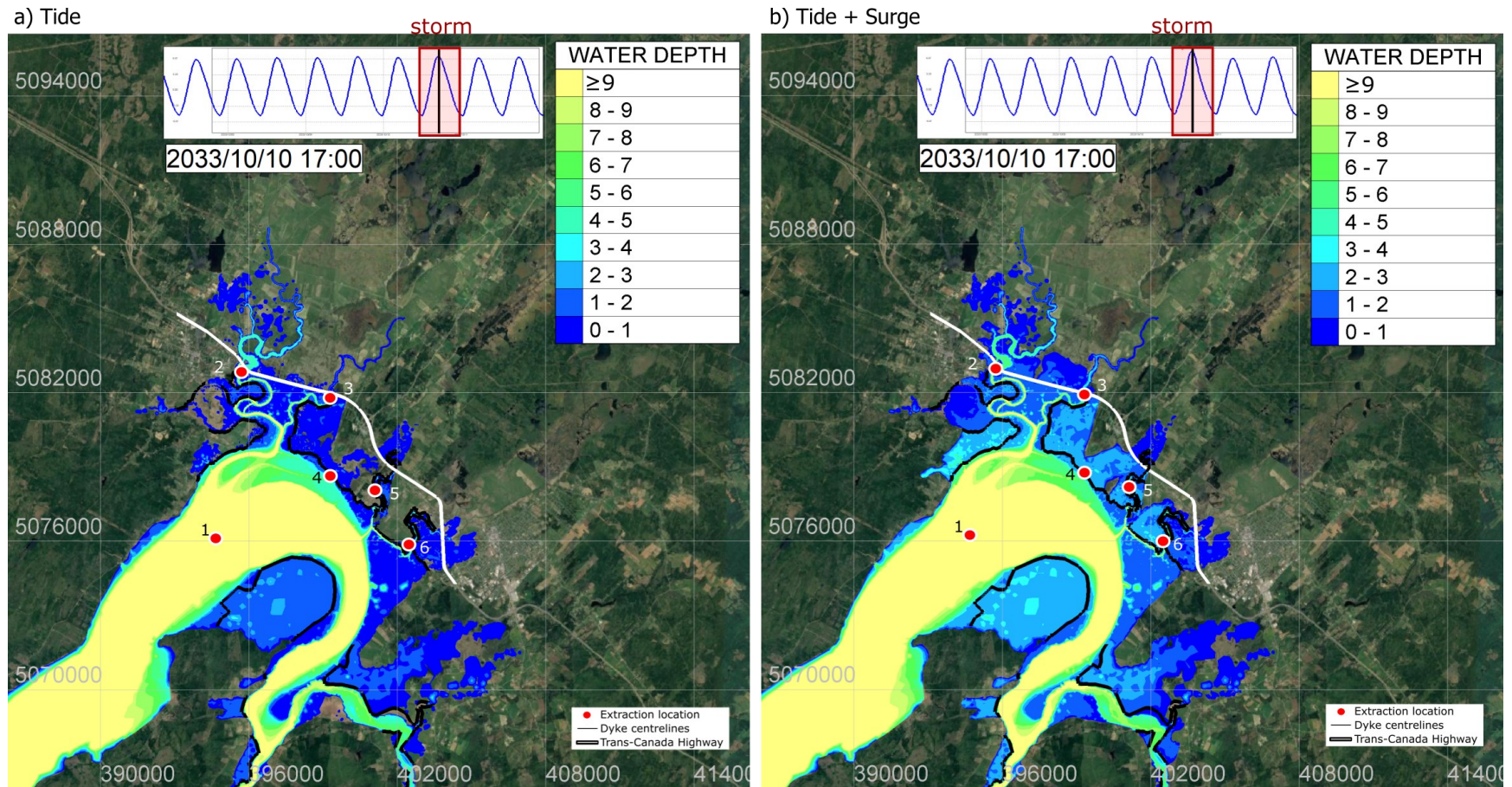


Figure 5.9. Snapshot of simulated water depths (m) for Scenario 3 – Groundhog Day storm-type with SLR2100 at peak tide 2033 (October 10th 2033 17:00 UTC) for a) Scenario 3A (tides-only); b) Scenario 3B (tides + surges). The maps are overlaid with six identified locations for extraction of free surface elevation (Table 4.2): 1 - Cumberland Basin Offshore, 2 - Tantramar River, 3 - Aulac River, 4 - Cumberland Basin Nearshore, 5 - Missaguash River, and 6 - LaPlanche River.

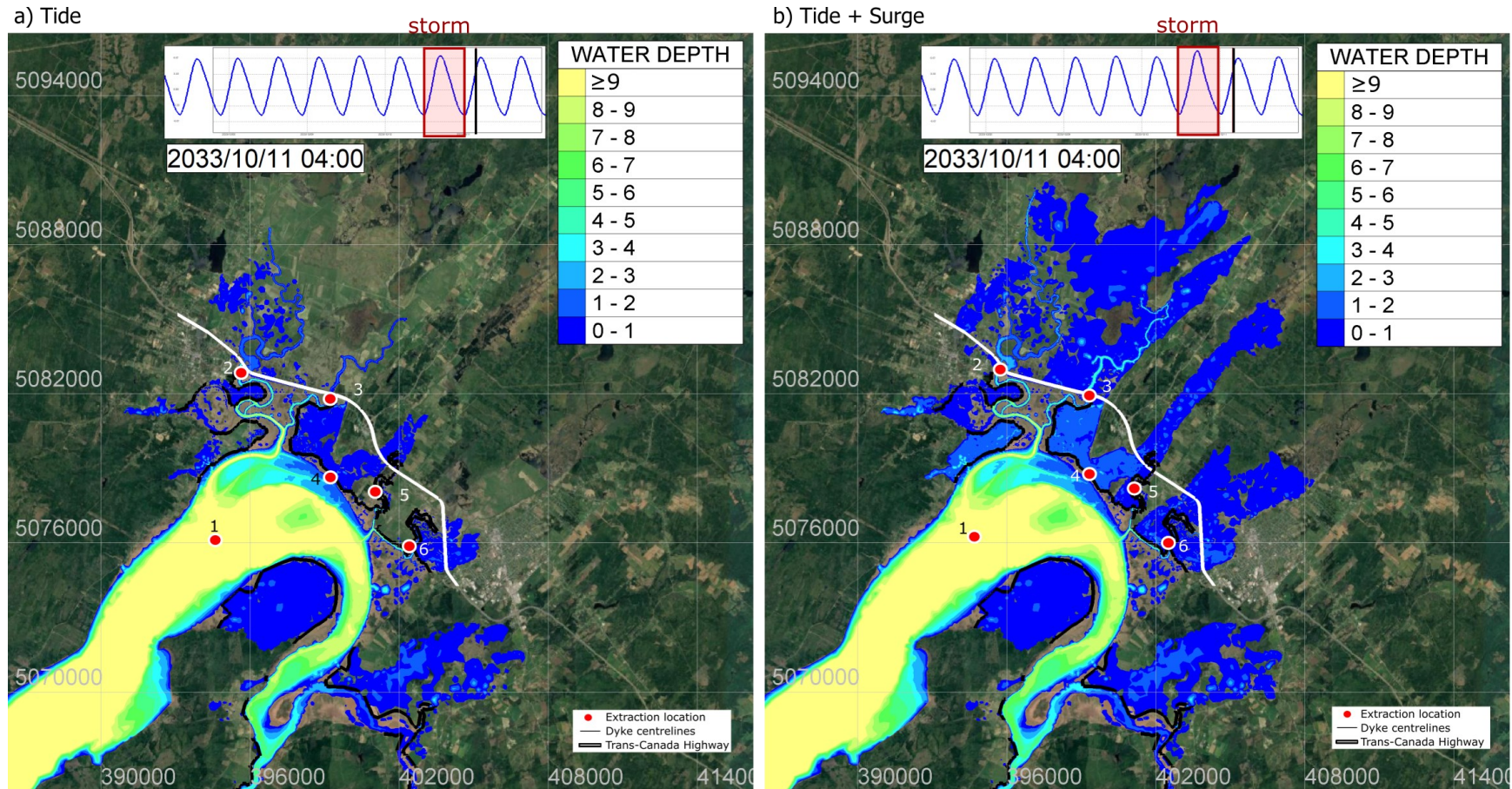


Figure 5.10. Snapshot of simulated water depth (m) for Scenario 3 – Groundhog Day storm-type with SLR2100 at peak tide 2033 (October 11th 2033 04:00 UTC) for a) Scenario 3A (tides-only) and b) Scenario 3B (tides + surges). The maps are overlaid with six identified locations for extraction of free surface elevation (Table 4.2): 1 - Cumberland Basin Offshore, 2 - Tantramar River, 3 - Aulac River, 4 - Cumberland Basin Nearshore, 5 - Missaguash River, and 6 - LaPlanche River.

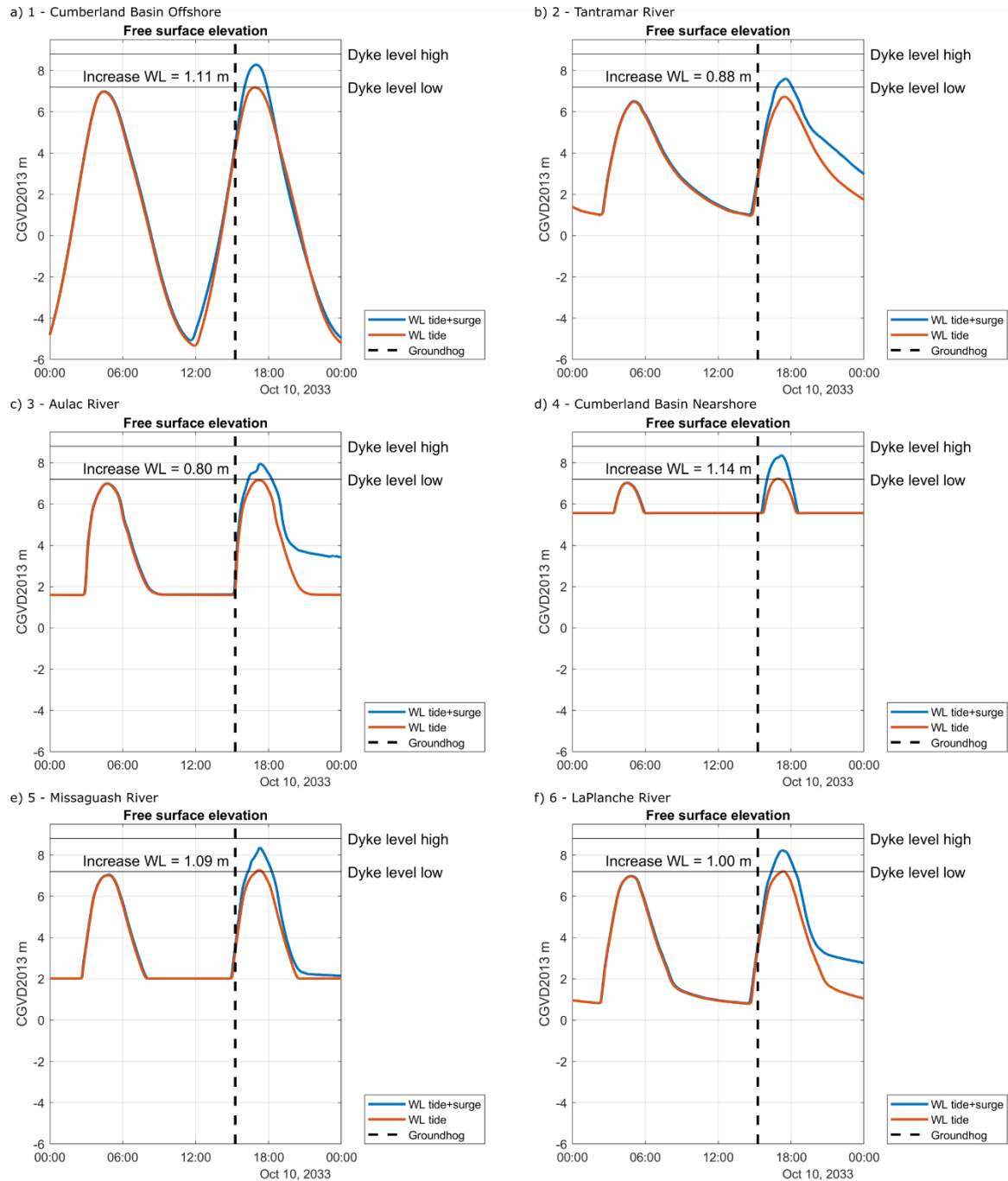


Figure 5.11. Model extraction of Scenario 3 – Groundhog Day storm-type with SLR2100 and peak tide 2033, of free surface at six locations (Table 4.2) at a) 1- Cumberland Basin Offshore, b) 2 - Tantramar R., c) 3 - Aulac R., d) 4 - Cumberland Basin Nearshore, e) 5 - Missaguash R. and f) 6 - LaPlanche R. The dashed line indicates the ERA5 maximum wind speed at location 1. The blue line represents model results of Scenario 3B (tides + surges), while the orange line represents Scenario 3A (tides-only). Horizontal black lines indicate the high and low dyke elevations (+7.2 – +8.8 m CGVD2013) as discussed in Section 4.3.3. The increase in water level represents the difference between Scenario 3B (tides + surges) minus Scenario 3A (tides-only) at high tide after the maximum wind speed of Groundhog Day storm-type, which (in the simulation) occurred around 17:00 UTC on October 10th.

5.4. Scenario 4 – Groundhog Day Storm Coinciding with Peak Tides

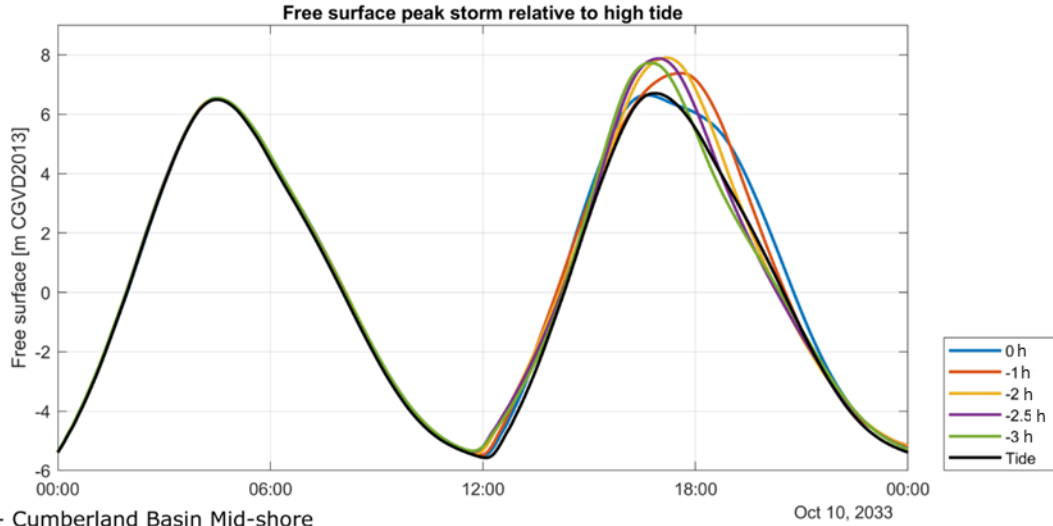
Figure 5.12 shows the free surface results at location 1 (Cumberland Basin Offshore) and 7 (Cumberland Basin Mid-shore) as defined in Table 4.2 and Figure 4.4. The initial simulation aligned the peak of the storm with peak tide 2033, referred to as the 0 h run. The tides-only results are indicated in black for reference (Scenario 4A). Instead of an increase in absolute water levels, the 0 h run simulation indicated increased duration of peak water levels leading to prolonged flooding after high tide. A sensitivity analysis was therefore conducted to determine the optimal timing of peak wind speeds relative to a peak for the highest expected water level.

The results, illustrated in Figure 5.12, indicate that as the maximum wind speed occurs earlier, its effect on total water levels becomes more synchronized with the peak tide. However, with a shift of up to -3 hours, the water level begins to decrease as the maximum wind speeds precede high tide. This suggests that additional shifts would continue to lower water levels.

The sensitivity analysis reveals that a -2.5 h shift between peak wind speed and high tide results in the highest expected water levels in the Cumberland Basin. Therefore, this setup, where the peak wind speed occurs 2.5 h before peak tide 2033, was used in Scenarios 2 and 3 to achieve the target of generating the highest expected water levels. The sensitivity analysis highlights the importance of timing with respect to peak wind speeds relative to high tide in the Chignecto Isthmus. Storms hitting the area during low tide will have a relatively low impact, but the impact is significantly exacerbated if the storm, in this case maximum wind speed, occurs around high tide.

Although the -2.5 h shift between the peak wind speed and the high tide results in the highest expected total water levels, there is a broader window of 4-6 hours during which water flowing over the top of the dykes remains a possibility. In Scenario 2, which simulates a Groundhog Day storm-type with SLR2033, the results indicate that, in the absence of a storm, water levels remain below the low dyke elevations. Consequently, the window of potential overflow is limited to the timing of the peak wind speeds relative to high tide when storm surge increases. This window is estimated to occur approximately between a -5 h and a -1 h shift between the maximum wind speed and high tide. In contrast, Scenario 3, which simulates a Groundhog Day storm-type with SLR2100, predicts that water levels already reach or exceed low dyke elevations even in the absence of a storm. As a result, the extended duration of high-water levels, such as noted in a 0 h shift, impacts the amount of water that could overflow the dykes. Compared to Scenario 2, the window of impact in Scenario 3 is extended, spanning approximately from a -6 h and a 0 h shift between the maximum wind speed and high tide. In addition to the rise in water levels, the results of Scenario 3 indicate that SLR also influences the relative increase in water levels observed during a storm. **Therefore, to more precisely determine the window of potential flow over the top of the dykes for both Scenarios 2 and 3, further study of storm timing is required.**

a) 1 - Cumberland Basin Offshore



b) 7 - Cumberland Basin Mid-shore

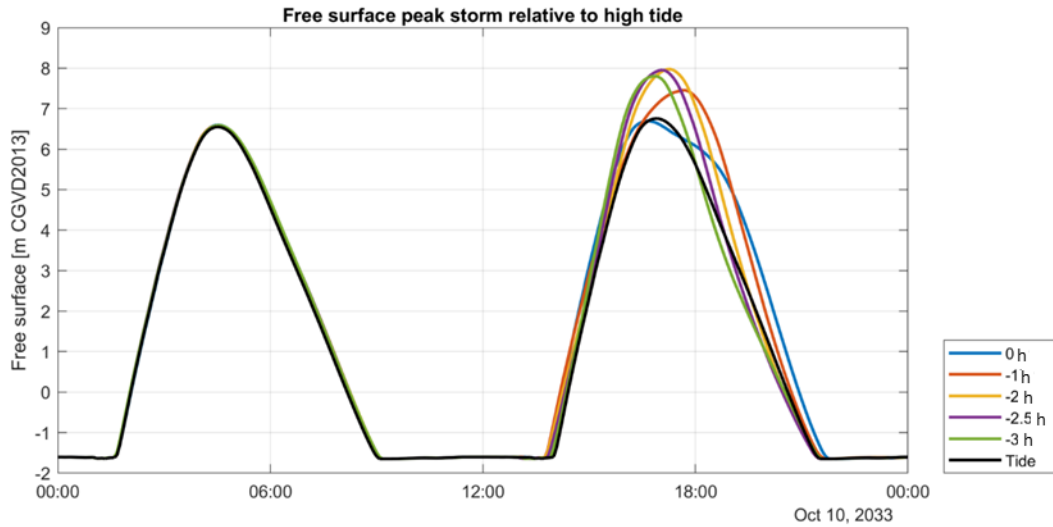


Figure 5.12 Sensitivity analyses of the timing of Groundhog Day storm peak, relative to peak tide 2033. Time series of simulated free surface elevations at: a) location 1 (Cumberland Basin Offshore), b) location 7 (Cumberland Basin Mid-Shore) during Scenario 4 – Groundhog Day storm without SLR. The black line indicates Scenario 4A (tides-only) results as a reference. The coloured lines indicate the various shifts in hours of Scenario 4B (tide + surge). The shift in hours is defined as the difference between the maximum wind speed and high tide at peak tide 2033.

6. Conclusion

The Chignecto Isthmus is a low-lying land formation connecting the provinces of New Brunswick and Nova Scotia, safeguarded by an extensive network of coastal dykes. These dykes protect low-lying communities and infrastructure from flood hazards driven by tides and storm surges in the Bay of Fundy. However, projected SLR and the increasing intensity of extreme weather events, such as post-tropical storm Fiona, pose significant risks to the region. This study aims to understand and quantify the contributions of tides and storm surges to total water levels at Chignecto Isthmus during post-tropical storm Fiona and similar events. This is essential knowledge to ensure for climate resilient improvements to the coastal dyke infrastructure.

Initially, the post-tropical storm Fiona was simulated to assess its impact on water levels in the Chignecto Isthmus. The model results showed that the local storm surge impact was mitigated by the northwesterly wind over the Cumberland Basin and its occurrence during low tide. The positioning of the Bay of Fundy means that storms with southwesterly winds are expected to generate higher storm surges. The timing of such storms relative to the tidal cycle is crucial, as it will determine whether significant flooding occurs in the Chignecto Isthmus.

To explore these dynamics further, three additional scenarios were simulated using the Groundhog Day storm, known for its significant impact on water levels in the Cumberland Basin in 1976. For this study, the storm was projected to 2033, coinciding with the next peak in tides caused by the 18.6-year lunar nodal cycle. To account for climate change, water levels were adjusted for projected SLR for 2033 (Scenario 2) and for 2100 (Scenario 3) based on RCP8.5 median predictions. Another scenario (Scenario 4) examining the coincidence of storm surge and peak tides was also investigated without a projected SLR, which was crucial in establishing Scenarios 2 and 3.

The model results demonstrate that a storm coinciding with high tide can significantly impact storm surge. The highest total water level (tide + storm surge) is observed when the maximum wind speeds occur 2.5 h ahead of the astronomical high tide. For the Groundhog Day storm-type scenarios this resulted in an increase in free surface elevation up to +1.22 m. It should be noted that the Groundhog Day storm, with its air pressure and wind speeds, is not as extreme as, for example, the post-tropical storm Fiona. The results indicate a critical 4-to-6-hour window, depending on SLR, during which maximum wind speeds can significantly affect water levels per tidal cycle. If highest storm surge occurs outside of this critical window, particularly during low tide, its impact would be significantly reduced.

By 2033, with predicted tides and projected SLR, water levels are expected to remain below the current dyke elevations in the absence of a storm. However, with projected SLR by 2100, water levels are expected to exceed existing dyke elevations even without storm surge.

This research shows that the timing of storms relative to astronomical tides, and the storm wind directions, are more critical in generating high storm surge in the Cumberland Basin than the intensity of the storm. This highlights the urgency for resilient coastal dyke infrastructure improvements to withstand future extreme events and SLR.

7. Model Limitations and Further Recommendations

The conducted study offers valuable insight into the hydrodynamics of the Cumberland Basin and the relative contributions of tides and storm surge to total water levels at Chignecto Isthmus during the passage of storm events. Current model limitations are summarized below, and where applicable, recommendations for further exploration are suggested.

1. Model skill and uncertainty depends on the quality, type and location of available data. This study employs the most recent water-level measurements and topographic-bathymetric data available at the time of model development. However, the lack of recent bathymetric data in the sub-tidal and offshore regions of the Cumberland Basin (as discussed in Section 2.1) is a source of uncertainty. Also, the absence of a permanent tide gauge in the Chignecto Isthmus – providing long-term water-level records and a greater number of extreme events for model validation (as discussed in Section 2.4) – contributes to uncertainty surrounding model skill.

Recommendation:

- **Address gaps in bathymetric data in the Cumberland Basin through conventional (single-beam or multi-beam) bathymetric surveys, and/or bathymetric LiDAR (if feasible considering turbidity). This information would contribute to increasing the model's predictive skill in the Cumberland Basin.**
 - **Establish a permanent tide gauge in the Cumberland Basin. This information would facilitate improvements in model skill, and more robust quantification of uncertainty, by providing long-term, highly accurate water-level data spanning a variety of tidal conditions and weather events. Over time, the data would also support a more accurate prediction of tides, and could be used in the future to feed into real-time monitoring or early warning systems for coastal flooding on the Isthmus.**
2. The model does not include bridges, aboiteaux, culverts or other subterranean drainage infrastructure in the Chignecto Isthmus, except for the water control structure at Tantramar River and the aboiteau at La Planche River as indicated in Section 2.1. Consequently, the model is expected to provide a conservatively high estimate of tide- and storm surge-generated water levels on the seaward side of the dykes, while potentially underestimating the flood inundation extents landward of the dyke system. This is because, in the model, tide- and surge-driven flows in the landward direction are fully constrained by the dykes (unless overtopped), whereas in reality, some landward-directed flows may be routed through culverts or other hydraulic structures lacking non-return gates or valves. If these culverts or hydraulic structures were faithfully implemented in the model, they would effectively increase the available water storage landward of the dykes, possibly resulting in slight reductions in water levels on the seaward side of the dykes but potentially resulting in additional flooding on the landward side (if flows exceed the capacity of culverts or upstream channels). On the other hand, the current model setup does not allow any water that overtops the dykes during more extreme water level scenarios to drain seaward through culverts and aboiteaux with the falling tides, likely overestimating the duration of flooding in areas landward of the dykes. If detailed information on culvert and aboiteaux geometries (e.g., shapes, elevations, material roughnesses) and operations (e.g., one-way flow valves or gates) were integrated, this information could be used to improve the realism of the model.

Recommendation:

- **Enhance the existing model with more accurate drainage infrastructure. Including these data would enhance the model, leading to a better understanding of tidal inundation from the Bay of Fundy both seaward and landward of the dykes.**
3. An additional potential enhancement to the model, landward of the dykes, is to incorporate contributions from precipitation and runoff, aspects that were beyond the scope of this work.

Recommendation:

- **Incorporate hydrologic information (i.e. river flows), if available, to provide a more detailed representation of landward inundation caused by rainfall-induced inland flooding.**
 - **Should streamflow data not exist, develop estimates to provide flow inputs to the existing Cumberland Basin model.**
4. The model assumes a fixed topography-bathymetry and does not simulate morphological changes like erosion or dyke damage (e.g. breaching) that can occur during extreme events.

Recommendation:

- **A geotechnical assessment of the dyke system should be undertaken to characterize dyke stability, identify weak points, and identify potential failure mechanisms, probabilities, and likely breach dimensions. This information could be used as input to dyke breach simulations using the TELEMAC-2D to provide a more comprehensive flood hazard and risk assessment.**
5. The model does not account for wind-wave effects such as wave setup, wave runup, and wave overtopping discharges. These factors are site-specific and can increase water levels seaward of a dyke or result in wave overtopping of the dyke crest, especially during storms. Incorporating these effects would help to assess the potential for dyke overtopping (as opposed to direct inundation), though a separate study would be needed to quantify wind-wave contributions to dyke overtopping and flood hazards. The magnitude of wave effects is typically highly localized and dependent on foreshore and infrastructure profiles, geometries and roughness, but order of magnitude regional estimates may be obtained from Murphy et al. (2019).
6. While the model has been used to explore several historical storm scenarios, the importance of the timing of storm surges relative to astronomical tides, fluctuations in astronomical high tides (the lunar nodal cycle), and a future SLR scenario, no probabilities (or likelihoods) have been assigned to these scenarios. Further research would be needed to characterize joint probabilities of tides, storm surges, and wave contributions to flood hazards and to develop probabilistic events for planning and design applications.

Recommendation:

- **Perform a comprehensive analysis of long-term tide gauge records at the nearest permanent gauge site (underscoring the need for a permanent tide gauge in Cumberland Basin for future applications), and/or**
 - **Simulate a broader range of scenarios to generate extreme value probability distributions for various hazard sources.**
7. Wind-sea momentum transfer coefficients are often considered calibration parameters in storm surge modelling, and are therefore a source of uncertainty. In the absence of long-term storm surge data in the Cumberland Basin to support a more rigorous calibration, the model relied on existing input parameters (calibrated for tidal forcing) and default wind-sea momentum transfer parameterizations, highlighting the need for a permanent tide gauge (as suggested under Limitation and Recommendation point 1. above).
8. The model does not simulate changing land use, geomorphology, or vegetation dynamics, which could influence flood hazard predictions (through roughness parameters) for future scenarios.

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The Cumberland Basin hydrodynamic model has been produced by the NRC-OCRE based on Canadian Hydrographic Service charts and/or data, pursuant to CHS MOU No. 2021-0106-1260-NRC. The incorporation of data sourced from CHS in the model shall not be construed as constituting an endorsement by CHS of the Cumberland Basin hydrodynamic model. This model does not meet the requirements of the Charts and Nautical Publications Regulations, 1995 under the Canada Shipping Act, 2001. Official charts and publications, corrected and up-to-date, must be used to meet the requirements of those regulations.

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