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**CONNECTIONS BETWEEN LAND AND SEA AT A
BAR-BUILT ESTUARY: MORPHOLOGICAL
MODELING CARMEL RIVER LAGOON USING
DELFT3D**

by

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**CONNECTIONS BETWEEN LAND AND SEA AT A BAR-BUILT
ESTUARY: MORPHOLOGICAL MODELING CARMEL RIVER LAGOON
USING DELFT3D**

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ABSTRACT

Almost half of the world's rivers are categorized as bar-built estuaries with seasonal and climate dependency, impacting current and future Naval and Marine Corps operations nearshore. These dynamic coastal systems are characterized by the interaction of sediment transport, hydrodynamics, and morphological evolution. Understanding the intricate interplay between these forces influences planning for maritime operations and coastal engineering. This study will enhance the understanding of how bar-built estuaries evolve over time and space using Delft3D numerical modeling. This research uses in-situ data from Carmel River State Beach during March 2020 and several numerical simulations. Numerical model calibration is completed by testing numerical parameters sensitivities, wave characteristics, sediment properties, bathymetry, inlet morphology, and tidal exchange. The insights gained from these simulations inform the dominant morphological processes and numerical parameters governing the geomorphologic response of the system while refining existing numerical models for predictive capability. Simulations indicate that the river bathymetry most influences the water level response more than the location of the inlet. Shallower bathymetry yields rapid widening of the channel with northward migration compared to deeper bathymetry. Offshore wave direction has minimal impact on the inlet morphology. Removing river discharge impacts inlet geometry and reduces the migration rate north.

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LIST OF ACRONYMS AND ABBREVIATIONS

BBEs	Bar-built Estuaries
Bed	Current-related Transport Vector Magnitude Factor
BedW	Wave-related bed-load Transport Factor
CDIP	Coastal Data Information Program
CNMOC	Commander Naval Meteorology and Oceanography Command
CRSB	Carmel River State Beach
DMO	Distributed Maritime Operations
DON	Department of the Navy
FNMOC	Fleet Numerical Meteorology and Oceanography Command
IRES	Intermittent Rivers and Ephemeral Streams
MOP	Monitoring and Prediction
MORFAC	Morphological Scale Factor
MPWMD	Monterey Peninsula Water Management District
NDBC	National data Buoy Center
NOAA	National Oceanic and Atmospheric Administration
Sus	Current-related Reference Concentration Factor
SusW	Wave-related Suspended Transport Factor
ThetSD	Factor for Erosion of Adjacent Dry Cells
UxS	Unmanned Systems

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I. MOTIVATION

There is an increasing emphasis on environmental sensing and tactics in the littorals for Navy and Marine Corps operations as our Nation's focus shifts away from land and open ocean conflict. The littorals, a vital and dynamic region where land and sea converge, stands a critical arena. There is a powerful interplay of morphologic and hydrodynamic forces that make this area susceptible to constant change. While dynamic, this zone is critical for military strategic planning, both offensive exploitation and defending penetration points. The ability to sense, predict, and forecast this environment will inform decision-makers and planners to gain an advantage.

In March 2021, the Department of the Navy (DON) expressed the demand for Unmanned Systems (UxS) in releasing the Unmanned Campaign Framework. A year later, the CNO's Navigation Plan 2022 followed a similar demand and prioritized six Force Design Imperatives, which included generating the decision advantage by out-sensing our adversaries to accelerate our decision cycle. There are ongoing efforts with Task Force 59 to demonstrate the capability of UxS to enhance Distributed Maritime Operations (DMO) and increase environmental awareness. Commander Naval Meteorology and Oceanography Command (CNMOC) tasks the enterprise to use all environmental data collections to sense, analyze, predict, and forecast to deliver decision superiority in all domains.

In situ data, leveraged by the UxS, can help inform global numerical models for higher fidelity predictions. Due to the complex nature of the littoral zone, persistent in-situ data will remain a challenge for coastal models. This challenge increases the demand to understand the numerical modeling limitation for decision-making superiority.

Fleet Numerical Meteorology and Oceanography Command (FNMOC) runs Delft3D for hydrodynamic predictions and forecasts. Currently, users are unable to request morphologic model predictions. This research focuses on modeling the morphology of the littorals, which can provide valuable insights into scenario planning and decision support for nearshore operations and coastal management.

This research uses the Carmel River State Beach, a bar-built estuary, to improve the understanding of modeling the morphology by leveraging available observations and knowledge of nearshore processes. Bar-built estuaries are common coastal water features in every continent which are formed through sediment movement. These systems are prevalent in arid to semi-arid ‘Mediterranean’ climates. Furthermore, non-perennial rivers are assessed to become the dominant type of waterway due to climate change and human water demands (Messenger et al. 2021). The Navy has a personal stake in monitoring, understanding, and predicting the environmental characteristics of littoral waters.

These estuaries have different iterative morphological states, varying from strong and weak currents through the river into bays and oceans, to closed and separate waterways. Due to these highly contrasting states of the river mouth, they are complex resources to manage, with associated risks to the population that relies on its water source; flooding prevention for infrastructure, human safety, agriculture; and environmental stewardship of the ecosystem. The morphologic and hydrodynamic processes that influence the changes impact a large region, from the surf zone to the deep continental shelf to upstream marshes on many coasts worldwide. Coupled with changes in beach morphology and the changing climate, understanding the dynamics, and establishing model fidelity now will help the Navy with short and long-term operational planning and coastal engineering planning.

II. INTRODUCTION

This chapter familiarizes readers with the study site, Carmel River State Beach, and provides information on similar research in this field. The thesis research objectives are also included in this section.

A. INTERMITTENT RIVERS

Inlets where the coastal lagoon system is seasonally connected to the ocean with periodic flow cessation, are categorized as seasonally open tidal inlets (Ranasinghe et al. 1999), ephemeral rivers (Hughes 2005), bar-built estuaries (BBEs) (McSweeney et al. 2017), or intermittent rivers and ephemeral streams (IRES) (Messenger et al. 2021). BBEs have been modeled worldwide and are proven to represent the dominant waterway with increasing prevalence due to climate change (Messenger et al. 2021). BBEs are most common along microtidal and wave-dominated coastlines of Mediterranean-type climates with seasonal-driven precipitation and littoral transport of non-cohesive sediments (Ranasinghe et al. 1999; McSweeney et al. 2017). The inlet geometry depends on the dynamic nature of sediment movement with the formation of an ebb-tidal delta (Michael Fenster and Dolan 1996) and erosion of a sill or sand bar (Ranasinghe et al. 1999b). The movement of sediment is highly variable, depending on the hydrodynamic forces on the system.

The accretion and sediment erosion are influenced by environmental factors that alter the beachscape and inlet mouth. The stability of the inlet is influenced by lagoon basin volume with the wave and tidal forces acting upon it (Bruun 1978), which promotes breaching and closure events. When the lagoon is small, the tidal prism is hampered, and the inlet is unstable, making it ephemeral (Bruun 1978). Cross-shore and long-shore sediment movement from waves with reduced river discharge which fosters closures (Orescanin and Scooler 2018). Strong ebbing river discharge promotes the breaching and flushing of lagoon sediment (Fortunato et al. 2014). Extreme meteorological events associated with flooding and strong river flow or artificial human intervention can further

influence these events. The sediment alteration around these highly dynamic systems influences coastal defense, reliable coastal navigation, and infrastructure challenges.

These systems' growing prevalence and influences on coastal safety have warranted studies on morphological development through modeling. Models of varying complexities have explored the breaching process through hydrodynamic forces and sediment transport response. Modeling case studies have tested and validated the sensitivities of different morphological (Lesser et al. 2004) and hydrodynamic parameters (Rueda-Bayona et al. 2020). As well as, testing morphological parameters and breach width of sidewall erosion (Wainwright and Baldock 2015). Varying from simplistic 1D models that investigate the sedimentation evolution of irregular inlets (Davidson et al. 2009, Behrens et al. 2015) to conceptual hindcast models that evolve the hydrodynamic and morphologic responses compared to remotely sensed observations of a storm-induced breach (Montoya et al. 2018). Another study uses a hybrid model, Delft3D and XBeach, to reproduce long-term sediment trends after a storm-induced breach (Ormondt et al. 2020). Others focus on tidal inlet migration rates using a mass balance framework and predictive model of 22 systems along the U.S. East Coast (Nienhuis and Ashton 2016). Nienhuis and Ashton (2016) demonstrated that with a simple mass balance framework, flood-tidal deltas act as sediment sinks where migration results from erosion of the downdrift barrier beach. This framework was quantitatively compared with observations from sandy east coast beaches.

Still, it is unknown if migration rates differ on rocky coastlines and pocket beaches typically found on the west coast. While forecasting short-term inlet migration is an area of exploration, there is also ongoing research for forecast modeling for larger time scales, such as global impacts of climate change on the stability of these inlet systems (Duong et al. 2018) and understanding deltaic processes for resiliency to sea-level rise challenges (Caldwell and Edmonds 2014; Duong et al. 2018; Messenger et al. 2021) and water quality (Mendes et al. 2021). Morphodynamical models are indispensable for understanding sediment transport and exploring the physical parameters that influence coastline geometry, rivers, inlets, and lagoons worldwide.

Inlet breaching and closures are naturally occurring processes but can be initiated manually for coastal engineering, geochemical flushing, safety, and ecological concerns. The decision to manually or artificially breach a system can be necessary to minimize the risk of flooding neighboring low-lying infrastructure and influence species transition or inhabiting the lagoon (Kraus et al. 2008; Wamsley et al. 2005). The method of controlled breaching was established in the early 1980s to prevent the negative consequences of artificial breaching (Kraus et al. 2008). Controlled breaching required a clear understanding of the hydrodynamic influences on the opening and closure rates and system responses to meteorological events (Moreno et al. 2010; Wamsley et al. 2005). The location of a controlled breach is crucial to properly increase the flow gradient and velocity by reducing the channel length (Wamsley et al. 2005). Numerical modeling is a powerful tool for understanding beach morphology and coastal management planning for both natural and artificial breaching of BBEs.

The physical understanding of these systems must be understood to apply effective engineering solutions. Migration rates for tidal inlets vary as a function of littoral drift, which includes the erosion and deposition of sediment and the wave climate, along with the tidal prism, beach slope, and river discharge, which determines inlet stability (Bruun 1978; FitzGerald 1988; Buonaiuto and Kraus 2003; Pacheco et al. 2008; Tung et al. 2009). However, most of these studies look at morphology for long-term (yearly) averages on sandy shores but do not account for the short-term (daily) changes and migration observed at BBEs along rocky coastlines.

B. RESEARCH SITE: CARMEL RIVER LAGOON

Carmel River Lagoon is an outlet of the Carmel River, postured on a pocket beach, Carmel River State Beach (CRSB) in Monterey County, California. This lagoon drains a 255-square-mile watershed in the Santa Lucia Range, intermittently connecting it to Monterey Bay as part of the Pacific Ocean. The beach is constrained by two rocky headlands located north and south with bedrock below at approximately 20 meters (Figure 1, image D). As a non-perennial river, the inlet's seasonal opening or breaching is partially

driven by meteorological systems with increased precipitation and associated river discharge, higher wave energy, and larger storm surge (wave-overtopping).

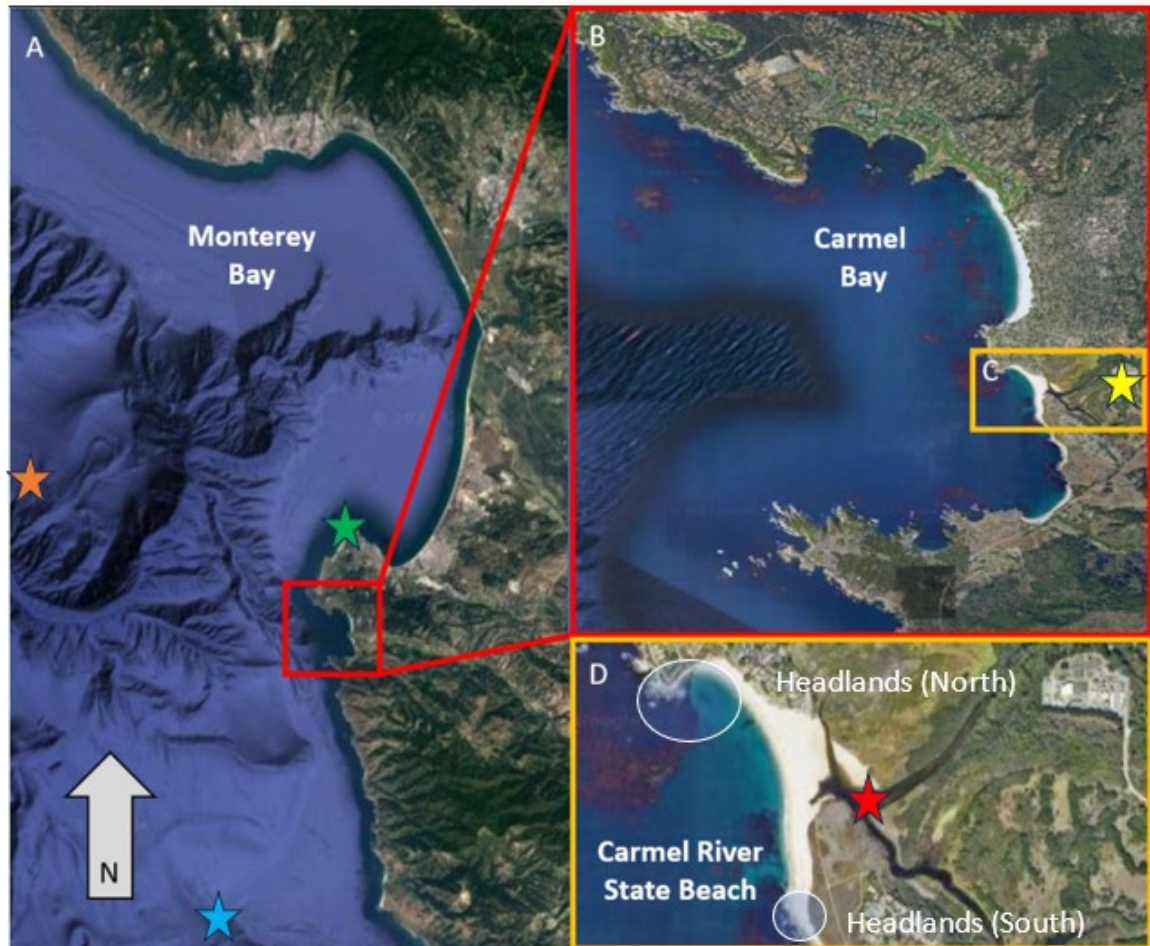


Image A is a zoomed out view of Monterey Bay. Inside the red box in image B is Carmel Bay. The small yellow box (C) and zoomed in image D is Carmel River State Beach. The approximate locations for tide data (green star), waves data (blue star: NDBC West Monterey Bay Buoy and orange star: Point Sur Buoy), the lagoon water-level or river marker (red star) and River Discharge (yellow star) observations are marked.

Figure 1. Geographic reference; Monterey Bay, Carmel Bay, Carmel River State Beach, and headlands. Source: Google Earth.

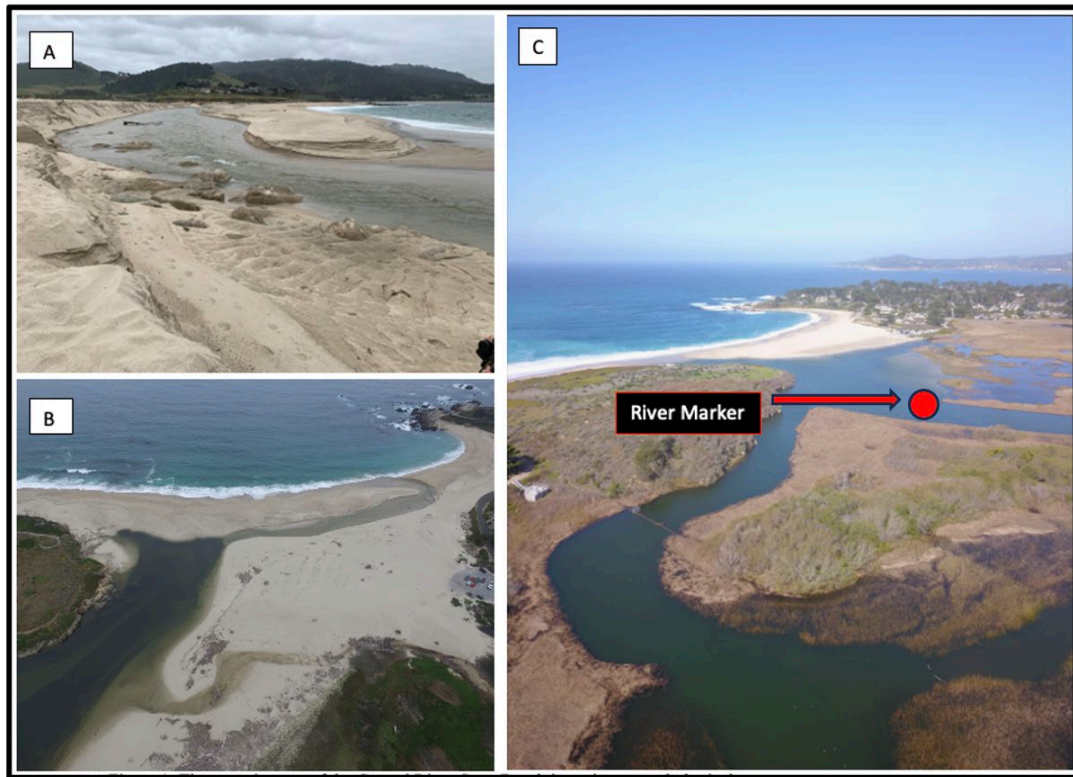
Seasonal changes drive the Carmel River and its intermittent breaching and closing. The Santa Lucia Watershed has approximately 660 km² of water, which feeds into the 58 km-long Carmel River (Orescanin and Scooler 2018). In the Fall and Winter, west and northwest swells from 280–300 degrees are generated by storms in the Northern Pacific

Ocean, with wave heights varying from 1 to 5 m. When accompanied by spring tides, these swells can overtop the CRSB by increasing the lagoon water levels with ocean water (James 2005). The meteorological activity influences the discharge rates of the river, where 0.83 feet of rain at San Clemente Dam is required to advance the river to the lagoon (James 2005). A closed inlet, characterized by discharge rates between 0.7 m³/s and 2.1 m³/s for 24 to 48 hours, can flood nearby low-lying areas if not breached naturally or artificially (James 2005). Once breached, discharge rates of about 3 m³/s (6 m³/s) will maintain an open inlet 90% (100%) of the time (James 2005). During the wet season, flows less than 2 m³/s with supportive swells, tides, wind waves, and sediment transport increases the chances that the sandbar will build up and block the outflowing channel (James 2005). Discharge rates below 0.3 m³/s will almost always result in inlet closure regardless of oceanic influences (James 2005). The inlet typically closes in late Spring or Summer, and water levels recede due to evapotranspiration and decreased wave heights. The southerly swell in the summer can occasionally overtop the berm but is not as significant as the northwest swells generated by storms. Monitoring oceanic and meteorological events influences management planning and breach or closure forecasting.

A natural breach is expected once water levels exceed the berm height. This system is known to breach every year and sometimes artificially breached (bulldozed) for flood control, safety to surrounding communities, and environmental stewardship. Carmel Lagoon has proven to be a perched estuary, meaning there is always an offshore pressure gradient between the ocean and the lagoon water levels, more easily allowing river discharge and rapid berm scouring. There are also observed closures through the Fall and Winter, indicating that ocean forces reduce river flow through a momentum balance (Orescanin and Scooler 2018) and enable sedimentation in the inlet.

The sedimentation and erosion patterns influence the inlet geometry. Breaches observed at CRSB have documented that the inlet migrates 50% of the time after the first seasonal breach, profoundly affecting lagoon water level fluctuation patterns (James 2005). An elongated channel is sometimes formed in the late spring or early summer, like shown in Figure 2, panel B, which increases the lagoon levels but decreases discharge with time, so lagoon water cannot drain adequately at low tide (James 2005). A two-year

morphological study of CRSB found that there was a net loss of sediment during inlet migration. During non-migratory seasons there was a gain of sediment that resulted in pre-migration elevations (Orescanin et al. 2021). This suggests that this could be a cyclical system for sediment transport.



(A) The CRSB in a breached state with a northward migration that bends sharply south as it enters the surface zone, (B) Aerial image of the river migration (North) compared to the surrounding beach (The Carmel River in a breached state with elevated lagoon water levels) Note that panel A and B were taken on the same day. (C) River in a closed state. The red circle on (C) provides the location of the River Marker, where persistent water level data was collected and used for model calibration.

Figure 2. Views of Carmel River State Beach with closed inlet and north migrated inlet.

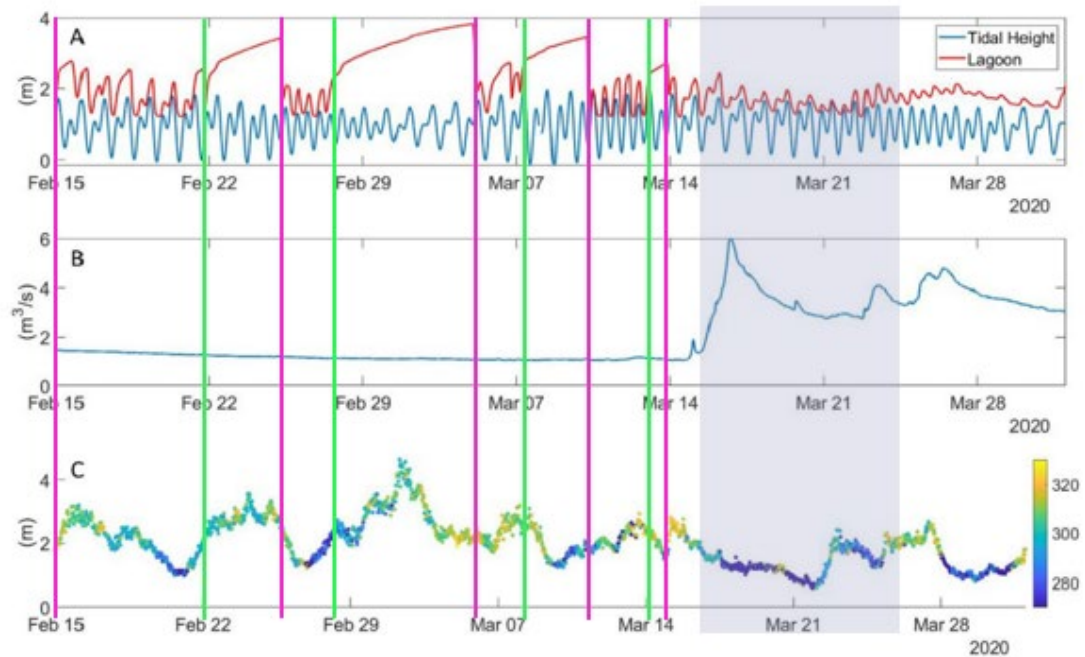
C. CARMEL RIVER 2020 BREACH

The morphodynamical life cycle of intermittent inlets is a result of sedimentation, erosion, and hydrodynamic forcing from the ocean and river (Rich and Keller 2013). The dynamic environment makes persistent observations difficult and sparse, making

forecasting breaching events' timing and location difficult. Numerical models serve as a tool to help understand how the different environmental forces affect the timing and location of an inlet breach. This study will explore the forces influencing a breach using data from observations collected before, during, and after the breach in March 2020 and observed inlet patterns from over five years of in situ observations and aerial imagery. Effectively modeling and understanding the morphodynamical response to different forcings will help predict and understand sedimentation and erosion associated with real system inlet patterns globally.

In-situ environmental data and periodic morphological observations were collected in February 2020 and March 2020 to set up the boundary conditions used for this research (Figure 3). The river opened and closed several times during that period, making continuous morphological observations difficult. These changes in the system can occur in a short time and greatly change the beachscape (Figure 4). The inlet opened on 10 February, followed by several closures and breaches, with sporadic observations. Bathymetric data used to establish the grid was taken from 2018 FEMA Lidar the National Oceanic and Atmospheric Administration (NOAA) Coastal Data Access Viewer for parameter calibration (Cavins 2021). River surveyor data from 5 March 2020 was later used for bathymetric analysis and calibration in section IV, F (McPherson 2020). The observed data sets will be used to tune the model.

Persistent in situ data sets were used to set the boundary conditions and for parameter sensitivity analysis. Water level data (Figure 3, A) from the River Marker (Figure 2, red circle) is used to calibrate the model parameters. The observed water levels were 15-minute intervals of recorded water level data from the Monterey Peninsula Water Management District's (MPWD) sensor. Hourly tidal data from NOAA Municipal Wharf in Monterey Bay, California, established the model boundary conditions. River discharge (Figure 3, B) information was processed from the MPWD sensor along Carmel River at Highway 1 overpass. Wave direction and significant wave heights from the National Data Buoy Center (NDBC), West Monterey Bay (Station 46114) and Pt. Sur (Station 46239) (Figure 3, C). The persistent datasets help inform the model boundary conditions and analyze model outputs.



(A) Water level in the lagoon (River Marker) (Figure 1, red star) and tidal height (Figure 1, green star), (B) Instantaneous river discharge rate (Figure 1, yellow star), (C) NBDC West Monterey Bay Buoy (Figure 1, orange star) and Pt. Sur Buoy (Figure 1, blue star) wave height and direction. The gray shaded box indicates the period this study will focus on, March 16, 2020 – March 24, 2020, for model calibration. Magenta lines indicate opening (breached) inlet and green lines indicate closed inlet. The river breached on Feb 10th, 15th, 25th, and March 5th, 10th and 14th. The River closed on Feb 15th, 22nd, 28th and March 7th and 13th. Source: McPherson (2020), Cavins (2021), Williamson (2023)

Figure 3. The CSRB environmental forcing parameters. Source: Cavins (2021), McPherson (2020)



These images show different states of the river during the period being modeled. The top photo shows February 28, 2020, where the inlet is initiating a breach state. The middle photo is taken on March 2, 2020, just after the inlet closes. The bottom photo is taken on March 31, 2020, when the inlet was breached and migrated north.

Figure 4. Images of various states during the analyzed time.

D. RESEARCH OBJECTIVES

The morphological model of Carmel River using Delft3D offers a comprehensive and versatile method for studying and simulating the river's hydrodynamics and sediment processes. This research will focus on the short duration yet dynamic period, 1 March 2020

to 31 March 2020. The data collected during this period will help calibrate the previously established model (Cavins 2021, Williamson 2023). Delft3D is an invaluable tool for this research to explain and hindcast the physical processes governing morphological changes within the inlet and surrounding areas. This study will evaluate whether a model can indicate or forecast physical changes in the inlet.

Using a state-of-the-art process-based numerical model, Delft3D, this research aims to explore and calibrate various morphological parameters to simulate the morphological evolution of CRSB during 15 March 2020 – 31 March 2020. The method used can be viewed as a hybrid exploratory-hindcast-simulation method to understand the morphological response to modeling an ephemeral river by analyzing various morphological parameters. This research aims to gain insight into the physical forces governing sediment movement and understand Delft3D limitations for modeling small time scales.

The research hopes to test and understand the sensibility of morphological parameters and assess morphological performance. Model performance will be compared to the system's known and expected morphological evolution coupled with a statistical analysis using observed water levels. With a calibrated model, this research will evaluate the impacts of varying bathymetry, offshore wave direction, river discharge, and inlet location on the system's morphologic response.

III. METHODOLOGY

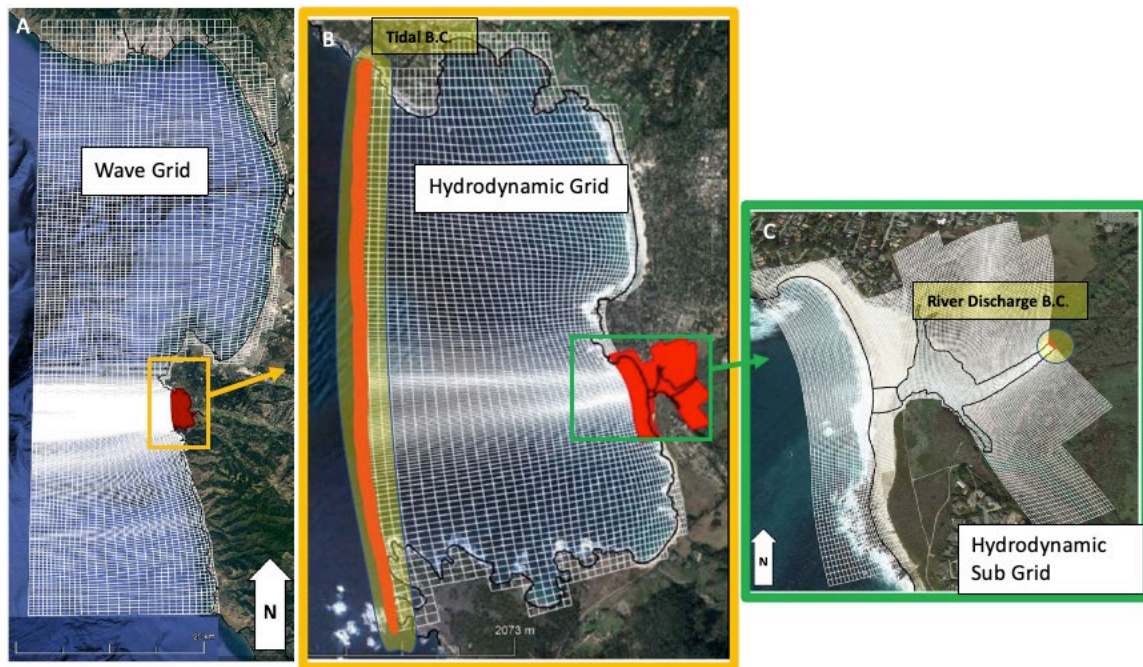
This chapter explains Delft3D and the technique used to calibrate and refine the model. The calibrated model is then used to further the physical understanding of the system.

A. DELFT3D CAPABILITIES AND PREVIOUS RESEARCH

Delft3D, a process-based model, is invaluable for understanding and managing coastal behaviors and processes worldwide. This software package enables numerical modeling capabilities with its combined dynamics, including hydrodynamic, wave, sediment transport, and morphological processes through its embedded modules. There are three modules; flow (FLOW), wave (WAVE), and morphology (MOR, which is included in FLOW). FLOW solves the Navier-Stokes equations of an incompressible fluid with the Boussinesq, shallow water, and hydrostatic pressure assumptions (Deltares 2023). The WAVE module uses the third-generation wave model Simulating WAVes Nearshore (SWAN) (Booij et al. 1999). The simulation starts with the integration of FLOW and WAVES, with regular intervals of synchronization to account for the wave forces on the hydrodynamics and boundary conditions. Sediment transport is a result of waves and currents which is solved through the advection-diffusion equation where spatiotemporal morphological patterns can be analyzed. Deltares (2023) and Lesser et al. (2004) explain the mathematical formulations in further detail, hence not repeated here.

The system of equations in Delft3D is solved using finite differences in a discrete space via curvilinear grids and a set of initial and boundary conditions. The CRSB model includes two hydrodynamic grids. The larger (Figure 5, panel B) 15x15 meters resolution grid encompassing Carmel Bay is coupled with the smaller (Figure 5, panel C) 2x2 meters resolution grid focusing on the lagoon and river. The simulations run from 1 March 2020 to 31 March 2020 with a 3 second (.05 minutes) time step. An established 14-day spin-up time for hydrodynamic calibration is an initialization phase to establish stable water flow dynamics. During this phase, the model runs all hydrodynamic calculations and initial conditions. The wave calculations begin on 14 March 2020 and run for 24 hours to reach

equilibrium before morphology is initiated on 15 March 2020. The model map output files update every 2 hours to reasonably capture changes without sacrificing storage capacity. The CRSB model boundary conditions were established by (Cavins 2021) and tested by (Williamson 2023). Tidal boundary conditions were delineated on the western edge of the larger-resolution hydrodynamic grid (Figure 5, panel B). The river discharge boundary condition was set on the eastern edge of the higher-resolution lagoon grid (Figure 5, panel C). Delft3D incorporates a wave module based on SWAN to compute the wave environment, which is crucial on the wave-dominated coastline at CRSB. The computational grid for SWAN is shown in Figure 5, panel A, with a 750x750 meters resolution grid of Monterey Bay. Tidal fluctuations and wave- and current-induced flows are accounted for in the simulation and, in return, allow the model to calculate water levels, currents, discharge, and velocities essential for understanding the different forces acting on the inlet and causing morphological change.



(A) is the 750x750 meters wave grid, (B) is the 15x15 meters hydrodynamic grid with the associated tidal boundary condition (red curve highlights in yellow), and (C) is the higher resolution 2x5 meters hydrodynamic grid with the associated river discharge boundary condition.

Figure 5. The wave and hydrodynamic grids. Source: Cavins (2020)

Fundamentally, the purpose of Delft3D modeling is to simulate and analyze complex hydrodynamics and morphodynamics in various environments. Delft3D can compute sediment transport to provide an understanding of the subsequent morphological evolution, which is the focus of this research. This tool can calculate erosion and sedimentation from the sediment transport model from the effects of waves and currents using the Van Rijn method (Van Rijn 1993). Based on the sediment transport rates, user-determined settings, and morphological feedback, Delft3D updates the beach profile at each simulation time step.

Estimating suspended sediment transport is critical to understanding morphological changes. This involves modeling the movement of sediment carried within the water column. Delft3D uses turbulence closure models to compute the turbulent diffusivity, which determines the rate of suspended sediment mixing. The concentration of suspended sediments is then computed using advection-diffusion equations, considering factors like settling velocity, turbulence, and bed interaction.

To simulate erosion and sedimentation, Delft3D utilizes bed-level changes caused by waves, currents, and discharge. Bed shear stress is calculated based on hydrodynamic parameters and used to evaluate sediment erosion and deposition rates. Delft3D uses sediment transport formulations to estimate the sediment transport rates caused by bed shear stress. These formulations consider factors like sediment grain size, flow velocity, and turbulence intensity to determine the magnitude and direction of sediment movement.

Morphological updates in Delft3D are performed by integrating the sediment transport rates with the existing bathymetry. During each computational time step, the model tracks the volume of sediment transported and redeposited in each computational grid cell and adjusts the bed elevation accordingly. The model computes erosion and sedimentation patterns based on the hydrodynamic conditions and their influence on the magnitude and direction of each grain and updates the bathymetry.

The Carmel River Bay (Bay) and Carmel River Lagoon (Lagoon) grids and boundary conditions used for this project were created by Cavins (2021). The initial bathymetry used to set up the model was a data set from the Spring of 2018 on NOAA's

Coastal Data View. Williamson (2023) analyzed the hydrodynamic boundary conditions and their effects on the lagoon water levels and initiated the first morphology simulation; the baseline morphology settings that will be calibrated and expanded upon are in Table 1.

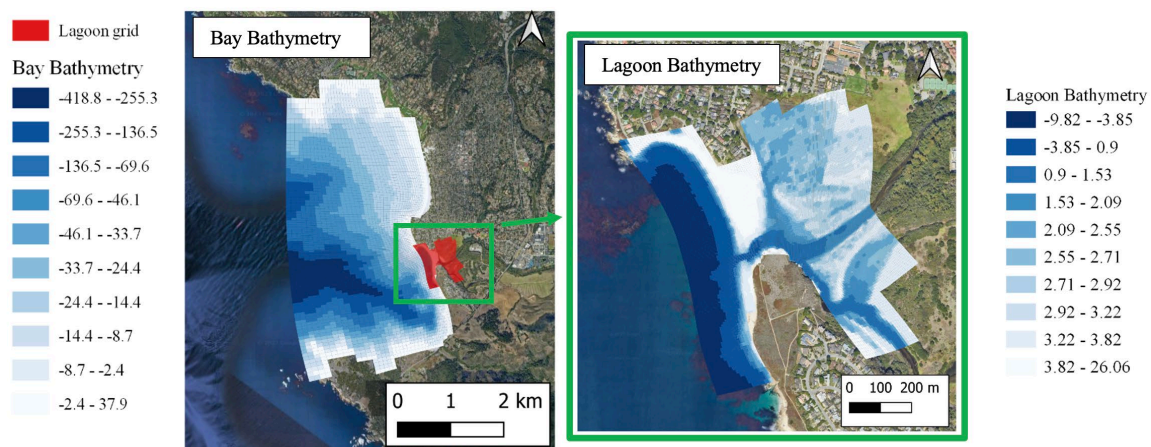
Table 1. Baseline configuration for morphology settings. Source: Williamson (2023)

General Set up	
Morphological Scale Factor (MORFAC)	5
Spin Up interval before Morphological Changes	29 days
Minimum depth for sediment calculation	0.1 m
Sediment Transport Parameters	
Van Rijn's Reference height factor	0.5
Threshold Sediment Thickness	0.050000001 m
Estimated Ripple Height Factor	2
Calibration Factors	
Factor for erosion of adjacent dry cells (ThetSD)	0.8
Current-related reference concentration factor (Sus)	1.0
Current-related transport vector magnitude factor (Bed)	1.0
Wave-related suspended transport factor (SusW)	0.15
Wave-related bed-load transport factor (BedW)	0.15

B. COASTLINE MODIFICATION TO BATHYMETRY

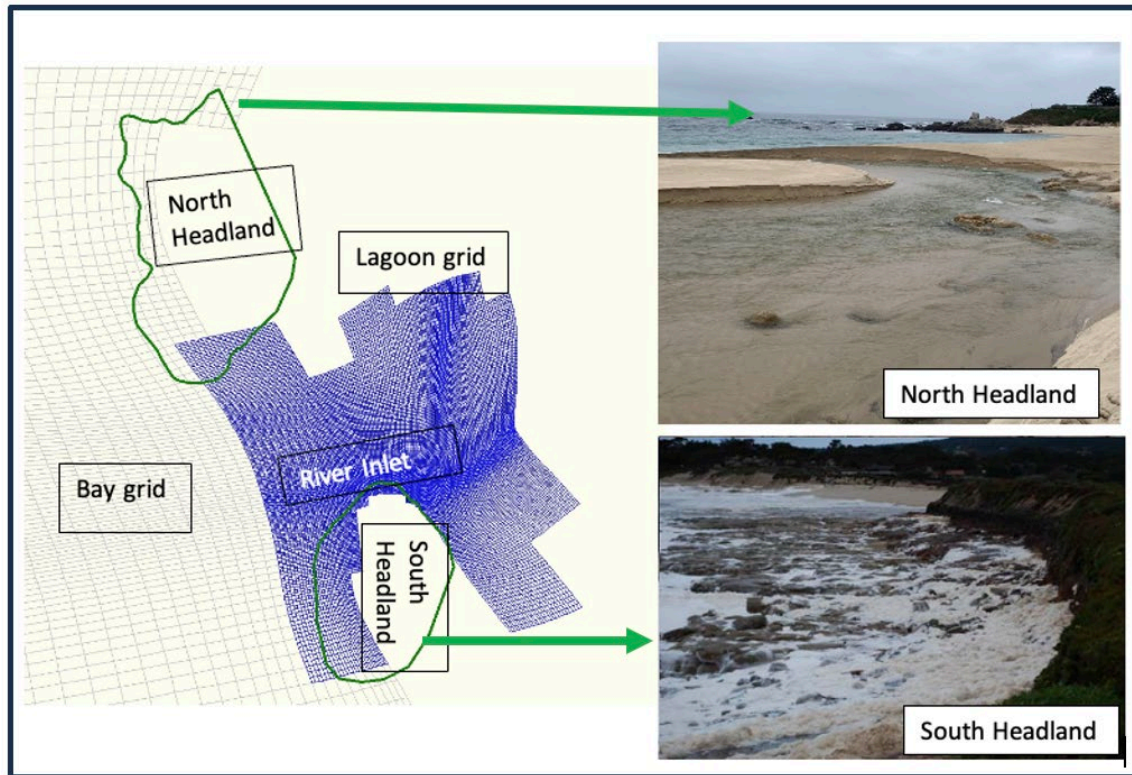
This research focuses on the rapid and seasonal changes of the perennial Carmel River inlet. The original bathymetry (Figure 6) was modified to account for key coastline features. CRSB is an embayed beach with rocky headlands to the north and south. This

coastline geometry is critical to the morphological and hydrodynamical cycles, rapid erosion and sedimentation both on and offshore, the momentum balance of the river discharge and waves, and wave reflection at the coastline. Thus, in addition to the bathymetry, headlands were schematized on the bay and lagoon grids (Figure 7). The headlands are included in the model by reducing the bed thickness, which reduces the amount of sediment available for erosion. The northern headland resembles a low cliff and typically exposed rock formations above the water level. The southern headlands are approximately 185 meters (600 feet) to the south. These headlands differ and are subaqueous granodiorite rock that extends into the surf zone and is close to the traditional location of the river's initial breach (Storlazzi and Field 2000). To account for these different features, the northern headland is set in Delft3D with zero meters of sediment thickness. This means that there is no sediment for erosion. Conversely, the southern headland is set in the model for two meters of sediment available for erosion above the granitic bedrock. The bed thickness, or the available sediment for movement, is set to 20 meters at all other grid cells not contained in the headland polygons. These values of bed thickness were determined from aerial imagery of the beach in various conditions, walking survey data, and observational data.



The left image is the initial bathymetry for Carmel Bay, where the darkest blue indicates the deepest areas. The right image is the original bathymetry for the Carmel River Lagoon. The color scales are in meters.

Figure 6. Initial bathymetry of the Carmel Bay (left) and Carmel River Lagoon (right).



To accurately capture the constraints to sediment movement around the inlet, polygons indicating rocky formations were sketched for the Bay and Lagoon grids. The green polygons represent the north and south headlands. The images on the right show the visual differences and locations of the north and south headlands.

Figure 7. North and south headlands incorporated in the bathymetry.

C. CALIBRATION METHOD

As a process or physical-based model, Delft3D is used to compute the hydrodynamics and sediment transport of natural systems through a series of equations. The Van Rijn hydrodynamic calculations inform the suspended sediment calculations using the advection-diffusion (mass-balance) equations (Deltares 2023). The model output accuracy is predicated on model assumptions, inputs, and parameter estimates. Parameters allow models to simplify reality and, through parameterization, account for missing information either from complexity or spatial and/or temporal convolution. These parameters come in the form of user settings in Delft-3D MOR, which do not necessarily represent the beach's quantifiable attributes; thus, the values must be determined through

calibration. This calibration is a cause-and-effect analysis comparing the model input and output to available information from the system.

Calibrations require the execution of many model simulations with different parameter settings. The model outputs for each parameter are then compared to available observation data for the best fit. Delft3D-MOR computations in 3D mode typically take 25–30 hours, so testing the available ranges for all parameters was unfeasible. The starting model settings were taken from quantitative norms of other studies and refined or verified.

This research conducted a one-at-a-time calibration analysis, exploring the effects of each variable on the sediment movement and hydrodynamic response. This study examined the spatial trends of sedimentation and erosion for the various parameters and configured each variable based on conceptual and in-situ information available for CRSB. Modeled and observed water levels were compared at the River Marker (Figure 2). Some parameters warranted further analysis with depth-averaged discharge values at the River Marker for model-to-model output comparisons for pattern recognition.

The following parameters were tested and calibrated; morphological scale factor (MORFAC), factor for erosion of adjacent dry cells (ThetSD), current-related reference concentration factor (Sus), current-related transport vector magnitude factor (Bed), wave-related suspended transport factor, (SusW) and wave-related bed-load transport factor (BedW) (Table 2).

Table 2. Morphological parameters and calibration ranges.

This table provides the general set-up parameters and the parameter values that were used for calibration. The bolded values are the baseline values.

General Set up	
Spin Up interval before Morphological Changes	16 days
Minimum depth for sediment calculation	0.1 m
Sediment Transport Parameters	
Van Rijn's Reference height factor	0.5
Threshold Sediment Thickness	0.050000001 m
Estimated Ripple Height Factor	2.0
Calibration Factors	Values Tested (Bold value is baseline value)
Morphological Scale Factor (MORFAC)	1.0, 5.0 , 8.0, 10
Factor for erosion of adjacent dry cells (ThetSD)	0.6, 0.8 , 1.0
Current-related reference concentration factor (Sus)	0.5, 1.0 , 3.0
Current-related transport vector magnitude factor (Bed)	0.5, 1.0 , 5.0
Wave-related suspended transport factor (SusW)	0.01, 0.15 , 0.5, 0.8
Wave-related bed-load transport factor (BedW)	0.01, 0.15 , 0.5, 0.8

Model performance was evaluated using the simulating water levels at the River Marker (Figure 2) for 9 days using the Pearson correlation coefficient (CC), root-mean-square deviation (RMSD), and Willmott skill (WS). Mathematical expressions of the formulas are as follows:

$$CC = \frac{\frac{1}{N} \sum_{n=1}^N (Mod_n - \overline{Mod}) (\overline{Obs} - Obs_n)}{\sigma_{Mod_n} \sigma_{Obs_n}},$$

$$RMSD = \left[\frac{1}{N} \sum_{n=1}^N (Mod_n - Obs_n)^2 \right]^{\frac{1}{2}},$$

$$WS = 1 - \frac{\frac{1}{N} \sum_{n=1}^N (Mod_n - Obs_n)^2}{\frac{1}{N} \sum_{n=1}^N (|Mod_n - \overline{Obs}| + |\overline{Obs} - Obs_n|)^2},$$

where $\overline{Obs}$ are the averaged values of the Obs_n and simulation Mod_n in a sample size of N (N=817). This N value represents the number of samples with 0.05 minute time steps from the observed 9-day period, 16 March to 24 March. The standard deviations for the model and observations are σ_{Mod_n} and σ_{Obs_n} , respectively. CC measures the linear correlation and relative difference between the model and observational water levels, where values between 0.5-1.0 indicate strong correlation, 0.3-0.49 is a moderate correlation, and low correlation is below 0.29. RMSD directly compares the model-to-water level; the lower value is a lower error. WS categorizes the quality of the model skill using poor (0-0.3), good (0.3-0.6), very good (0.6-0.8), excellent (0.8-1.0), and perfect (1.0) (Mao and Xia 2018). Following a thorough statistical review, iterative quantitative simulations were tested for all parameters and boundary conditions to enhance the model performance at simulating water levels in the lagoon.

D. MIGRATION/WAVE DIRECTION

The beach width above sea level varies seasonally as sand moves on and offshore. Still, generally, the long-term steady state berm elevation is 7.5 meters above sea level, with the north end of the beach traditionally higher than the south end. Channel migration is a critical feature, hypothesized to be a combination of reduced river discharge, wave height and direction, and tidal fluctuations that change beach berm height. As the inlet mouth meanders north, the high base elevation of the beach slows the river flow further, discouraging it from scouring the inlet closer to sea level (south). This research will isolate wave direction to understand its influence on sediment movement and migration of the

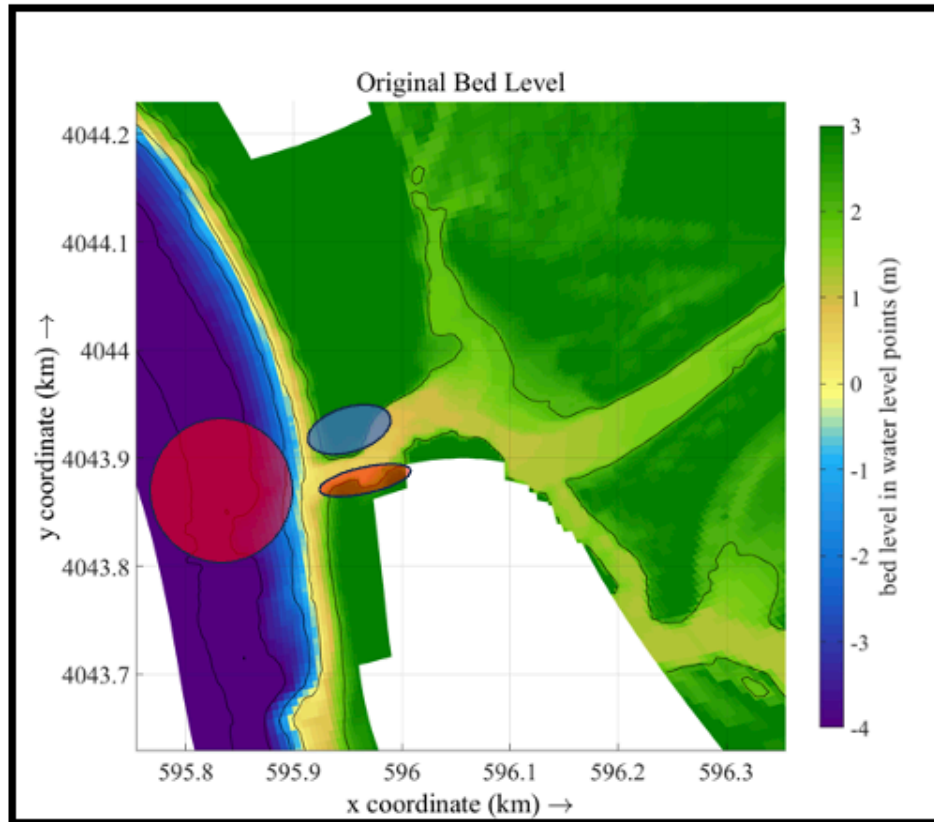
inlet, as well as understand model limitations to capturing these forces. This research will explore waves of consistent 3 meter height and 14 second period with varying wave directions. Wave direction will vary from various northwestern directions, specifically 250°, 290°, and 330°, which are typical for February and March.

IV. RESULTS

A. QUALITATIVE CALIBRATION OF MORPHOLOGICAL PARAMETERS

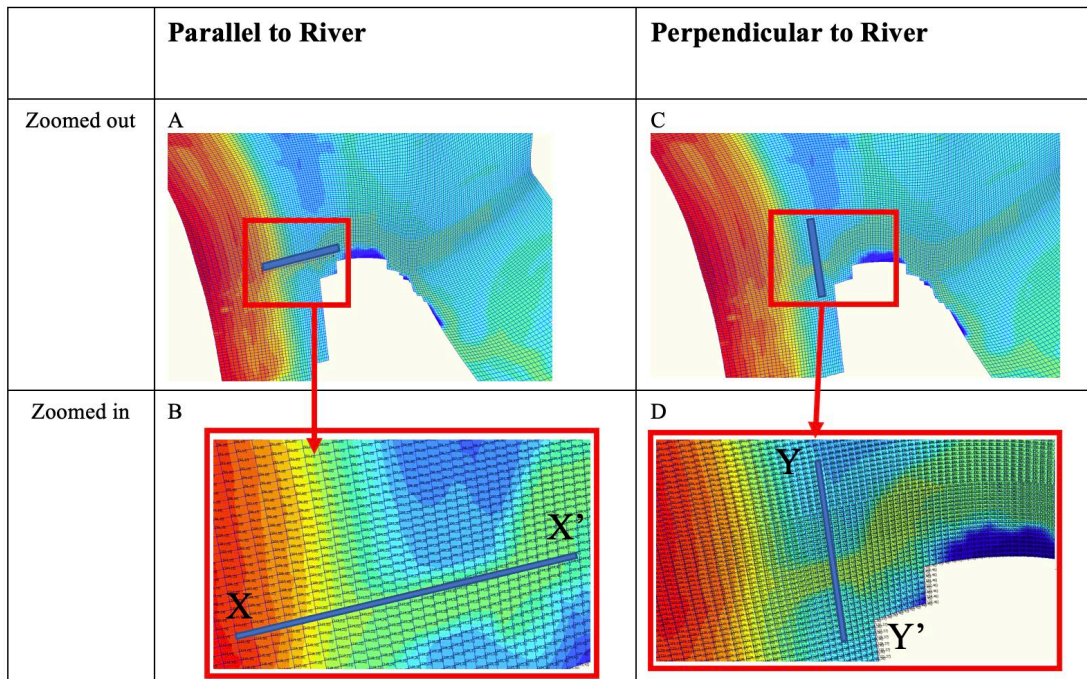
A qualitative analysis was used to compare and select each morphological parameter value. Each parameter value was initially selected by visually analyzing the inlet geometry after 17 days of morphological simulation, specifically the sedimentation and erosion for each parameter compared to expected inlet behaviors and patterns. The pattern analysis compared model results to the expected erosion and sedimentation behaviors (Figure 8). Aerial imagery, physical phenomena, and intermittent survey data informed the expected patterns to qualitatively select the best-fit value for each parameter. The northward bank is expected to be scoured (blue circle, Figure 8), which sets up the northward migration patterns, while the south bank is built up during migration (orange circle, Figure 8). The sediment from the river is transported seaward with an expected Ebb Delta formation offshore (red circle Figure 8). Each tested parameter is also analyzed and compared using quantitative statistics, specifically CC, RMSD, and WS. The quantitative results informed further parameter and boundary condition modifications.

The bathymetry along two inlet cross-sections (along and across inlet) (Figure 9) was extracted before and after morphological changes to understand how the inlet profile and cross section change. These cross sections will be used throughout the parameter analysis, starting with various MORFAC.



This is the original bathymetry overlaid with the expected areas of sedimentation and erosion. The red circles indicate the expected areas for sedimentation, and the blue circle indicates the expected erosion.

Figure 8. Expected bathymetry patterns for qualitative results.



These are the transects on the computational grid where initial and final bathymetries will be presented. Panels A&B are the section parallel to the inlet and panels C&D are the section perpendicular to the inlet. The X and Y are the starting positions and X' and Y's are the endpoints of the transect plots.

Figure 9. Along- and across-inlet transects where initial and final simulated bed levels are analyzed.

B. MORPHOLOGICAL SCALE FACTOR

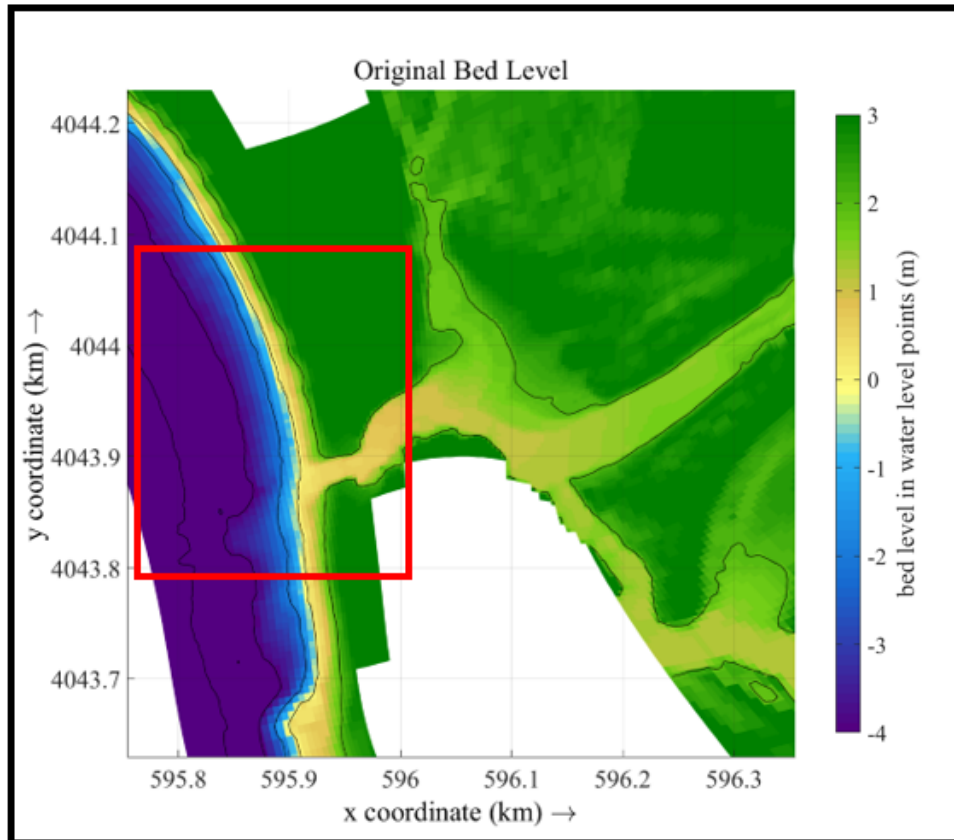
One of the inherent complications of modeling the coastal environment is the varying time scales of developing change, most noticeable in morphological projections based on hydrodynamic flows. Coastal morphological change can take hours, weeks, months, or sometimes years, while hydrodynamic forces change daily or hourly. Delft3D has a feature that compensates for this temporal gap, the Morphological Scale Factor (MORFAC). Manipulating MORFAC allows temporal changes in the morphology by scaling it to a relevant factor where it begins to impact the hydrodynamic flows. The MORFAC approach to modeling has enabled numerical coastal morphological evolution to be simulated at the decadal and millennial time scales by reducing computational time (Ranasinghe et al. 2011). Despite strategic research on MORFAC, there is no formula for

an effective criterion for the presupposed determination of a critical MORFAC (Ranasinghe et al. 2011).

This study is unique to other MORFAC comparisons because it explores MORFAC for a smaller (100s of meters/hours-days) spatial-temporal coastal environment. Ephemeral rivers experience rapid morphological change in hours to days (inlet breaching), seasonal (longshore transport and inlet closures), and years (beach erosion and accretion cycle). This study focuses on the system's evolution following a breach, an occurrence on a small temporal and spatial scale compared to other Delft3D modeling analyses.

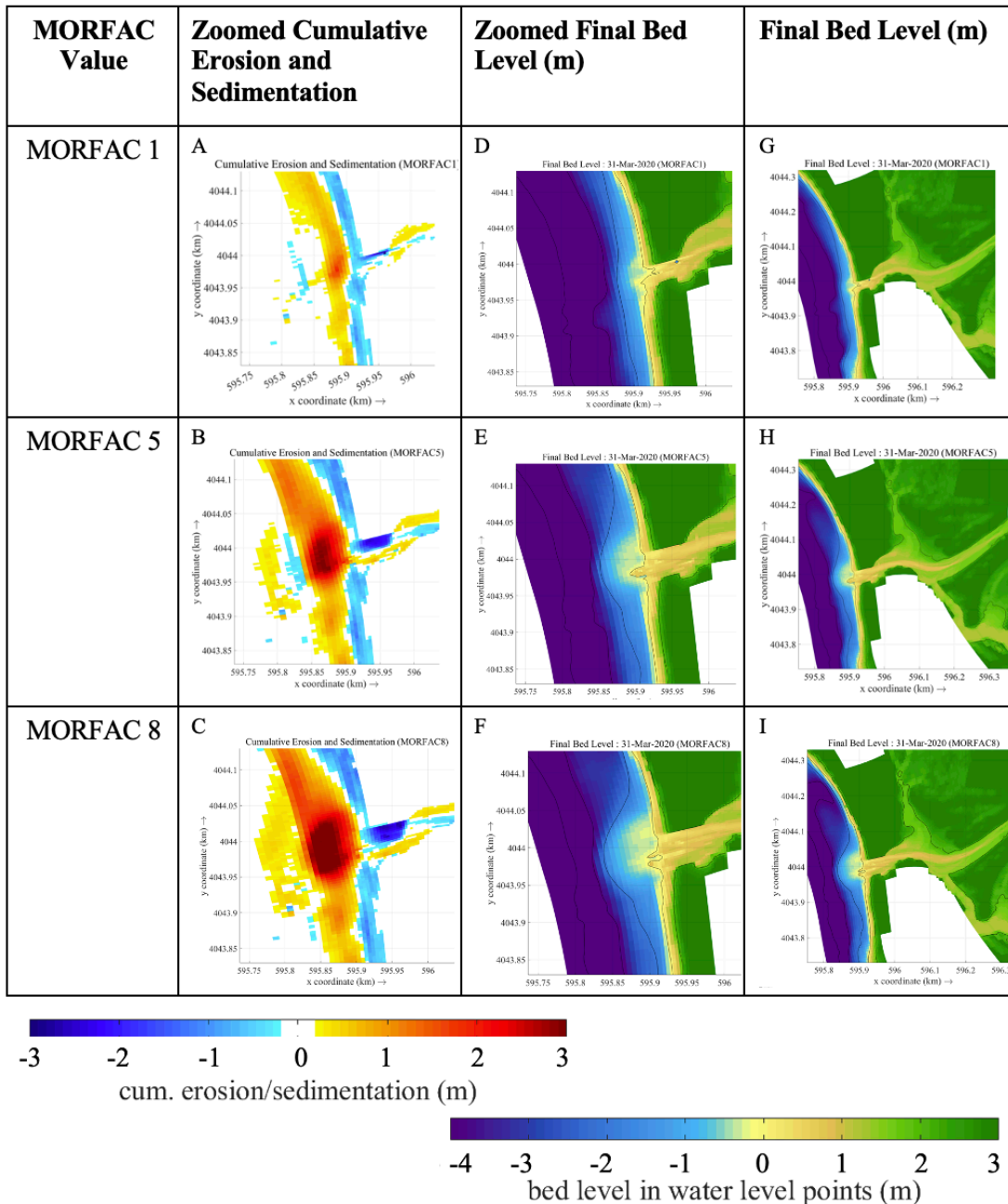
This research uses observational data and imagery to explore four different MORFACs and compare each morphological and hydrodynamic response. Although sparse bathymetry data exists, this approach compares observed sediment distribution patterns with expected morphological patterns and in-situ hydrodynamic responses, which shows the value of persistent observational data for model calibration testing. All changes were compared to the original bathymetry from the 2018 FEMA Lidar: Region 9 CA data set (Figure 10).

There were noticeable responses to manipulating the MORFAC. Using an idealized model of Carmel River, Brennan (2021) determined that MORFAC 5 appropriately modeled the behavior of sedimentation and erosion in bar-built estuaries. MORFAC 1, 5, 8, and 10 were analyzed, with MORFAC 10 resulting in hydrodynamic instabilities which prevented the model from completing. A higher MORFAC value indicates more sediment movement in a shorter duration. As the MORFAC value increases, so does the width and depth of the inlet, evident in panels D-F of Figure 11. In panels A-C of Figure 11, the area of erosion (blue) on the north side of the inlet increases, as well as the Ebb Delta sedimentation (red) offshore with increasing MORFAC. This indicates that the inlet's width expands northward from the protruding southerly headlands, as seen in the real system, which can be understood through a cross-section of the lagoon (Figure 9).



This is the original bathymetry that was used to set up the model from 2018 FEMA Lidar: Region 9, CA. This is used to compare the morphological response. The red box is the area used to compare the cumulative erosion and sedimentation and the final bed level in subsequent figures.

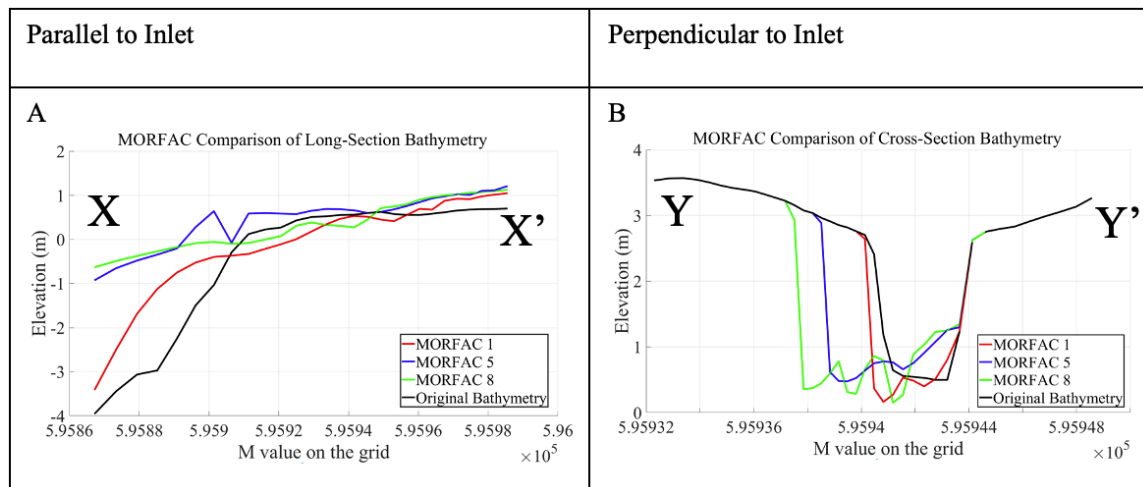
Figure 10. Original bathymetry.



Comparison of the simulated morphological response to different MORFACs. Panels A-C shows the Cumulative Erosion (blue) and Sedimentation (red) around the inlet (area inside the red box of Figure 10) on 31 March 2020. Panels D-F is the final bathymetry zoomed in on the inlet (same spatial extent as A-C) on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88). Panels G-I is the final bathymetry (bed level) in meters on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88).

Figure 11. Cumulative erosion and sedimentation with final bed level comparisons under different MORFAC values.

The modeled bathymetry showed that the Ebb Delta builds higher for the larger MORFAC, apparent in Figure 12, panel A, and the elevations at position X. Additionally, the bathymetry, which runs perpendicular to the river (Figure 12, panel B), proved the widening of the inlet with larger MORFAC. Here the inlet widens, yet the depth remains constant. As MORFAC increases, the riverbed develops sinusoidal patterns, indicating non-homogenous discharge through the horizontal.

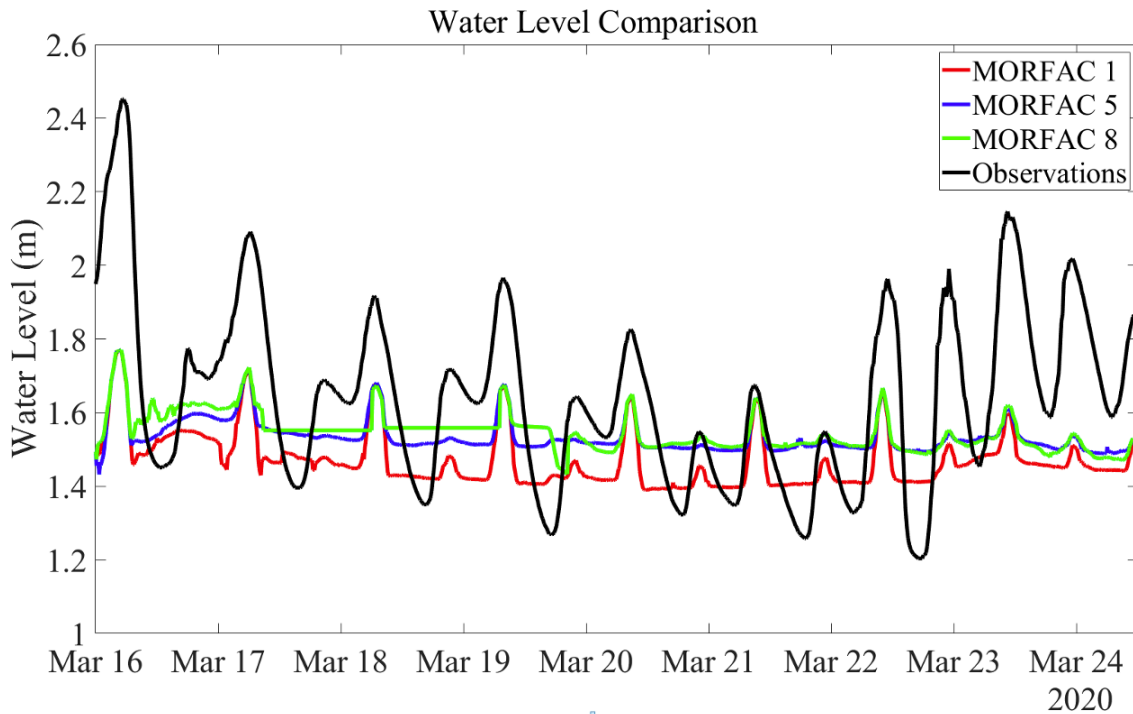


Panel A is the bathymetry parallel to the inlet showing sedimentation to the west compared to the original bathymetry (black). Panel B is the bathymetry perpendicular to the inlet, showing increased inlet width compared to the original bathymetry (black). X & Y are the starting positions, and X' & Y' are the endpoints from Figure 9.

Figure 12. Cross sectional bathymetry profiles parallel and perpendicular to the inlet under different MORFAC values.

This study used observed water level data to understand the hydrodynamic response to varying MORFACs. To understand the hydrodynamic response of the model to various MORFAC values, there was a comparative analysis of the modeled and observed water levels at the River Marker (Figure 2). The inlet was breached but not yet migrated during the observed period, from 16 March 2020 to 24 March 2020. This period was considered for hydrodynamic comparison because it was a fully breached period before the inlet was subject to migration. All the MORFAC values captured general trends with some tidal influences moderately well (Figure 13), with noticeable smoothing for MORFAC 8 (green)

around 17 March to 19 March. MORFAC 1 (red) under-modeled the water levels the most. MORFAC 1 took half the computational time as the other runs, but MORFAC 5 and MORFAC 8 had equivalent computational time. The statistical comparison of the MORFAC values and all other parameters, using Pearson Correlation Coefficient, Root-Mean-Square Deviation, and Willmott Skills are presented in section H. This calibration analysis of MORFAC confirmed MORFAC 5 is the preferred value and is the baseline simulation for further morphology parameter testing. The next parameter to investigate is the rate at which the wet areas transition to the nearby dry grid cells.



Water level for various MORFACs at the river marker (picture of the location of river marker in Figure 2) compared to measured water levels (black).

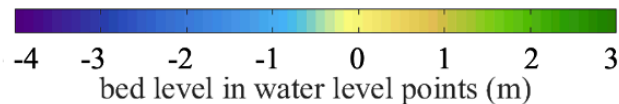
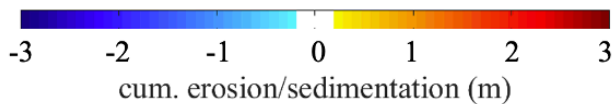
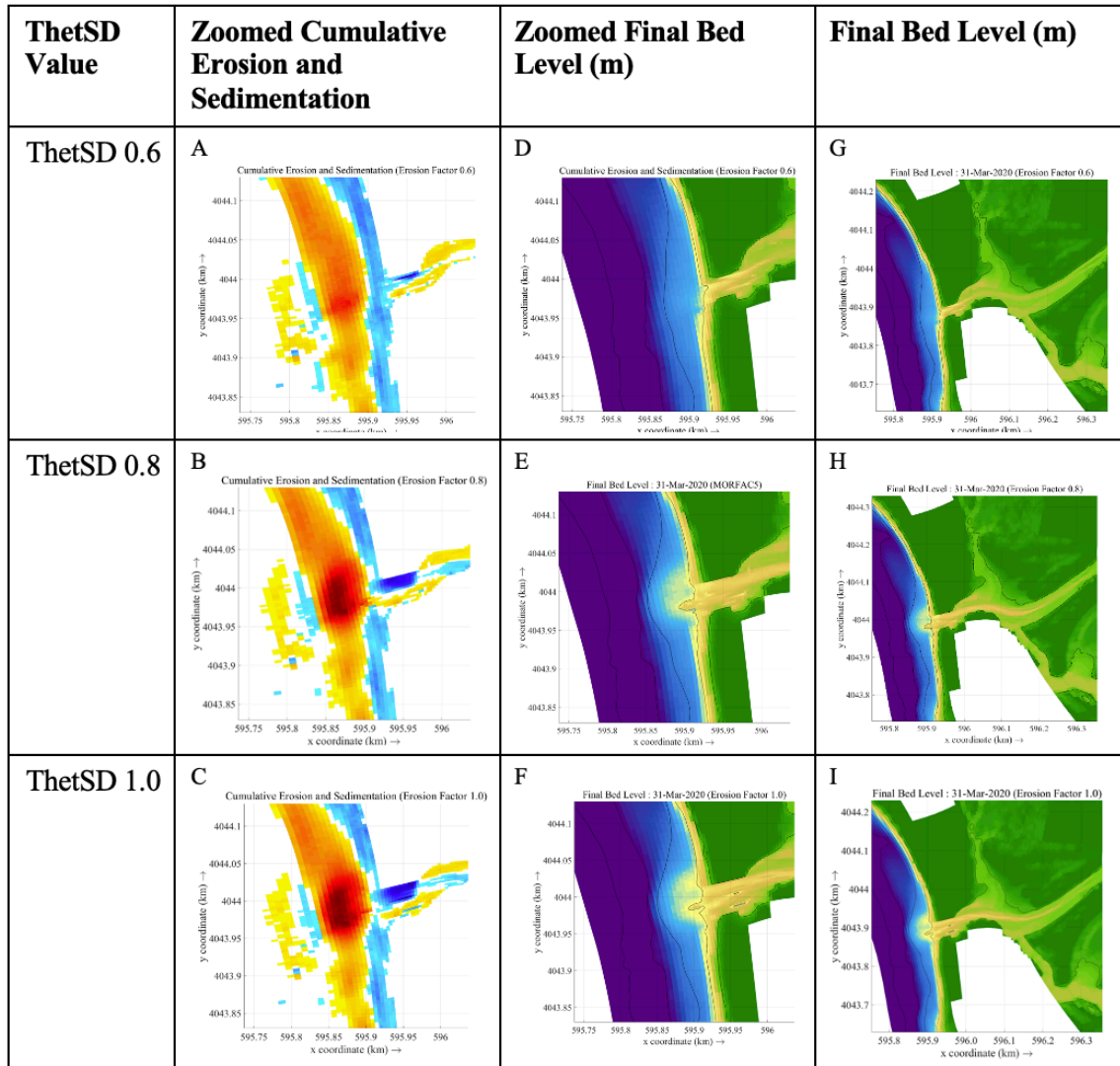
Figure 13. Observed and simulated water levels under different MORFAC values at the River Marker.

C. FACTOR OF EROSION OF ADJACENT DRY CELLS

Another unresolved morphodynamical modeling challenge is the rapid transition region from wet grid cells to adjoining dry cells. Parameterization of this phenomenon

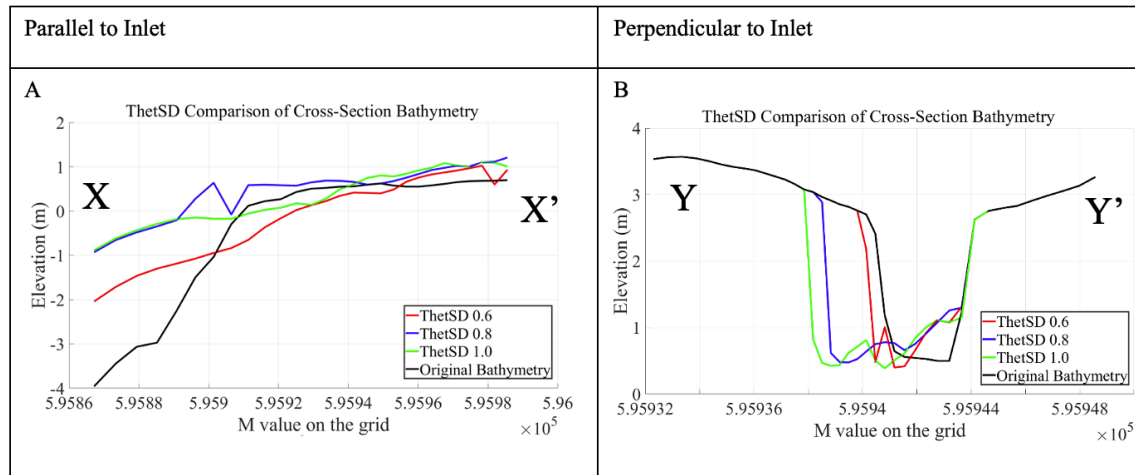
enables the lateral movement of water to adjacent dry cells for erosion. The user sets the distribution of the total amount of erosion over two adjacent cells, a factor of 1.0 (0.5) indicates that all (half) of the erosion of the wet cell is assigned to the adjacent dry cells evenly (Deltares 2023). Ongoing research is refining this parameterization in the long-term evolution of sediment transport over hundreds of years (Van der Wegen 2007). This is a crucial parameter to investigate because Carmel River's rapid inlet erosion is prominent. It is a perched system where the dry cell near the riverbank and inlet easily succumb to water and rapid erosion and migration.

Using the one-at-a-time sensitivity calibration, MORFAC 5 became the baseline simulation for exploring the factor for erosion of adjacent dry cells, referred to as ThetSD in the Delft3D code. This research explored ThetSD values of 0.6, 0.7, 0.8, and 1.0. Visually looking at the sedimentation (Figure 14, panel A-C) shows a larger area of Ebb Delta accretion with an increasing ThetSD. Additionally, there is a linear trend of increased ThetSD relative to increased inlet width (Figure 15, panel B). Notably, ThetSD 0.6 resulted in a sedimentation parallel to the beach from the river northward (Figure 15, panel A), significantly removing the offshore deep bathymetry. ThetSD 0.7 was tested but not shown in any figure due to minimal changes to morphology and hydrodynamic response from ThetSD 0.6.



Comparison of the simulated morphological response to different ThetSDs. Panels A-C shows the Cumulative Erosion (blue) and Sedimentation (red) around the inlet (area inside the red box of Figure 10) on 31 March 2020. Panels D-F is the final bathymetry zoomed in on the inlet (same spatial extent as A-C) on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88). Panels G-I is the final bathymetry (bed level) in meters on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88).

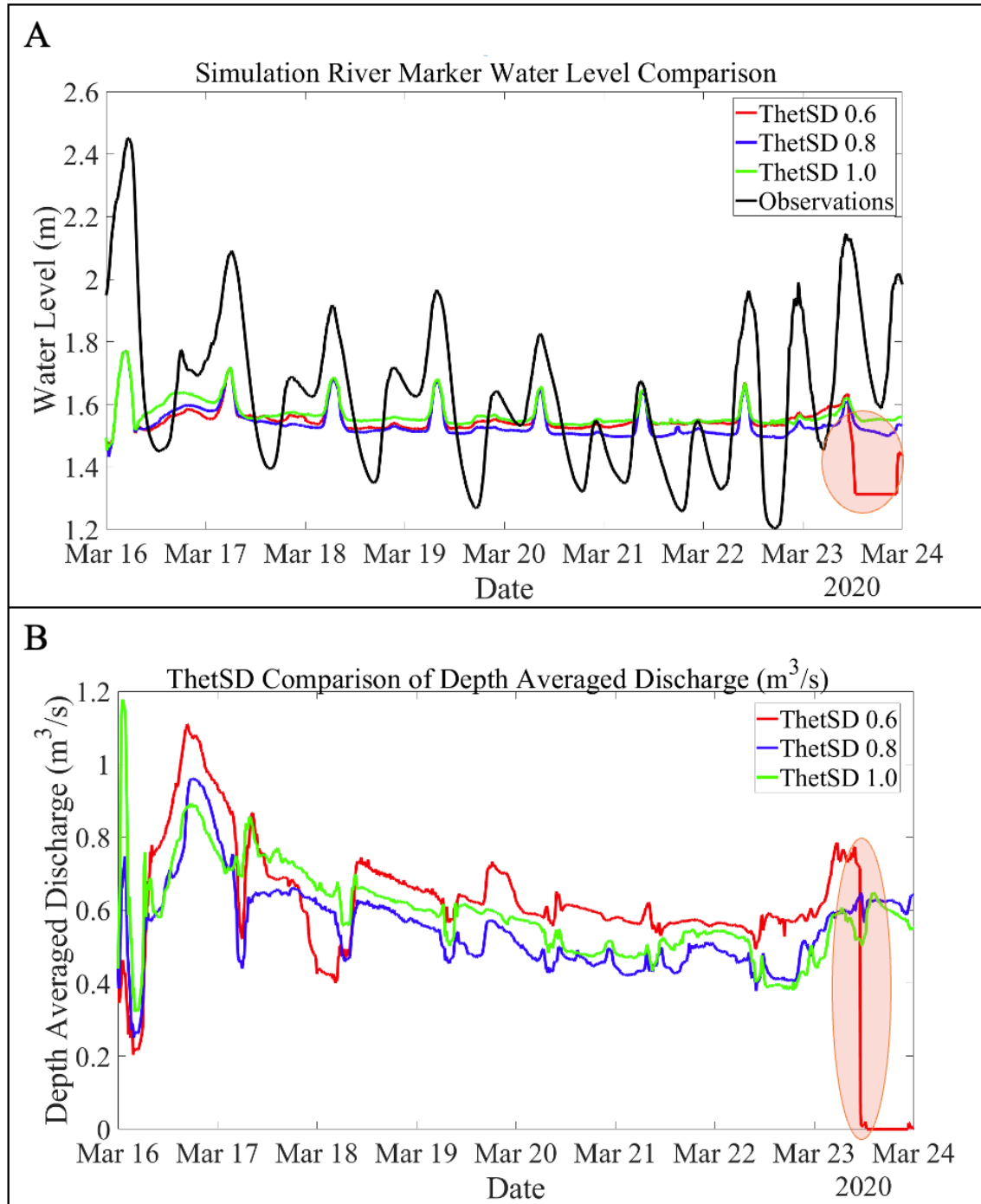
Figure 14. Cumulative erosion and sedimentation with final bed level comparisons under different ThetSD values.



Panel A is the bathymetry parallel to the inlet showing sedimentation to the west compared to the original bathymetry (black). Panel B is the bathymetry perpendicular to the inlet, showing increased inlet width compared to the original bathymetry (black). X & Y are the starting positions and X' & Y' are the endpoints from Figure 9.

Figure 15. Cross sectional bathymetry profiles parallel and perpendicular to the inlet under different ThetSD values.

From a hydrodynamic stance, this transition area where the river discharge meets the coastal water is highly dynamic with the exchange between tidal water level fluctuation, wave and wind-driven currents, swash, and wave energy variation, which necessitates exploration of this parameter's sensitivity. The observed water level was compared against the modeled water level for each ThetSD value, and ThetSD 1.0 followed the trends best with ThetSD 0.6 displaying instabilities around 23 March 2020 (Figure 16, panel A). Such instabilities are presented in Figure 16 panel B, where the depth-averaged discharge at the river marker dropped suddenly, leading to unrealistic model outputs.



The hydrodynamic response to various ThetSD values. Panel A is the water level (m) at the river marker, and panel B is the depth-averaged discharge (m^3/s) at the river marker. Note: instabilities of ThetSD 0.6 are circled in red.

Figure 16. Hydrodynamic response to varying ThetSD values – 0.6 (red), 0.8 (blue) and 1.0 (green) at the River Marker.

From Figure 16, panel B, ThetSD 0.6 resulted in a larger discharge value compared to other simulations, this result is likely related to the constriction of the smaller inlet width. Again, there were instabilities with ThetSD 0.6 around 23 March 2020. It was surprising to see that ThetSD 0.8 had the lowest discharge values for most of the period. For all ThetSD values, the modeled water level is still below the observed levels, apart from the high tide on 21 March 2020 (Figure 16 panel A). Based on the results of these sensitivity tests, a dry cell erosion factor of 1.0 gave the best model results compared to the systems trends. The selection of a larger ThetSD is reasonable, as Camel River is a perched system that enhances the movement and erosion of dry sand surrounding the riverbanks. The next parameter to test is the movement of suspended sediment.

D. MORPHOLOGICAL CALIBRATION CURRENT-RELATED FACTORS

The computed sediment transport contains two current-related contributions, current-related suspended load, and current-related bedload. These contributions can be scaled using f_{sus} and f_{bed} using Van Rijn's calculations. The sources and sink terms of the advection-diffusion equation are multiplied by f_{sus} and affect the current-related suspended load. Van Rijn transport formulas (Deltares 2023) refer to the current-related suspended transport as $S_{s,c}$ and current-related bedload transport as $S_{b,c}$.

1. Current-Related Reference Concentration Factor

The transport of suspended sand is enhanced by the force of currents and waves in the system (Nienhuis and Ashton 2016). This modeled parameter, f_{sus} , will be referred to as Sus , as it is found in the morphology input file. This analysis leverages the work from Van Rijn, which distinguishes between sediment transport below or above the reference height (Van Rijn 2007). Below the reference height is treated as bedload transport, and sediment above the reference height is treated as suspended load. Sus alters the suspended load proportionally to the relative availability of the sediment fraction in the top layer of the bed (Deltares 2023). Sediment entrained through the system is accounted for by imposing this parameter at the reference height.

Suspended sediment can be seen through aerial imagery as a plume, evident in the contrasting color of the water. This is most apparent when the Carmel River is breached,

and sediment discharge flows into the ocean (Figure 17). Delft3D resolves suspended sediment through the advection-diffusion equation. This study will explore Sus values of 0.5, 1.0, 3.0, and 5.0 to understand the impacts of suspended sediment on the morphological response of the system. The default value for Sus is 1.0 (Deltares 2023), where 0.5 will allow less sediment into suspension due to currents, and 5.0 will enable more sediment to be suspended for erosion and sedimentation. Sus is explored the same way as the previously determined MORFAC 5 and ThetSD 1.0, using the morphology output files and hydrodynamic response for Sus values 0.5, 1.0, 3.0, and 5.0.

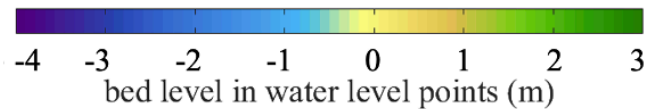
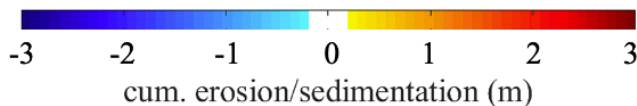
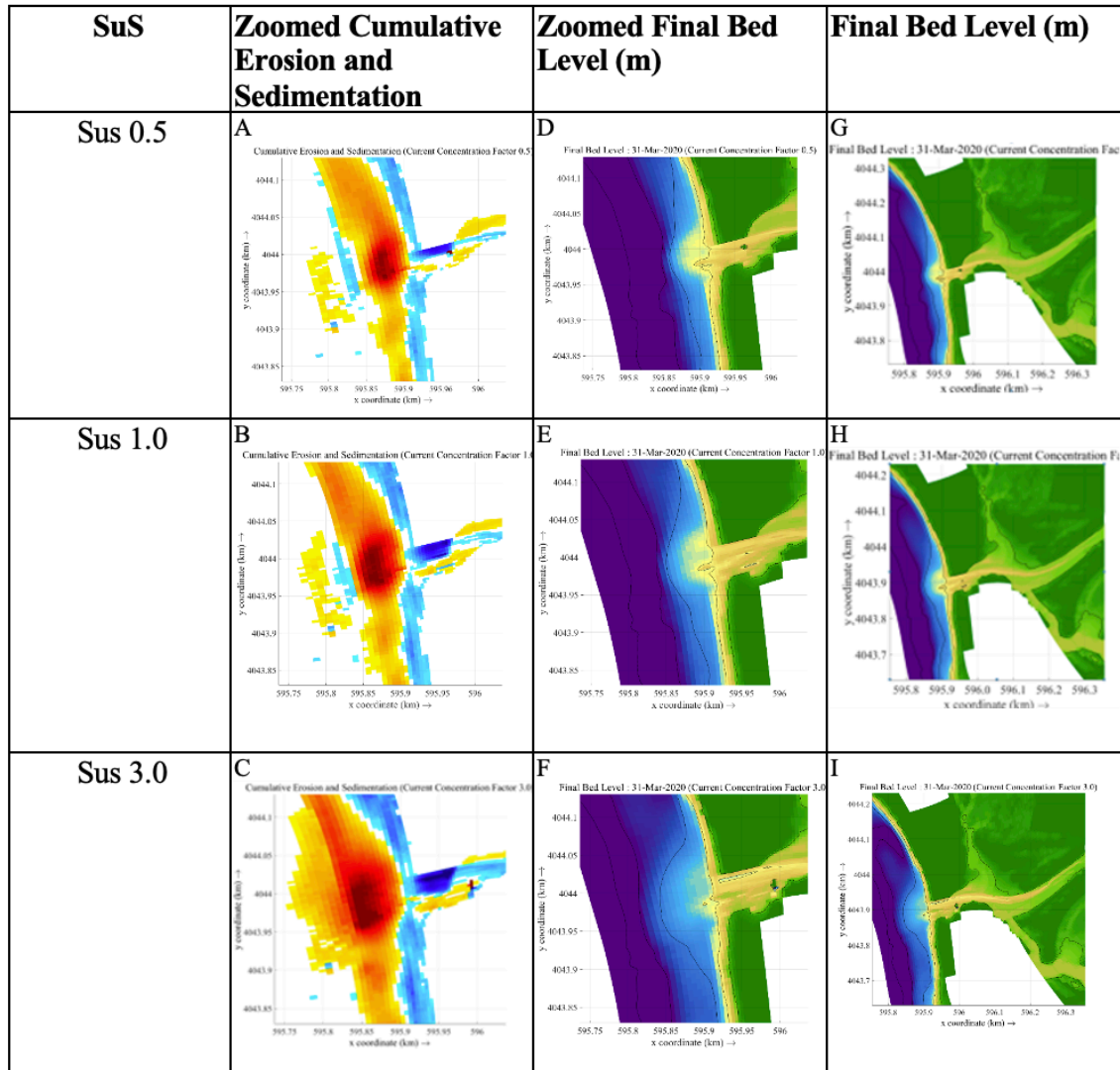


This is an example of the plume taken from aerial imagery. The water closer to the inlet is darker brown, indicating transported sediment in the water column.

Figure 17. Aerial imagery of a plume in the Carmel Bay.

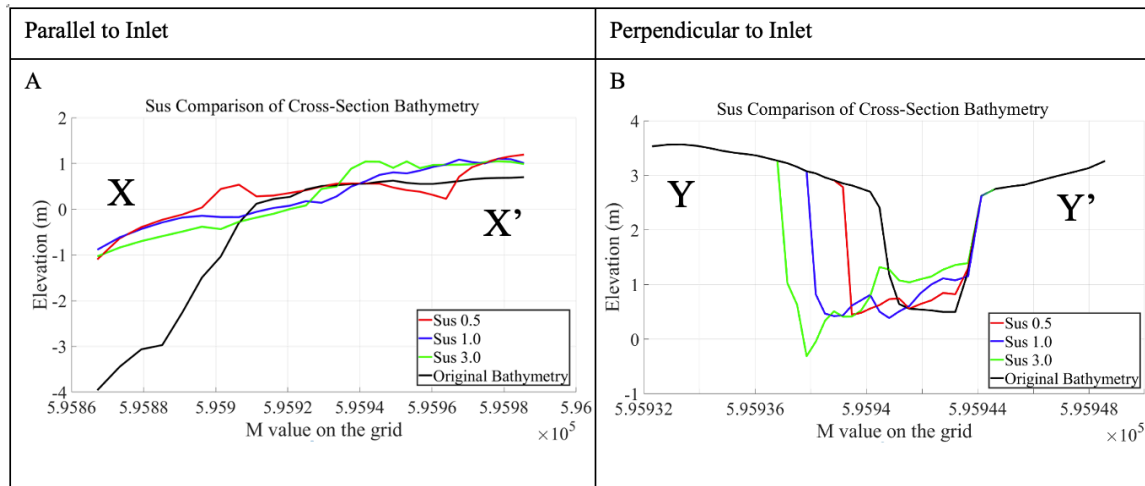
The transport gradients in the x- and y-direction respective of the current forcings are used in the sediment continuity equation (van Rijn and Roelvink 2001). This calculation is used to determine bed level changes (Figure 18). A Sus value of 5.0 resulted in instabilities that prevented the simulation from completing and, therefore, will not be used for comparison nor discussed further. There was an increased area of sedimentation offshore, forming an Ebb Delta, as Sus increased, apparent in Figure 18 panel A-C and Figure 19 panel A. This response is expected as the currents increase the amount of

suspended sediment transported from the river discharge, building up the Ebb Delta. Inlet width increases by northward erosion as Sus increases, which is also an expected outcome (Figure 19 panel B). The geometry on the inlet becomes more complex as Sus increases. As Sus increases, the channel becomes deeper and more defined in the back of the river. As the river gets deeper (Figure 18 panel G-I), the pockets of maximum erosion and sedimentation on the banks (Figure 18 panel A-C) become more apparent.



Comparison of the simulated morphological response to different Sus values. Panels A-C shows the Cumulative Erosion (blue) and Sedimentation (red) around the inlet (area inside the red box of Figure 10) on 31 March 2020. Panels D-F is the final bathymetry zoomed in on the inlet (same spatial extent as A-C) on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88). Panels G-I is the final bathymetry (bed level) in meters on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88).

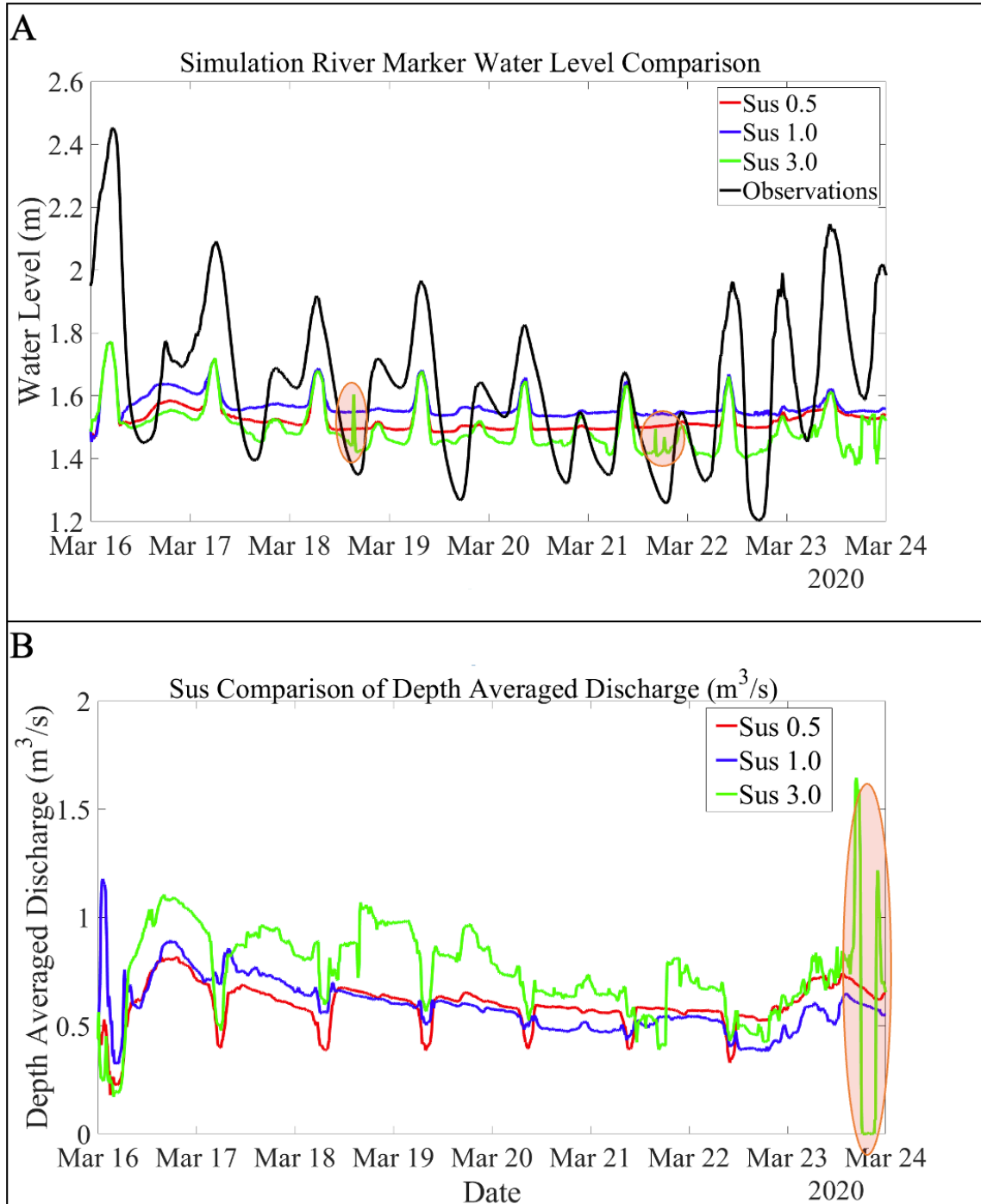
Figure 18. Cumulative erosion and sedimentation with final bed level comparison under different Sus values.



Panel A is the bathymetry parallel to the inlet showing sedimentation to the west compared to the original bathymetry (black). Panel B is the bathymetry perpendicular to the inlet, showing increased inlet width compared to the original bathymetry (black). X & Y are the starting positions and X' & Y' are the endpoints from Figure 9.

Figure 19. Cross sectional bathymetry profiles parallel and perpendicular to the inlet under different Sus values.

Analyzing the hydrological response from 16 March 2020 to 24 March 2020, aided the calibration of Sus. Evaluating both the discharge and the water levels at the River Marker (Figure 2) showed that Sus 3.0 suffered from instabilities, evident in the inconsistencies of the water level and discharge (Figure 20). For this reason, Sus 3.0 was determined unsuitable for this model. The water levels remain below the observational data for all the tested Sus values. On 18 March, the discharge of the smallest Sus value, 0.5, surpassed the discharge rate of the larger Sus value, 1.0. This correlates to the point when the width of the inlet for the smallest Sus is not increasing as fast as the width for Sus 1.0. This smaller width of the inlet constricts flow resulting in larger discharge values. Based on the results of this calibration analysis and the common practice of setting Sus to 1.0 (Deltares 2023; Briere et al. 2011). A Sus value of 1.0 produced the most realistic outputs without instabilities and is the best fit. Next, this study will calibrate the current-related transport vector magnitude factor, f_{bed} .



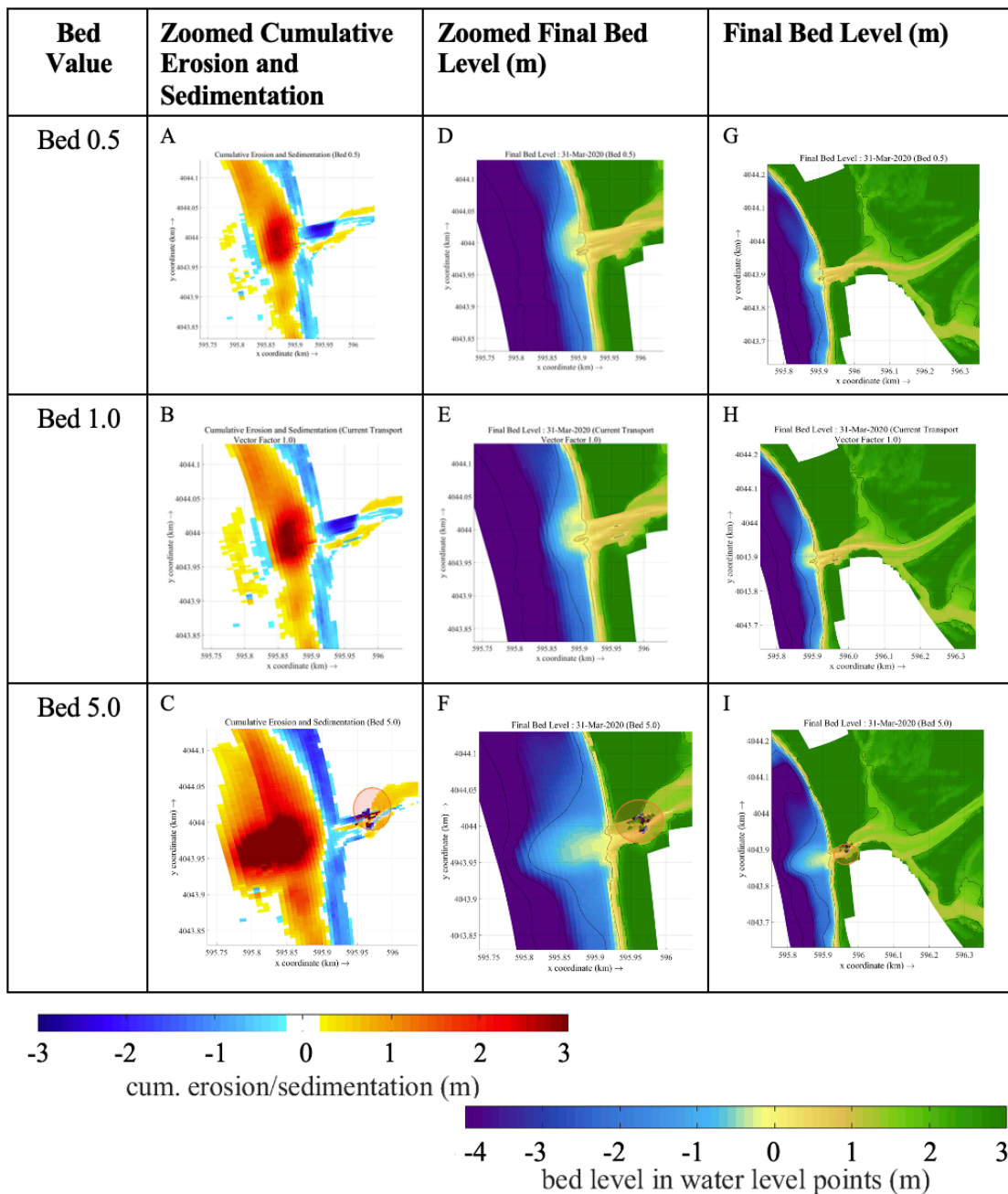
The hydrodynamic response to various Sus values . Panel A is the water level (m) at the river marker and panel B is the depth averaged discharge (m^3/s) at the river marker. Note the highlighted areas are areas of notable instabilities in the green line (Sus 3.0)

Figure 20. Hydrodynamic response to varying Sus values, 0.5 (red), 1.0 (blue) and 3.0 (green) at the River Marker.

2. Current-Related Transport Vector Magnitude Factor

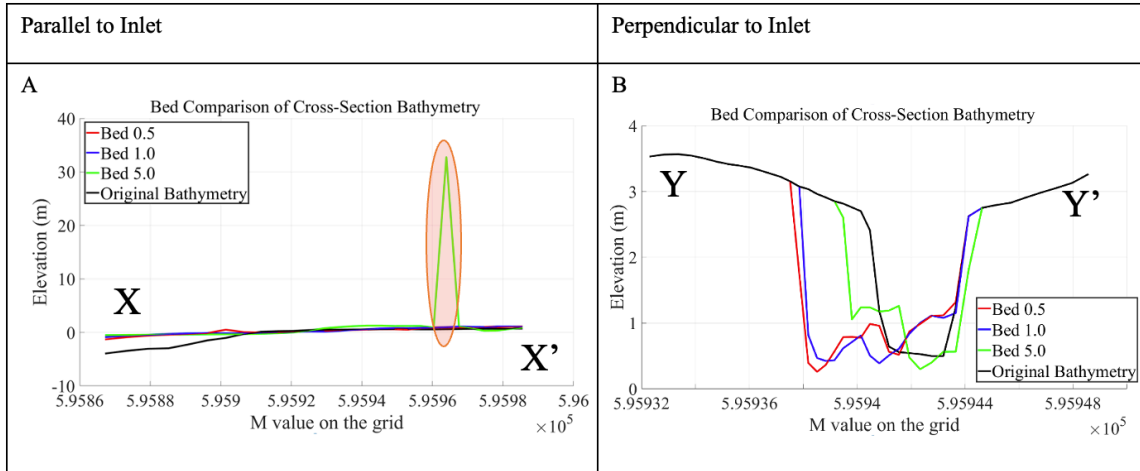
The current-related transport vector magnitude factor will be referred to as Bed from the morphology input file. With MORFAC 5, ThetSD 1.0, and Sus 1.0, Bed values of 0.5, 1.0, and 5.0 were used for calibration. The sediment on the bedload, below the reference height, is less inclined to be relocated with 0.5 value compared to 5.0 value from current related forces.

The morphological response to Bed 0.5, 1.0, and 5.0 showed an increased sedimentation area offshore with increased values. Bed 5.0 resulted in instabilities in the sediment outputs, bed level output, and cross-sectional output near the inlet, which made this value unsuitable (Figure 21, panels C,F,I, Figure 22, panel A). There is a minor difference in the morphological response associated with Bed 0.5 and 1.0; where Bed 1.0 resulted in slightly larger sedimentation (Figure 21 panel A&B). There was no difference in the inlet width for all values, but Bed 0.5 kept a consistent channel depth while the other values increased the depth (Figure 22, panel B).



Comparison of the simulated morphological response to different Bed values. Panels A-C shows the Cumulative Erosion (blue) and Sedimentation (red) around the inlet (area inside the red box of Figure 10) on 31 March 2020. Panels D-F is the final bathymetry zoomed in on the inlet (same spatial extent as A-C) on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88). Panels G-I is the final bathymetry (bed level) in meters on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88). Note the instabilities for Bed 5.0 circled in red.

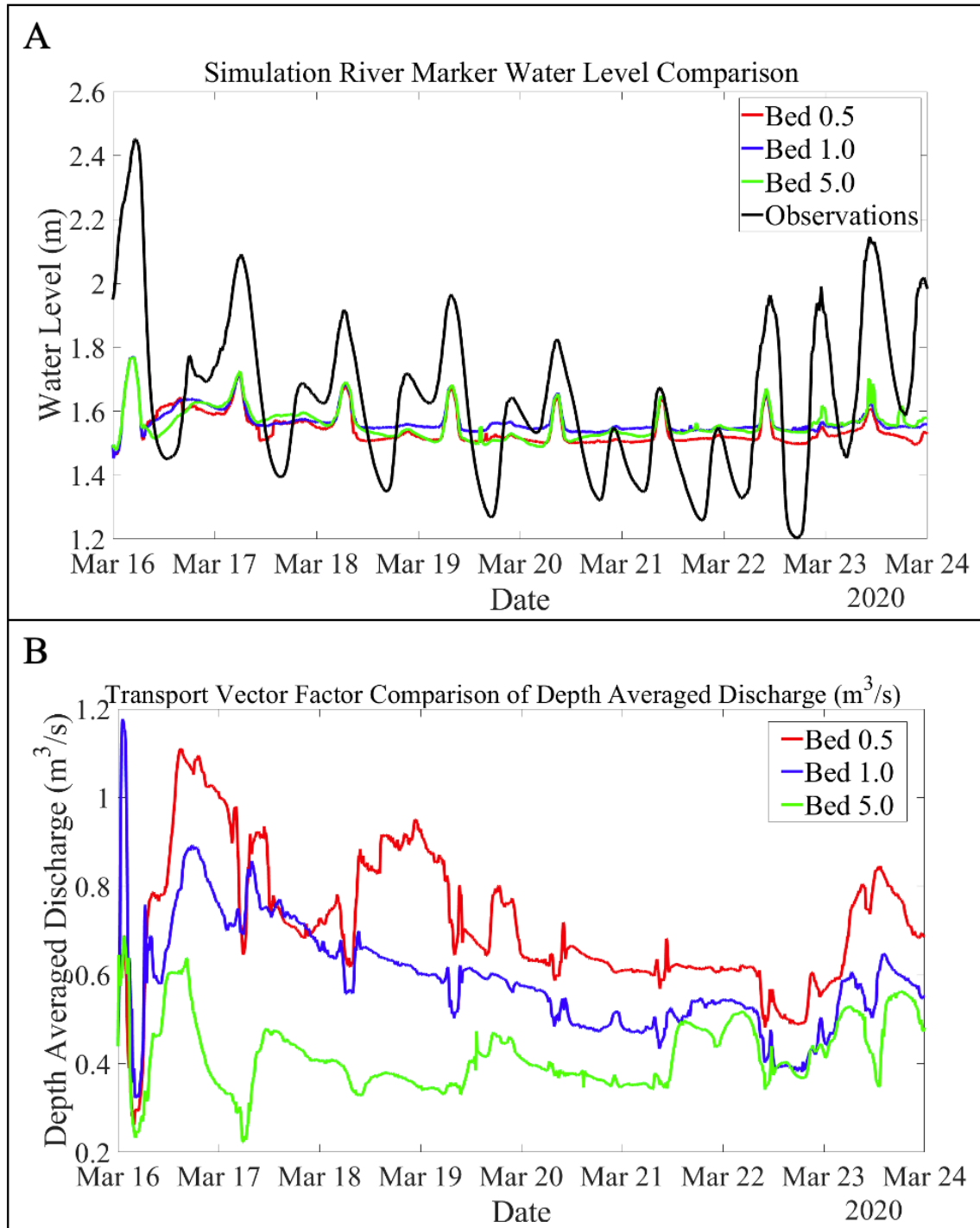
Figure 21. Cumulative erosion and sedimentation with final bed level comparisons under different Bed values.



Panel A is the bathymetry parallel to the inlet showing slight sedimentation to the west compared to the original bathymetry (black). Panel B is the bathymetry perpendicular to the inlet, showing increased inlet width compared to the original bathymetry (black). X & Y are the starting positions and X' & Y' are the endpoints from Figure 9. Note the area of instability for Bed 5.0 is circled in panel A.

Figure 22. Cross sectional bathymetry profiles parallel and perpendicular to the inlet under different Bed values.

Analyzing the hydrological response from 16 March 2020 to 24 March 2020, aided the calibration between Bed 0.5 and 1.0. Bed 1.0 is slightly closer to the observed water levels (Figure 23, panel A). Bed 0.5 showed slightly lower discharge values than 1.0, which correlates to the slightly larger inlet width of Bed 0.5 (Figure 23, panel B). Based on the calibration analysis results and the common practice of setting Bed to 1.0, a current-related reference concentration factor of 1.0 produced the most realistic outputs without instabilities. The next parameters to analyze are the sediment transport settings due to wave-related forces.



The hydrodynamic response to Bed values. Panel A is the water level (m) at the river marker and panel B is the depth-averaged discharge (m^3/s) at the river marker.

Figure 23. Hydrodynamic response to varying Bed, 0.5 (red), 1.0 (blue) and 5.0 (green) at the River Marker.

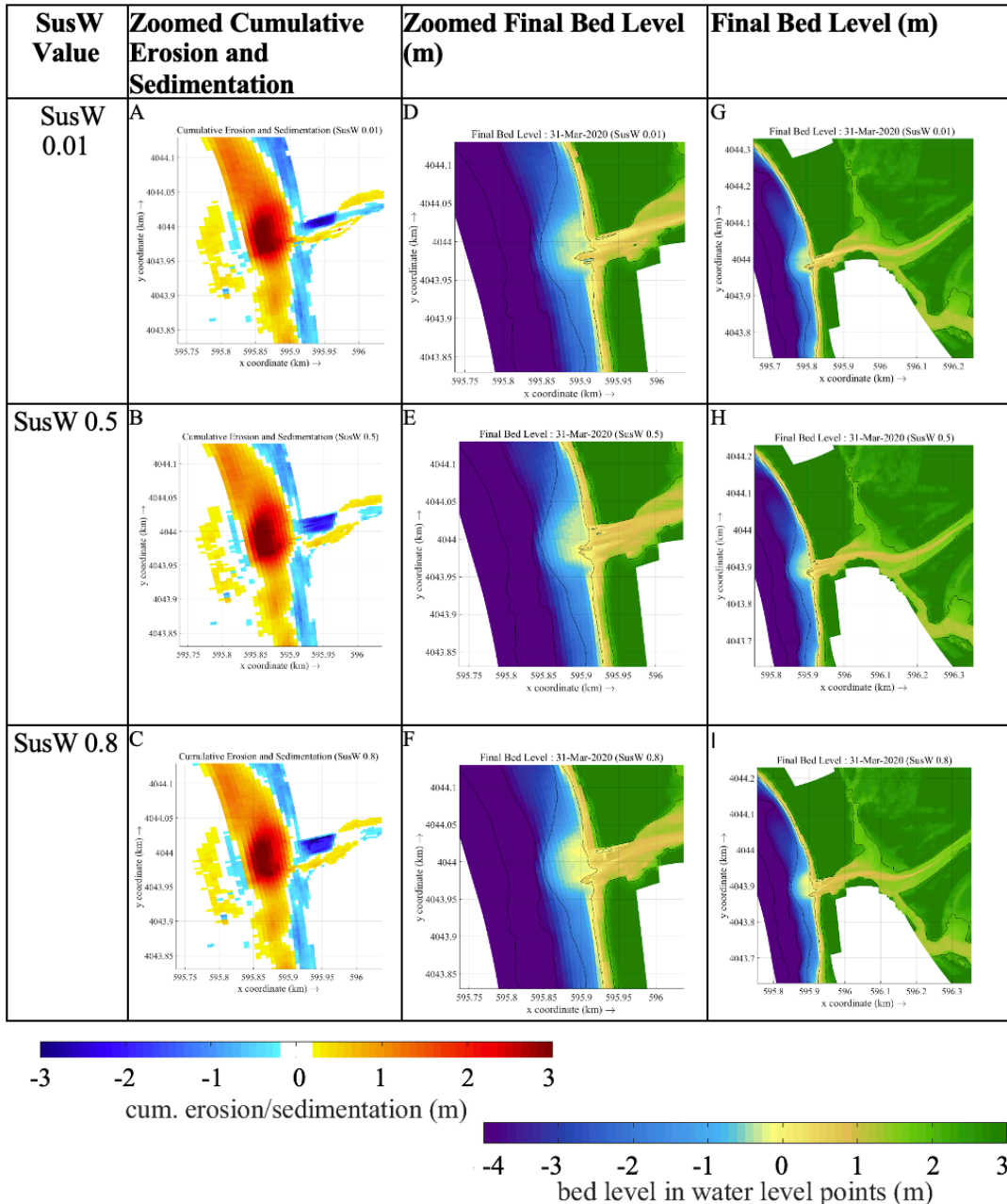
E. MORPHOLOGICAL CALIBRATION WAVE-RELATED FACTORS

The computed sediment transport contains two wave-related contributions, wave-related suspended load, and wave-related bedload. Using Van Rijn's calculations, these contributions can be scaled using $f_{sus,w}$ and $f_{bed,w}$, respectively. In Van Rijn transport formulas, wave-related suspended transport ($S_{s,w}$) and wave-related bedload transport ($S_{b,w}$) determine bed-level changes in the morphology outputs.

1. WAVE-Related Suspended Transport Factor

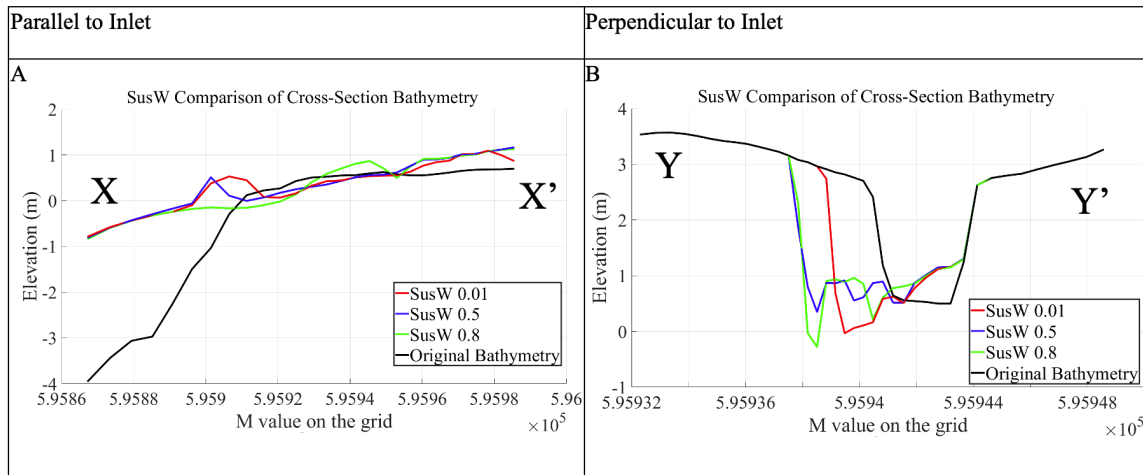
The wave-related suspended transport (SusW) approximates the suspended sediment movement due to the forces of wave velocity asymmetry. This calibration setting models the effect of asymmetric wave orbital velocities on the suspended material within about 0.5m of the bed. The following settings were used to calibrate SusW; MORFAC 5, ThetSD 1.0, and Sus 1.0, and Bed 0.5. This calibration explores the effect of SusW 0.01, 0.15, 0.5, and 0.8.

SusW parameter has a noticeable impact on the erosion of the northern bank of the channel. A SusW of 0.15 is not graphically depicted but can be viewed in the previous parameter (Figure 21, panels B, E, H). Although sedimentation of the Ebb Delta increases slightly for each increasing SusW values, it is not as apparent as the current-related calibration tests (Figure 24, panels A-C). Both SusW 0.1 and 0.5 built up the offshore area more than 0.8 (Figure 25, panel A). There is slightly enhanced deposition to the northern portion of the Ebb Delta; consistent with the northward migration. There is a substantial change to the inlet depth and width (Figure 25, panel B) and associated inlet erosion (Figure 25 panels A-C). The inlet width was nearly the same for SusW 0.5 and 0.8, but the channel depth increased more for SusW 0.8. This calibration setting also evaluated the hydrodynamic response to each changing SusW value.



Comparison of the simulated morphological response to different SusW values. Panels A-C shows the Cumulative Erosion (blue) and Sedimentation (red) around the inlet (area inside the red box of Figure 10) on 31 March 2020. Panels D-F is the final bathymetry zoomed in on the inlet (same spatial extent as A-C) on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88). Panels G-I is the final bathymetry (bed level) in meters on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88).

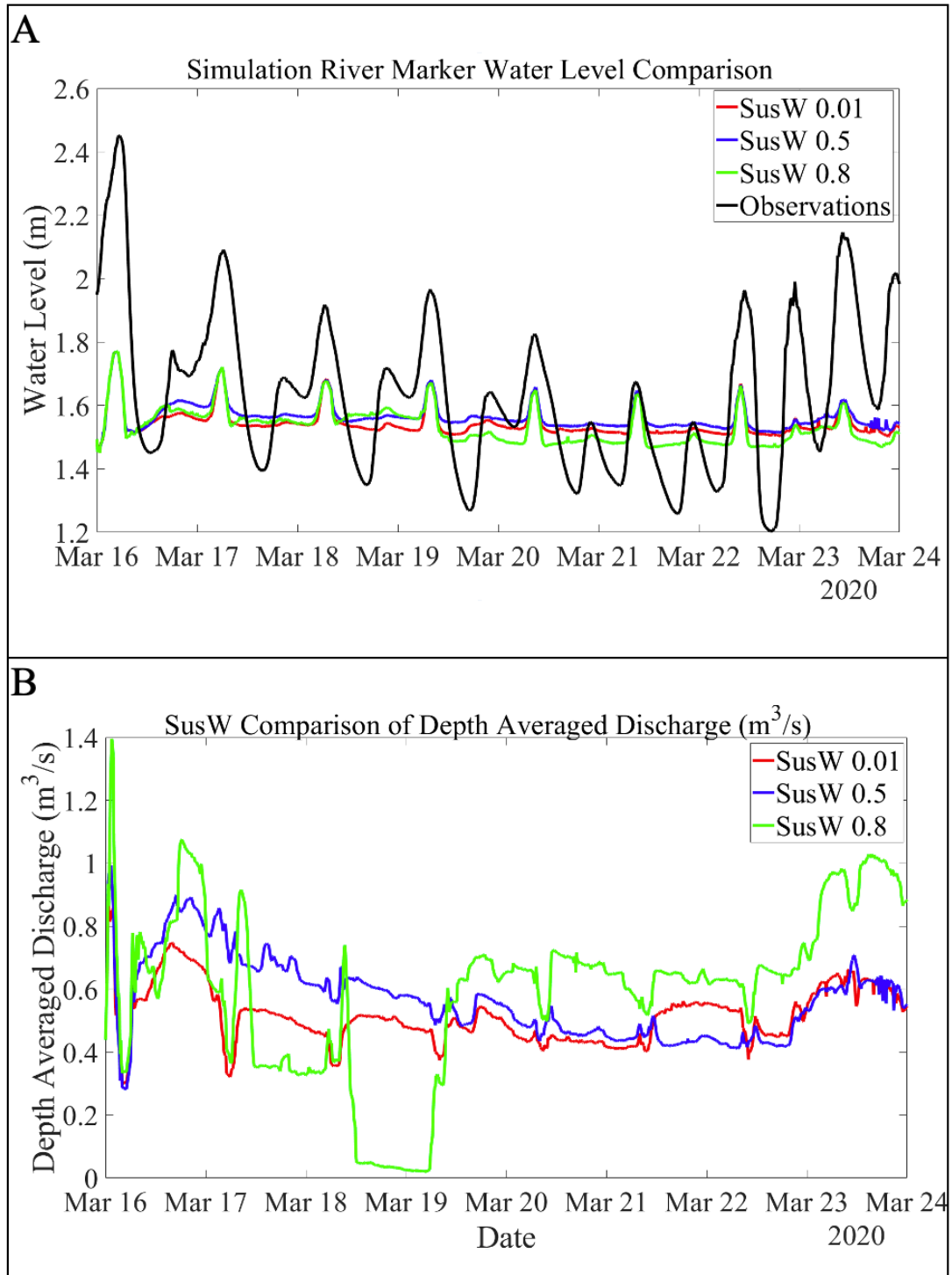
Figure 24. Cumulative erosion and sedimentation with final bed level comparisons under different SusW values.



Panel A is the bathymetry parallel to the inlet showing sedimentation to the west compared to the original bathymetry (black). Panel B is the bathymetry perpendicular to the inlet, showing increased inlet width compared to the original bathymetry (black). X & Y are the starting positions and X' & Y' are the endpoints from Figure 9.

Figure 25. Cross sectional bathymetry profiles parallel and perpendicular to the inlet under different SusW values.

The hydrodynamic response evaluated the water levels and the depth-averaged discharge at the River Marker (Figure 2). There was still a discrepancy between the measured water levels and all the evaluated SusW values (Figure 26, panel A) and variable discharge, with no discernable correlation between SusW values and discharge (Figure 26, panel B). SusW value 0.5 provided the most realistic results as there was substantial inlet width development with erosion on the northern side of the inlet without substantial channel depth increase. The northward erosion and consistent depths align with the northward migration and expected progression of the inlet at CRSB.



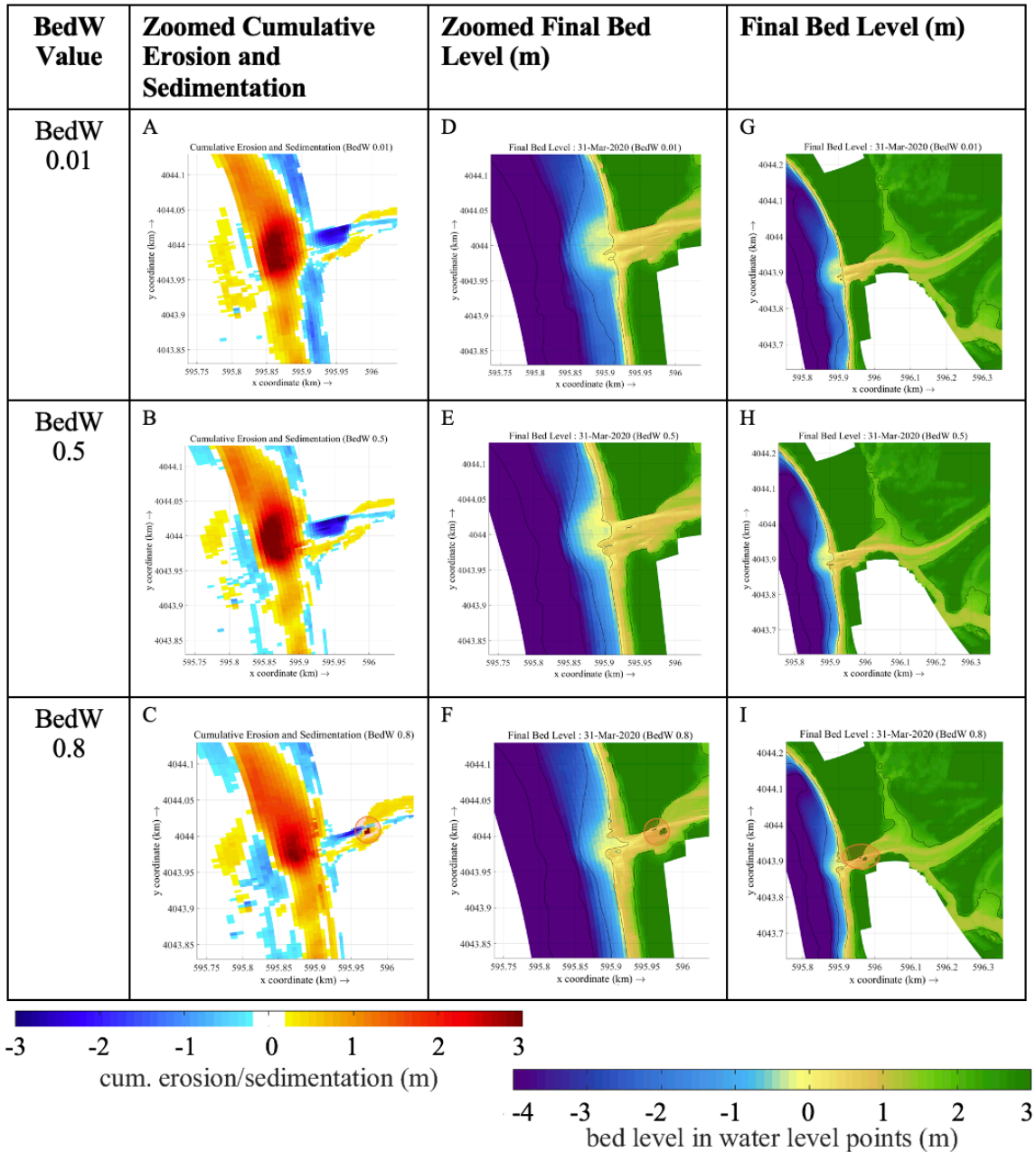
The hydrodynamic response to SusW values. Panel A is the water level (m) at the river marker and panel B is the depth-averaged discharge (m^3/s) at the river marker.

Figure 26. Hydrodynamic response to varying SusW, 0.01 (red), 0.5 (blue) and 0.8 (green) at the River Marker.

2. Wave-Related Bed-Load Transport Factor

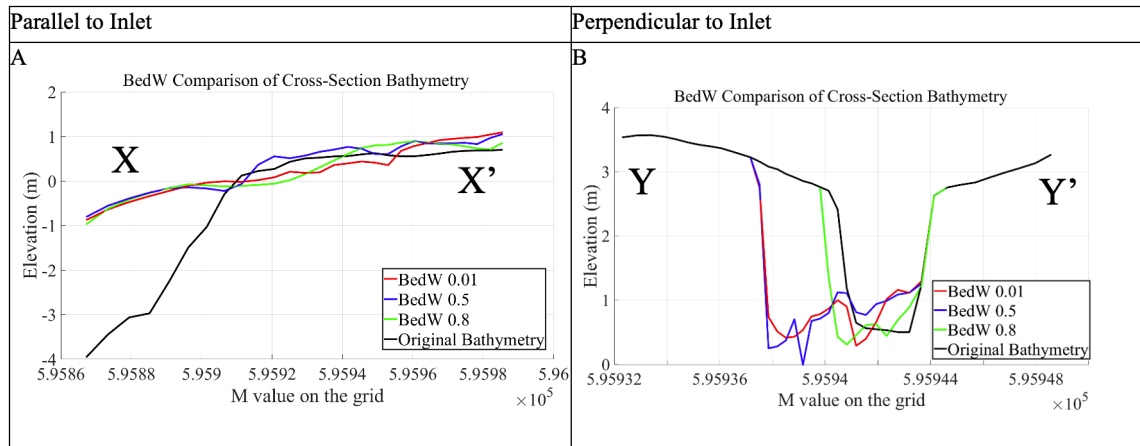
The wave-related bed-load transport factor (BedW) is calculated using time averaging of the instantaneous transport rate using the approximation method proposed by Van Rijn (2001). BedW was calibrated using MORFAC 5, ThetSD 1.0, and Sus 1.0, Bed 0.5, and SusW 0.5. This calibration parameter explored four different values for BedW; 0.01, 0.15, 0.5, and 0.8.

The offshore sedimentation area was similar with both BedW 0.01 and 0.5. BedW 0.8 had a larger swath of sedimentation northward (Figure 27 panels A-C). The width of the inlet was consistent with BedW 0.01 and 0.5 but was a smaller width for BedW 0.8 (Figure 28 panels E-G and Figure 28 panel B). In the morphology outputs, there were minor instabilities displayed in the channel in BedW 0.8.



Comparison of the simulated morphological response to different BedW values. Panels A-C shows the Cumulative Erosion (blue) and Sedimentation (red) around the inlet (area inside the red box of Figure 10) on 31 March 2020. Panels D-F is the final bathymetry zoomed in on the inlet (same spatial extent as A-C) on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88). Panels G-I is the final bathymetry (bed level) in meters on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88). Note the instabilities circles in red for BedW 0.8.

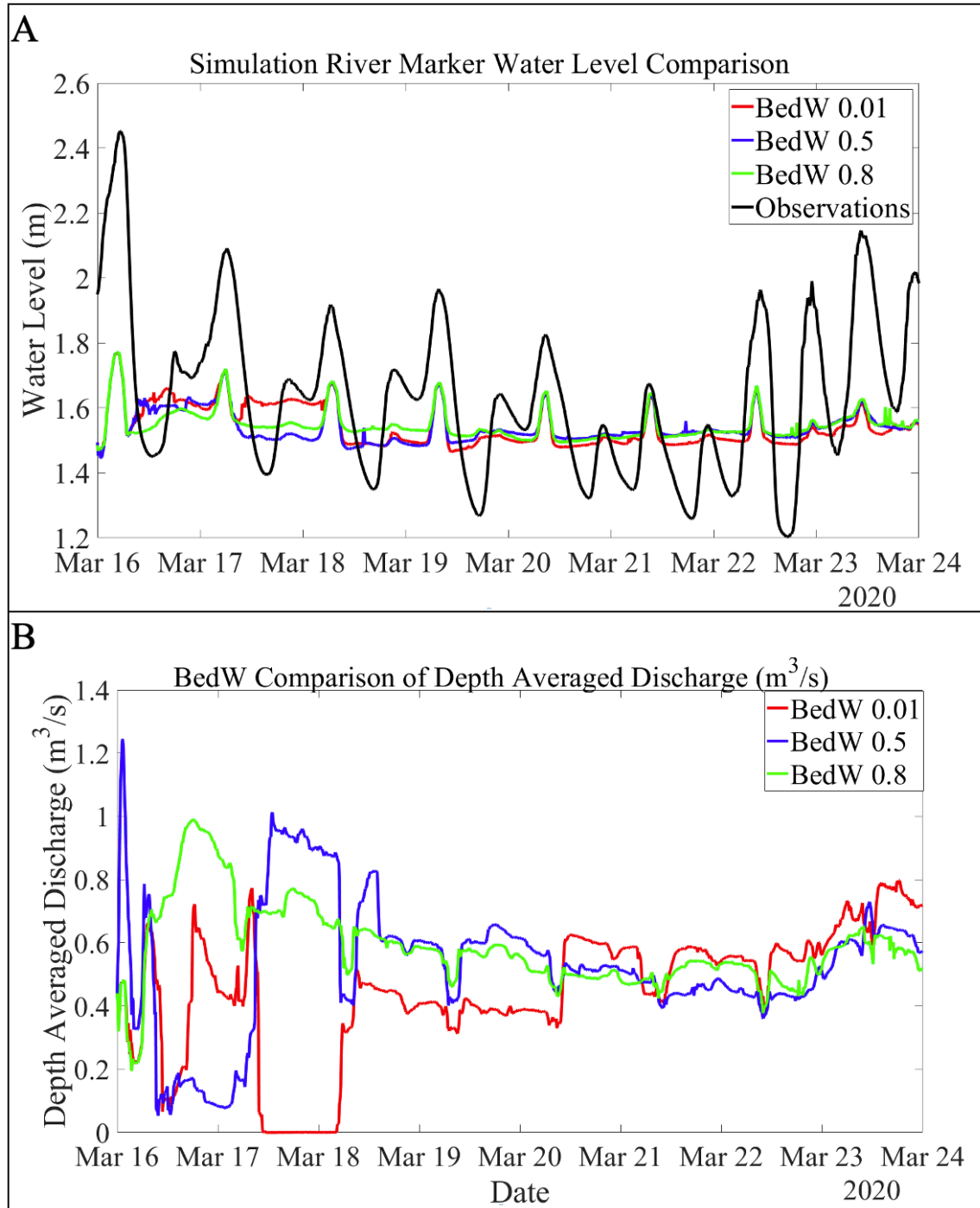
Figure 27. Cumulative erosion and sedimentation with final bed level comparisons under different BedW values.



Panel A is the bathymetry parallel to the inlet showing sedimentation to the west compared to the original bathymetry (black). Panel B is the bathymetry perpendicular to the inlet, showing increased inlet width compared to the original bathymetry (black). X & Y are the starting positions and X' & Y' are the endpoints from Figure 9.

Figure 28. Cross-sectional bathymetry profiles parallel and perpendicular to the inlet under different BedW values.

The hydrodynamic response to changing the BedW values did not resolve significant changes. There were no significant changes to the water level as all values were consistently below the observed water levels (Figure 29, panel A). The discharge values resembled a non-linear trend and fluctuated from March 16 to March 24th. The BedW 0.5 value was selected as it resulted in reasonable inlet width and expected northward migration without significantly increasing depth.



The hydrodynamic response to BedW values. Panel A is the water level (m) at the river marker and panel B is the depth-averaged discharge (m^3/s) at the river marker.

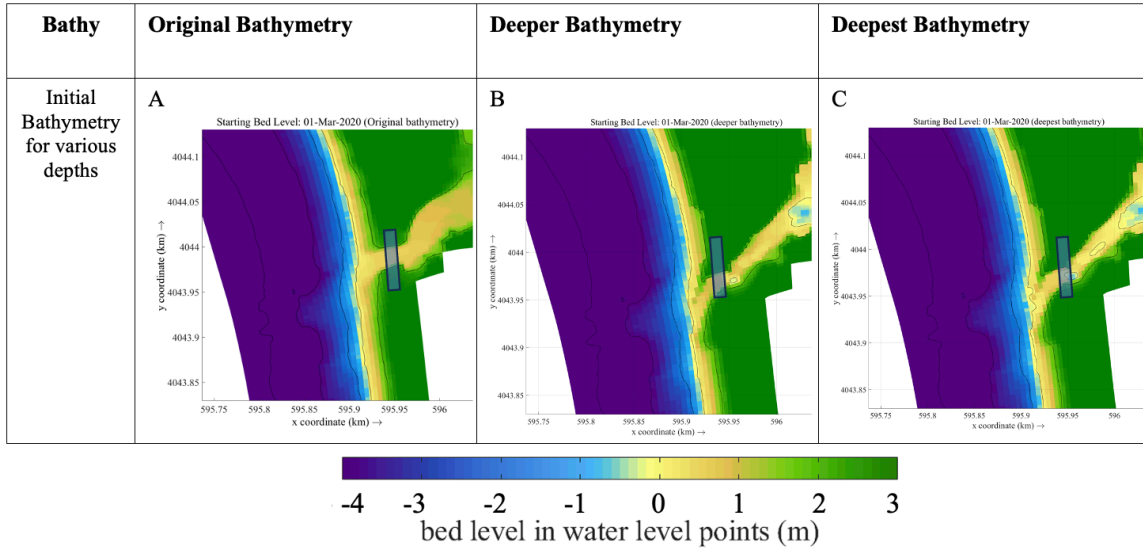
Figure 29. Hydrodynamic response to varying BedW, 0.01 (red), 0.5 (blue) and 0.8 (green) at the River Marker.

F. THE INFLUENCE OF INITIAL BATHYMETRY ON THE WATER LEVELS IN THE LAGOON

The bathymetry used to establish the lagoon grid was sourced from a 2018 data set (Figure 10) and this research aims to understand the influence of refined bathymetry. Previous simulations prove the dynamic nature of the inlet depth and width and constantly evolving sedimentation and erosion impacting inlet bathymetry and geometry. This prompted further analysis of the model's starting bathymetry and its influence in capturing tidal amplitude and water level fluctuations. Although the model reproduced expected general morphological trends, it did not replicate tidal amplitudes accurately, specifically at the low tide.

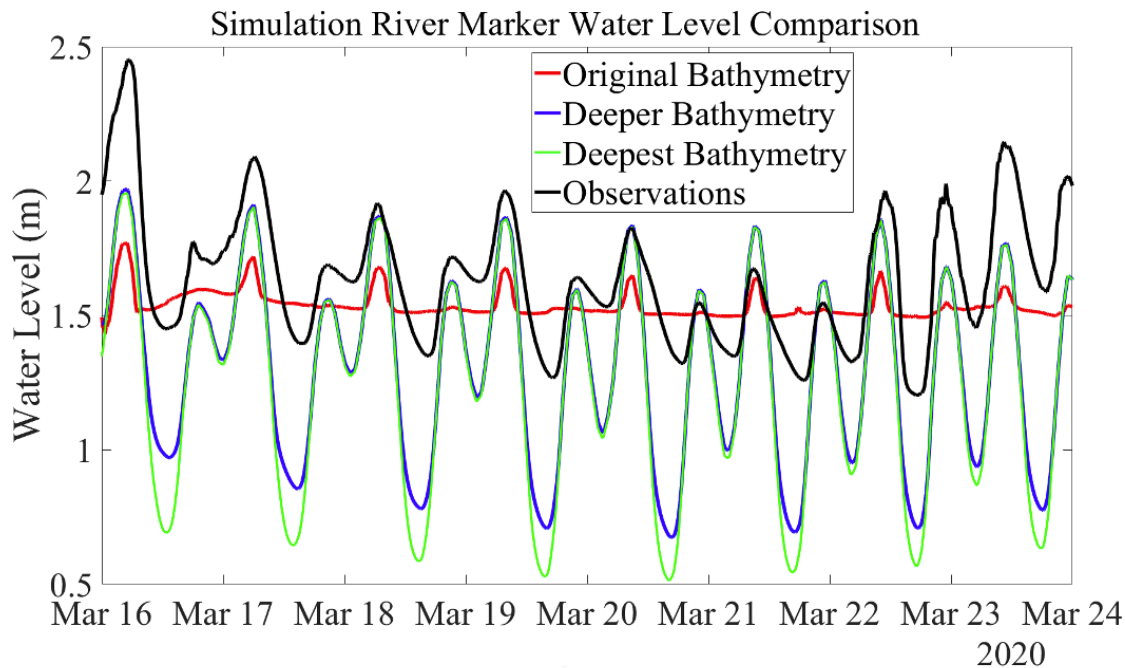
To accurately simulate the tidal amplitude observed at the River Marker (Figure 2), the lagoon grid bathymetry was modified from the original grid in a non-homogeneous manner which incorporated data from a river surveyor transect from 5 March 2020, during a breach from the 28 February 2020 closure (Figure 3). The bathymetry and inlet geometry were modified to incorporate in-situ data.

Several simulations were run with different initial bathymetries (Figure 30). Adjusting the bathymetry enhanced the amplitude in the water levels, showing tidal influences (Figure 31). To understand the influence of the deeper bathymetry, a subsequent simulation increased the depth of the bathymetry by 0.4 meters to quantify the influence of inlet depth on the tidal response. Although unable to replicate the water levels troughs, their amplitudes become more apparent with deeper bathymetry, and the tidal peaks matched closely with observed values. As the initial depth increased, the water level at low tide decreased. These three simulations aimed to refine the model and test if the tidal influence could be replicated in the water level response by refining boundary conditions for model accuracy while understanding the sensitivities to initial conditions.



This figure shows the three different initial (01 March 2020) bathymetry (bed level) plots used to understand the influence of bathymetry on the tidal amplitudes. Panel A shows the original bathymetry used for calibrating the parameters. Panel B shows a deeper bathymetry which incorporates the 5 March 2020 river surveyor data. Panel C shows the deepest bathymetry which is 0.4m deeper than panel B. All panels have a shaded box locating where the cross-section location is (out in Figure 32) which is the same cross section used in the parameter calibration.

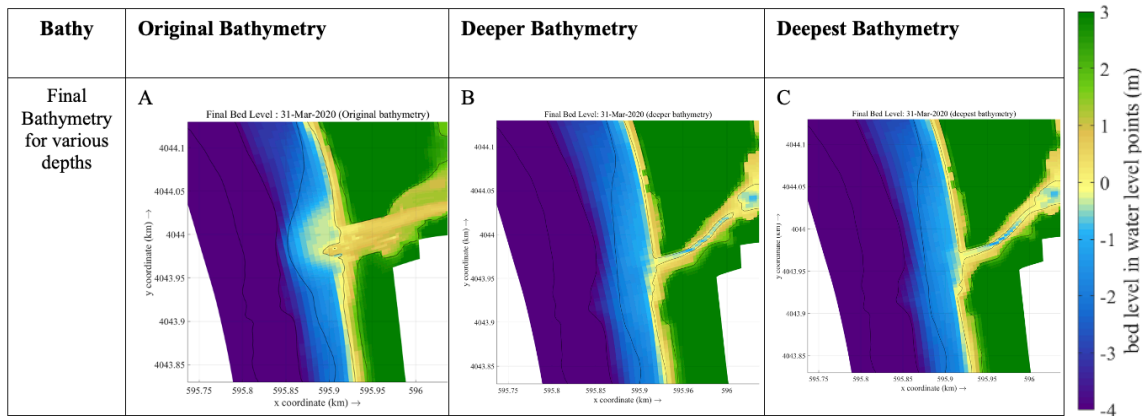
Figure 30. Analysis of the influence of inlet depth/initial bathymetry using bed level plots.



This figure shows the water level response at the River Marker with varying depths of bathymetry. The red line is the original bathymetry. The blue line is the deeper bathymetry. The green line is the deepest bathymetry, which is 0.4m deeper than the blue line. The black line is the observed water level data at the River Marker.

Figure 31. Water level response to varying initial bathymetry.

Three different bathymetries were evaluated; the original bathymetry, which is the bathymetry in the initial model used for the morphological parameter calibration, the deeper bathymetry, which incorporates the in-situ survey data; and the deepest bathymetry, which takes the survey data and makes it 0.4 meters deeper. The final bed level plots for the simulations with different bathymetries (Figure 32) showed that the Ebb Delta offshore was not as prominent as the lagoon depth increased from the original bathymetry. As the bathymetry deepens and the angle of the inlet changes, there is less scouring of the riverbank and less northward migration compared to the original bathymetry. With deeper bathymetry the inlet shows less noticeable change in the width (Figure 33).



This figure shows the three final bathymetry (bed level) plots for 31 March 2020. Panel A shows the original bathymetry. Panel B shows a deeper bathymetry with 5 March 2020 river surveyor data. Panel C shows the deepest bathymetry, 0.4m deeper than panel B.

Figure 32. Analysis of the influence of inlet depth/bathymetry using Bed Level plots.

G. STATISTICS FOR QUANTITATIVE CALIBRATION OF MORPHOLOGICAL PARAMETERS

The morphologic response for each calibration parameter was reviewed using the qualitative analysis presented in the previous sections. To complete this analysis, statistics were calculated to provide a quantitative evaluation. Statistical model performance (i.e., CC, RMSD, WS) compared the observed and simulated water levels in the River Marker (Table 3). It is noted that the values of each morphological parameter resulted in relatively similar statistics, indicating that no one parameter would completely offset the model performance (Table 3). All the selected values for each morphologic parameter resulted in values above 0.5 for the CC analysis which indicates strong correlation between the model and observed water levels (Table 3). All the values for each morphologic parameter were categorized as “good” and the refined “deeper bathymetry” resulted in “very good” based on the descriptive categories of WS as defined by Mao and Xia (Mao and Xia 2018).

This study analyzed the statistical values for each parameter and how it compared to the observed water levels from 16 March – 24 March 2020. This quantitative analysis informed changes to previously determined morphologic parameters during the qualitative analysis (Table 4). These calibrated morphological parameters and bathymetry (Table 4) are used to understand how the model responds to intentionally varied boundary conditions.

Table 3. Statistical analysis of each parameter from 16 March 2020 to 24 March 2020.

Parameter	Pearson Correlation Coefficient (CC)	Root-mean-square deviation (RMSD)	Willmott skill (WS)	Pearson Correlation Coefficient and Willmott Skill Category
MORFAC 1	0.70	0.24	0.56	Strong Correlation, Good
MORFAC 5	0.60	0.24	0.49	Strong Correlation, Good
MORFAC 8	0.53	0.24	0.47	Strong Correlation, Good
ThetSD 0.6	0.13	0.27	0.39	Low Correlation, Good
ThetSD 0.8	0.60	0.24	0.49	Strong Correlation, Good
ThetSD 1.0	0.53	0.24	0.43	Strong Correlation, Good
Sus 0.5	0.66	0.24	0.50	Strong Correlation, Good
Sus 1.0	0.53	0.24	0.43	Strong Correlation, Good
Sus 3.0	0.69	0.25	0.56	Strong Correlation, Good
Bed 0.5	0.55	0.24	0.48	Strong Correlation, Good
Bed 1.0	0.53	0.24	0.43	Strong Correlation, Good
Bed 5.0	0.63	0.23	0.48	Strong Correlation, Good
SusW 0.01	0.58	0.24	0.47	Strong Correlation, Good
SusW 0.5	0.54	0.24	0.45	Strong Correlation, Good
SusW 0.8	0.55	0.25	0.50	Strong Correlation, Good
BedW 0.01	0.51	0.24	0.50	Strong Correlation, Good
BedW 0.5	0.57	0.24	0.48	Strong Correlation, Good
BedW 0.8	0.65	0.24	0.49	Strong Correlation, Good
Final Parameters with original bathymetry	0.60	0.24	0.49	Strong Correlation, Good
Deeper Bathymetry	0.78	0.41	0.63	Strong Correlation, Very Good
Deepest Bathymetry	0.76	0.47	0.59	Strong Correlation, Good

This table shows the values for each morphological parameter and bathymetry simulated from an analysis using CC, RMSD, and WS. The right column shows the comparison criteria of the CC and WS from observed water levels from 16 March 2020 to 24 March 2020.

Table 4. Final calibrated morphological parameters.

Morphological Input file		
Keyword	Description (Default value From Table B.7 in Delft3D-Flow User Manual)	Final Calibrated Morphological Parameters
MORFAC	Morphological Scale Factor Constant (no Default)	5.0
ThetSD	Factor for erosion of adjacent dry cells (Default 0.0)	0.8
Sus	Current-related reference concentration factor (Default 1.0)	1.0
Bed	Current-related transport vector magnitude factor (Default 1.0)	1.0
SusW	Wave-related suspended transport factor (Default 1.0)	0.15
BedW	Wave-related bed-load transport factor (Default 1.0)	0.15
Bathymetry	Deeper bathymetry	

Listed are the best-suited morphological parameter values and bathymetry. These values were determined from an analysis of the hydrodynamic and morphologic response, as well as, a statistical analysis.

H. MODELED INLET WIDTH FOR VARIOUS MORPHOLOGICAL PARAMETERS

Inlet width and northward migration were features used for analyzing each parameter's morphologic response. Table 5 shows the inlet width for each parameter value tested. Results show that inlet width increased as MORFAC, ThetSD, and Sus values increased. The response of inlet width differed for the other parameters. The inlet width was calculated using the perpendicular transects (Figure 9) in the cross-sectional plots, specifically, the steepest gradient from the scoured edge of the riverbank north to south. Through the parameter analysis, inlet width varied from 30 to 50 meters, typical of the observational data. The 5 March 2020 inlet width was 30 m and other observational data sets indicate the inlet width at this location when breached is between 20m and 50m. The grain size was also analyzed in this study (Appendix VI.A) and did not enhance the model response, but rather resulted in instabilities.

Table 5. Inlet width for associated parameter values.

Parameter	Inlet Width (Meters)
MORFAC 1	30.2655
MORFAC 5	46.6476
MORFAC 8	50.4876
ThetSD 0.6	30.2655
ThetSD 0.8	40.3113
ThetSD 1.0	40.4475
Sus 0.5	30.4138
Sus 1.0	40.4475
Sus 5.0	50.4876
Bed 0.5	40.4475
Bed 1.0	40.4475
Bed 5.0	40.4475
SusW 0.01	30.4138
SusW 0.5	40.4475
SusW 0.8	40.4475
BedW 0.01	50.4876
BedW 0.5	50.4876
BedW 0.8	30.2655
Original Bathymetry	46.6476
Deeper Bathymetry	20.3961
Deepest Bathymetry	20.3961

The width distance was calculated using the steepest gradient from the scoured edge of the riverbank from the north to the south.

V. MODEL APPLICATIONS

With a calibrated model, the research will implement the model to inform physical understanding of the system. It will test the model response to changes in the off shore wave direction, influence of river discharge, and impacts of inlet position along the beach.

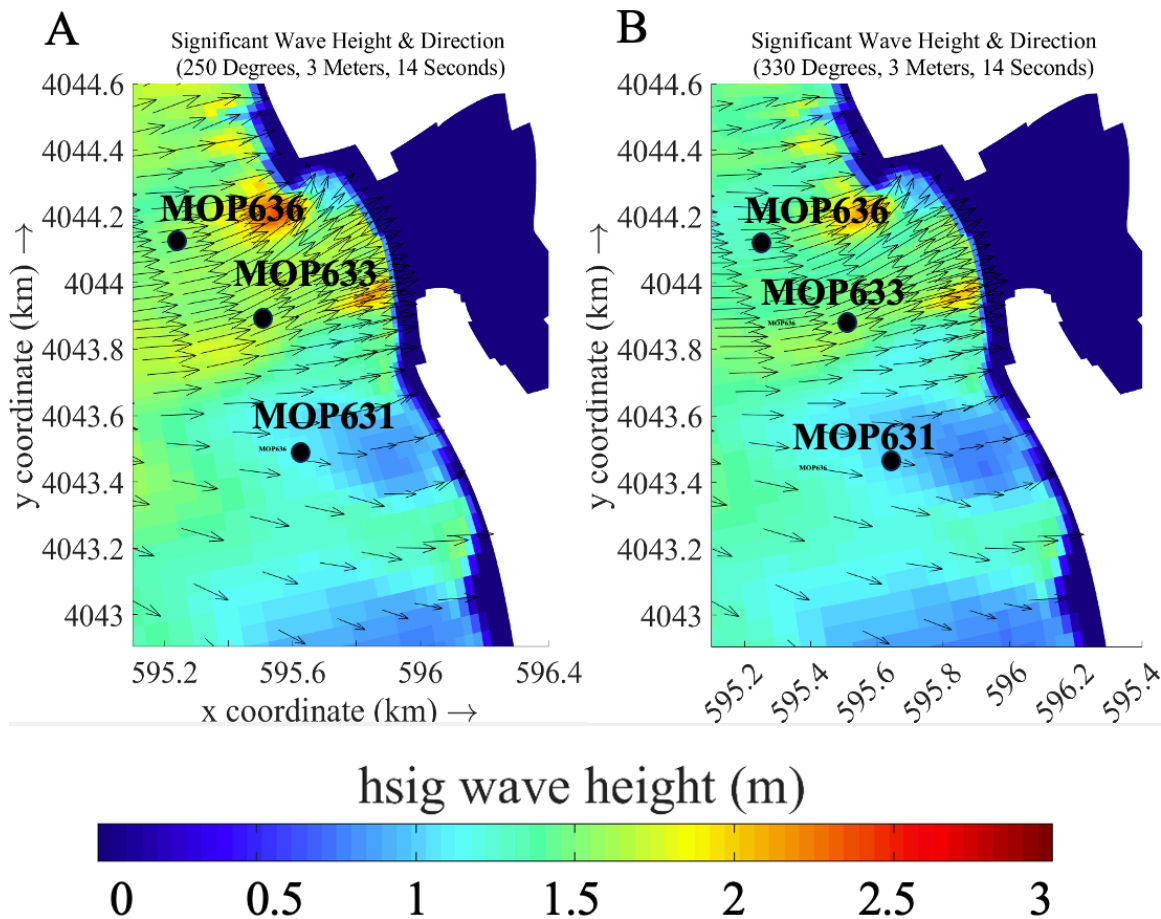
A. DIRECTIONAL WAVE ANALYSIS

With a reasonable reproduction of the water levels in the lagoon and a calibrated model, offshore wave directions were explored. To investigate the influence of wave direction on the inlet geometry, synthetic simulations were performed for different wave directions. The hypothesis is that two environmental factors dominate migration of a breached inlet; strong river discharge and longshore wave radiation stress (Orescanin et al. 2021). This series of simulations adjusted the wave direction to understand the directionality influence on coastal radiation stress and morphology. The river discharge boundary condition is unaltered in these simulations and remains the same as previous simulations (Figure 3). The wave height (3 meters) and period (14 seconds) will remain consistent with varying wave directions from 250°, 290°, and 330°. These simulations inform modeling morphological response to wave direction.

The selected offshore wave directions reflect the wave regime from observational data from the Coastal Data Information Program (CDIP) MOP (Monitoring and Prediction) v1.1 (Coughlin 2019). The most northern (330°) and southern (250°) wave directions are discussed in this analysis, including spatial outputs and wave direction outputs at three different MOPs; MOP631, MOP633, MOP636 (Figure 34).

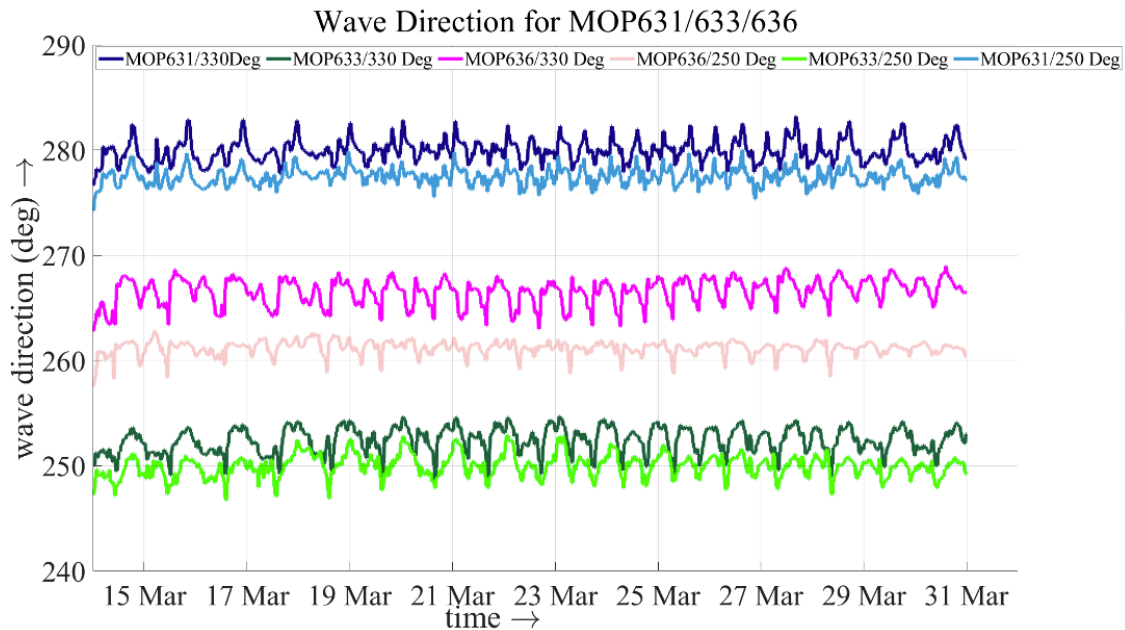
Regardless of the modeled offshore wave directional change, the simulated waves approached the lagoon at a similar angle (Figure 34). As the waves approach the shore, they refract and tend to arrive shore-normal, following the contour of the coastline. The offshore southern (250 degrees) waves approach the headlands with a greater significant wave height than the northern (330 degrees) waves (Figure 34). Analyzing model outputs at three locations corresponding to CDIP buoys, there is a 3 to 5 degrees directional difference in the model output for the northern and southern offshore waves (Figure 35).

The most significant direction difference is noticed at the northernmost buoy (MOP636), just offshore of the northern outcropping. With these slight changes offshore and nearly consistent shore-normal force, there is minimal morphologic change in the model outputs. Due to the various locations of each MOP buoy, the notional wave direction are as follows: MOP631 ranges from 250–260 degrees, MOP633 ranges from 235–250 degrees, and MOP636 ranges from 255–273 degrees (Coughlin 2019).



Panel A is the nearshore wave direction and significant wave height with offshore waves modeled at 250 degrees, 3 meters, and 14 seconds. Panel B is the nearshore wave direction and significant wave height with offshore waves modeled at 330 degrees, 3 meters, 14 seconds. MOP631, MOP633, and MOP636 buoy locations are overlaid.

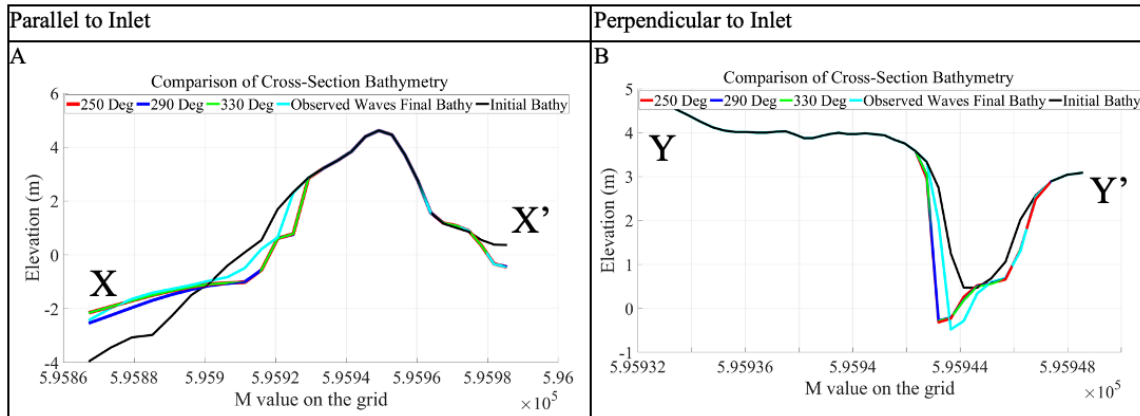
Figure 34. Nearshore response to offshore wave directional change.



This time series is the modeled wave direction (deg) with time at each of the three MOP buoys (MOP631, MOP633, MOP636) with different wave conditions (250 deg and 330 deg). The lighter shades are the 250 deg waves and the bolder colors are the 330 deg waves. The blue shades are of MOP631, the green shades are of MOP633, and the pink shades are of MOP636.

Figure 35. Wave direction of CDIP buoys with different offshore wave directions modeled.

The inlet morphology was consistent for all off-shore wave directions due to the directional change as it entered the beach due to wave refraction. The persistent northward migration is still observed for each wave direction. The inlet gets deeper for all wave directions tested (Figure 36, panel B). The perpendicular cross-section used in the parameter analysis is the same cross-section used here, which is located up the inlet. By the time the waves reach the inlet, the waves follow the direction of the channel regardless of offshore direction, explaining the minimal morphologic change at this location. Not shown here, wave directions at the mouth of the inlet were the same wave direction at high tide, and no wave direction signal at low tide, regardless of offshore wave conditions. These results indicate that wave direction minimally impacts morphological change inside the inlet; rather, its effects are more prevalent in the shoreface. Next, this research analyzes the influence of river discharge on morphologic modeling.



Cross-section plots parallel (A) and perpendicular (B) to the Carmel River, looking at the bed level for various wave conditions; 250 degrees (Red), 290 degrees (Blue), 330 degrees (Green), and observed waves (Cyan) compared to initial bathymetry (black). X & Y are the starting positions and X' & Y' are the endpoints from Figure 9.

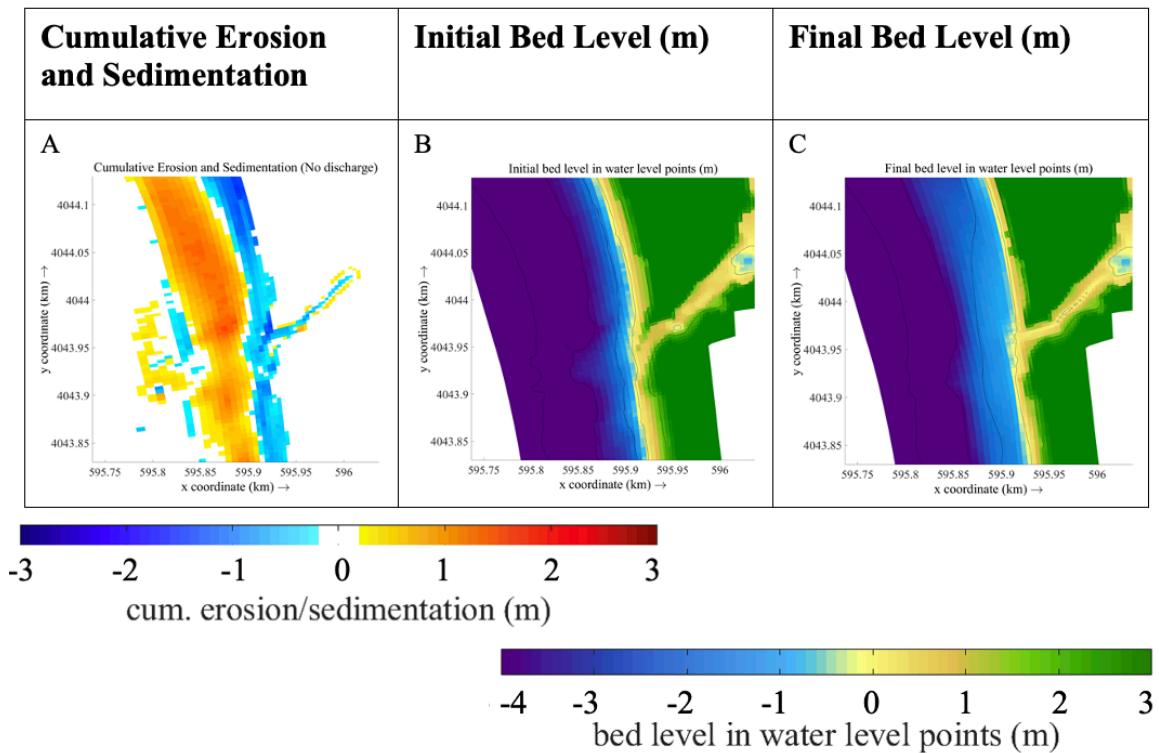
Figure 36. Cross sectional plots from various wave conditions.

B. RIVER DISCHARGE ANALYSIS

To explore the influence of river discharge on the inlet geometry, simulations using the calibrated model parameters, deeper bathymetry, with unmodified (observed) waves were used, and river discharge was set to zero. Previous research on the momentum balances between river discharge and ocean forcing, suggests that if the river discharge is turned off, the waves will transport sediment from offshore and close the inlet (Orescanin and Scooler 2018). These simulations inform the model morphologic response of a system with no river discharge.

This research analyzes the bed level changes and cross sections, cumulative erosion and sedimentation, water depth over tidal cycles, and water levels at the river marker (Figure 2). The most notable difference in cumulative erosion and sedimentation is that there is no Ebb Delta development when discharge is set to zero (Figure 37 panel A) compared to the previous erosion and sedimentation patterns. This pattern aligns with observations during low flow conditions. When the river discharge is reduced or zero, the deposit from the river is reduced. These observations are seen in the increased offshore water clarity when the river discharge is zero (closed) or reduced. This morphological pattern has seasonal implications. Enhanced river discharge results in deposited sediment

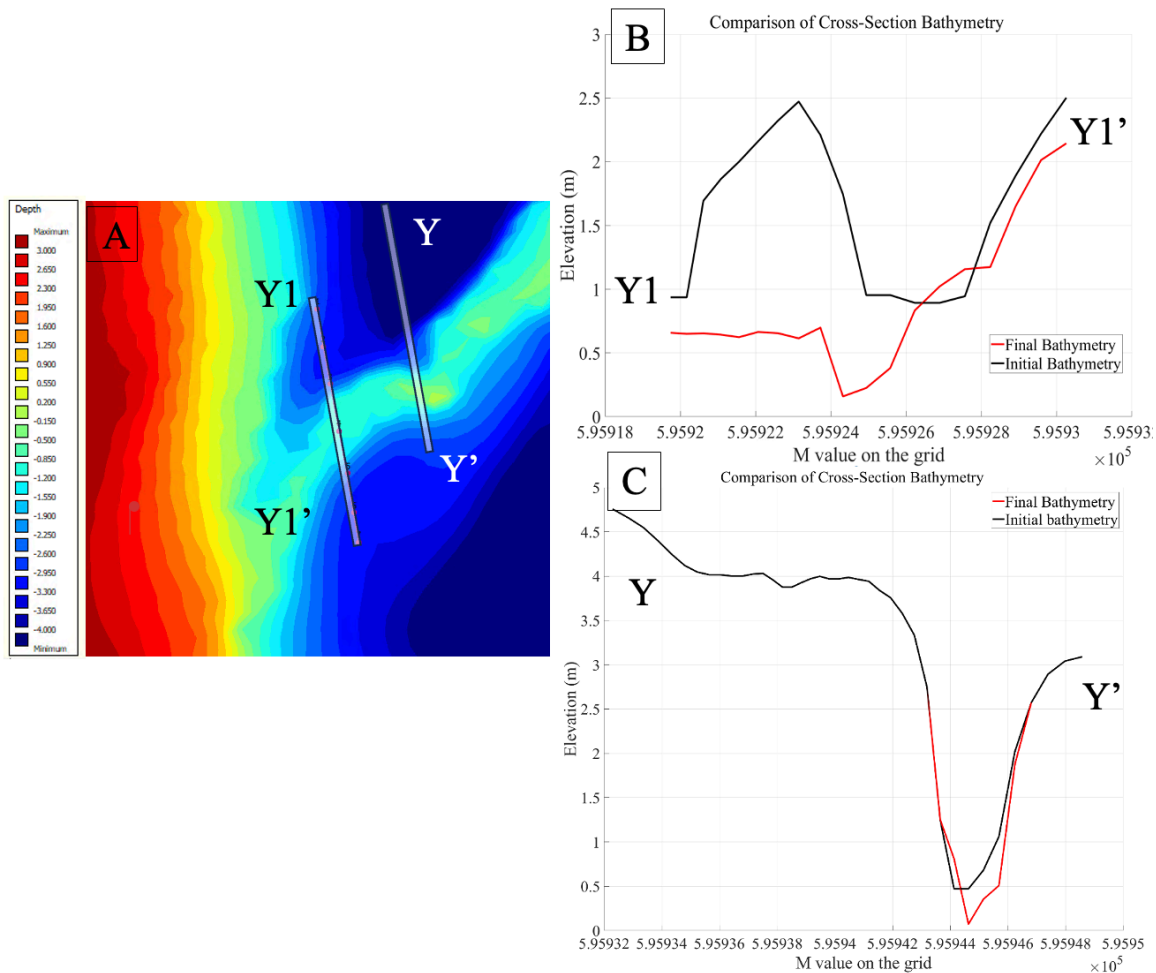
offshore from the river, and as river discharge is reduced, that sediment is pushed back onshore from waves. Our model did not run long enough to see these cyclic patterns. Unique to this simulation compared to the previous analysis, there was only slight inlet migration. Due to only slight migration associated with changes to both wave direction and river discharge, further analysis is needed to determine the driving forces for inlet migration.



The simulated morphological response to zero river discharge. Panel A shows the Cumulative Erosion (blue) and Sedimentation (red) around the inlet on 31 March 2020. Panel B is the initial bathymetry using the “deeper bathymetry” as tested previously 01 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88). Panel C is the final bathymetry (bed level) in meters on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88). All panels show the small spatial extent around the inlet (area inside the red box of Figure 10).

Figure 37. Cumulative erosion and sedimentation with initial and final bed level under no river discharge conditions.

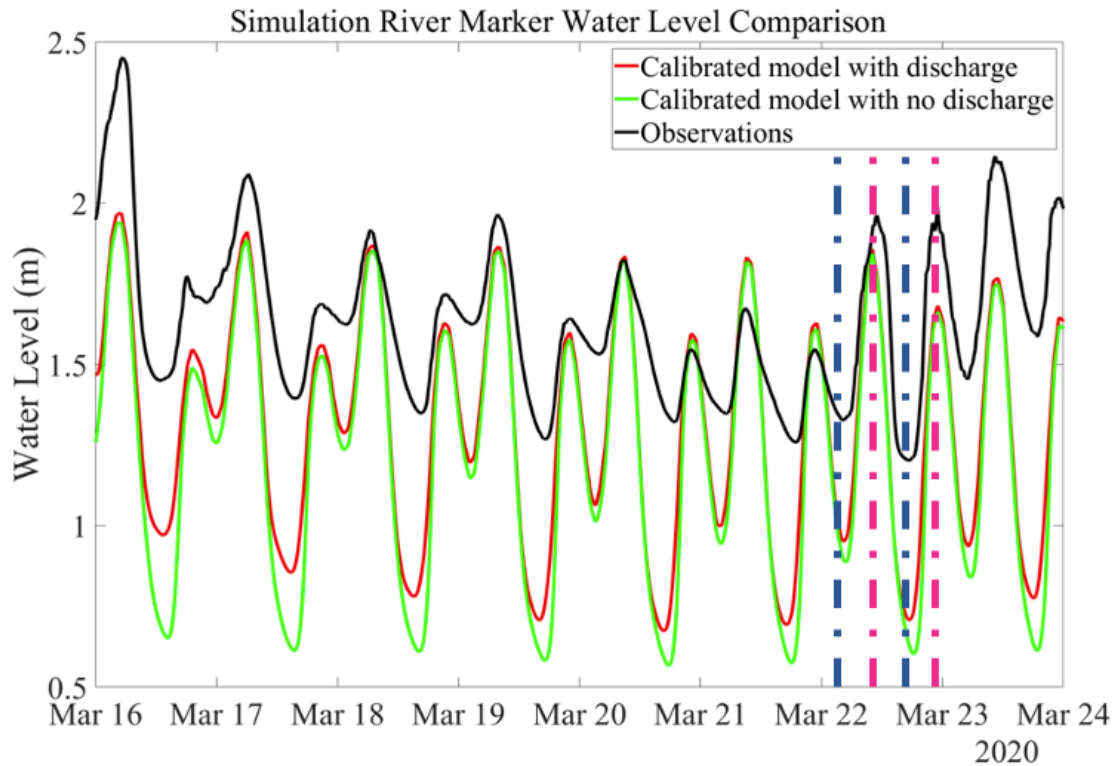
There is increased erosion around the inlet in the absence of river discharge. This morphological pattern results in a deeper channel and slight northward migration (Figure 37 and Figure 38). The inlet geometry is altered to a shore-normal direction with the coastline (Figure 37 panel C) which impacts inlet stability.



Panel A is the cross section used for previous analysis(Y/Y') and a new cross section (Y1/Y1') close to the river mouth overlaid on the depth from 3m (dark red) to -4m (dark blue). Panel B is the bathymetry perpendicular to the inlet, close to the inlet mouth, south to north, showing a deeper channel with slight northward migration compared to the original bathymetry (black). Panel C is the cross section used for previous analysis, in the lagoon, south to north, showing deepening and southward migration. These respective migrations correlate to resulting in a shore-normal inlet. Y/Y1 is the starting position and Y'/Y1' is the endpoint.

Figure 38. Cross sectional plot of no discharge scenario.

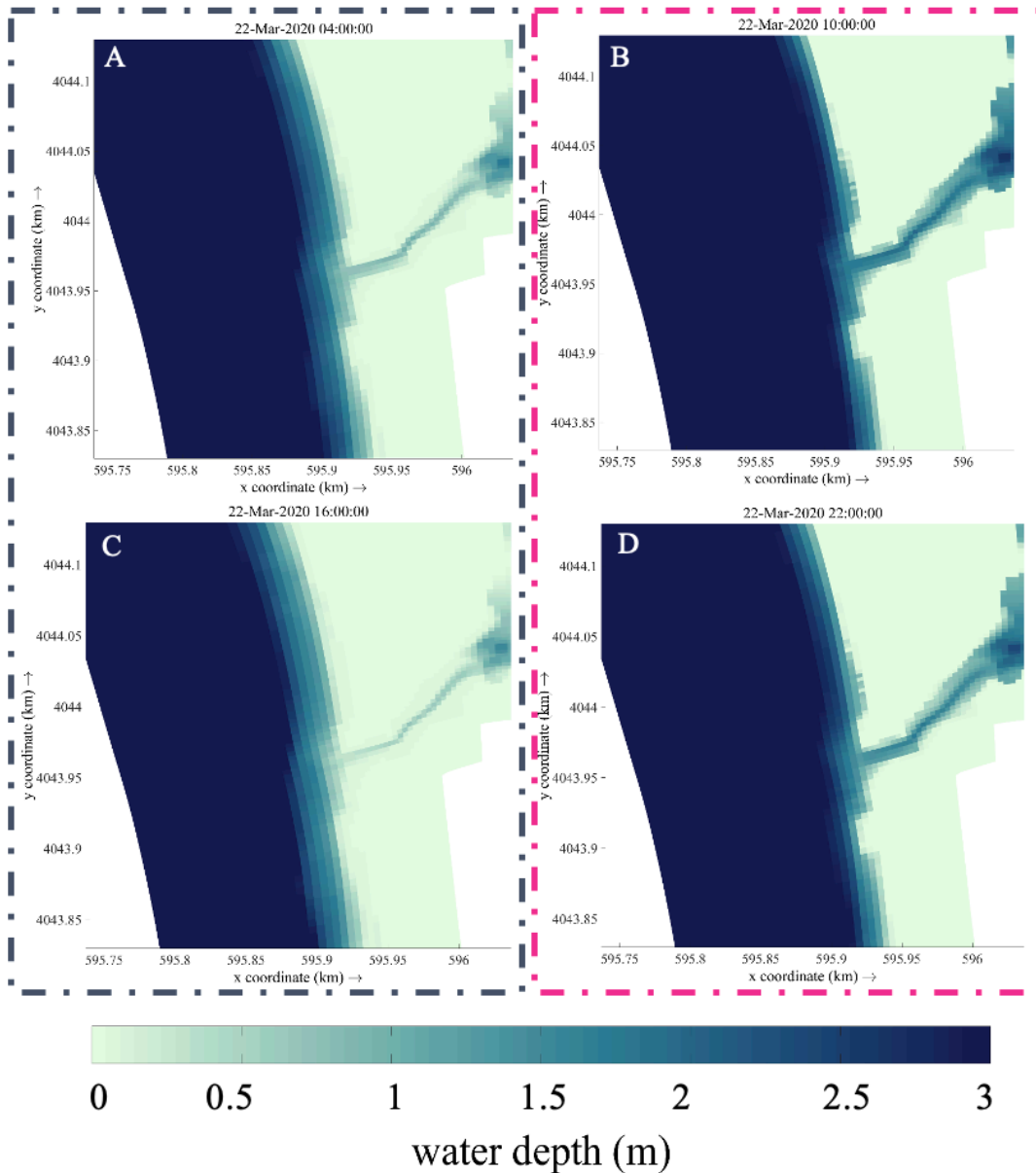
The inlet geometry, specifically the angle where the river mouth meets the ocean, shifts to shore normal which is evident in the two cross-sections and bathymetry plots where the westward cross section (Y1/Y1') migrated north and the eastward cross section (Y/Y') migrated south (Figure 38 & Figure 38 panel C). The inlet is hypothesized to be more efficient for water circulation with a shore-normal inlet geometry due to the shorter channel length enabling an increased tidal signal (Figure 39). Analyzing the water depth indicates that the inlet undergoes a nearly intermittent flow pattern, where there is flow during high tide, but the inlet becomes nearly cut-off during low tide (Figure 40). This pattern is observed throughout the tidal cycle but is most pronounced on 22 March 2020 due to the increased tidal range on this day. This period also correlates well with low discharge observations (Figure 3). It is hypothesized that it does not fully close due to wave overtopping enabled by decreased berm height or that the tidal prism is just large enough to prevent closure. This needs to be further explored to confirm which force is mainly preventing a full closure.



This figure shows the water level response at the River Marker with the calibrated model with discharge set to zero. The red line is the calibrated model. The green line is the calibrated model without river discharge. The black line is the observed water level data at the River Marker (Figure 2).

Figure 39. Water level response to no river discharge.

After analyzing the impacts on the system with no river discharge, this study investigates the system's morphologic changes and limitations of forecasting closures and breaches. Looking at the water depth (Figure 40), it is assessed that the model can give indications of inlet closures. When aerial imagery suggests no or reduced discharge, a calibrated model could aid in forecasting an inlet closure. The time frame of the system with both waves and morphology turned on, does not overlap with an active breach or closure of the system. The waves and morphology start on 14 March 2020 at 0000, which is following a closure (13 March 2020) and a breach (14 March 2020) of the system. Further investigation should compare a calibrated model's performance to an observed closure and breach.



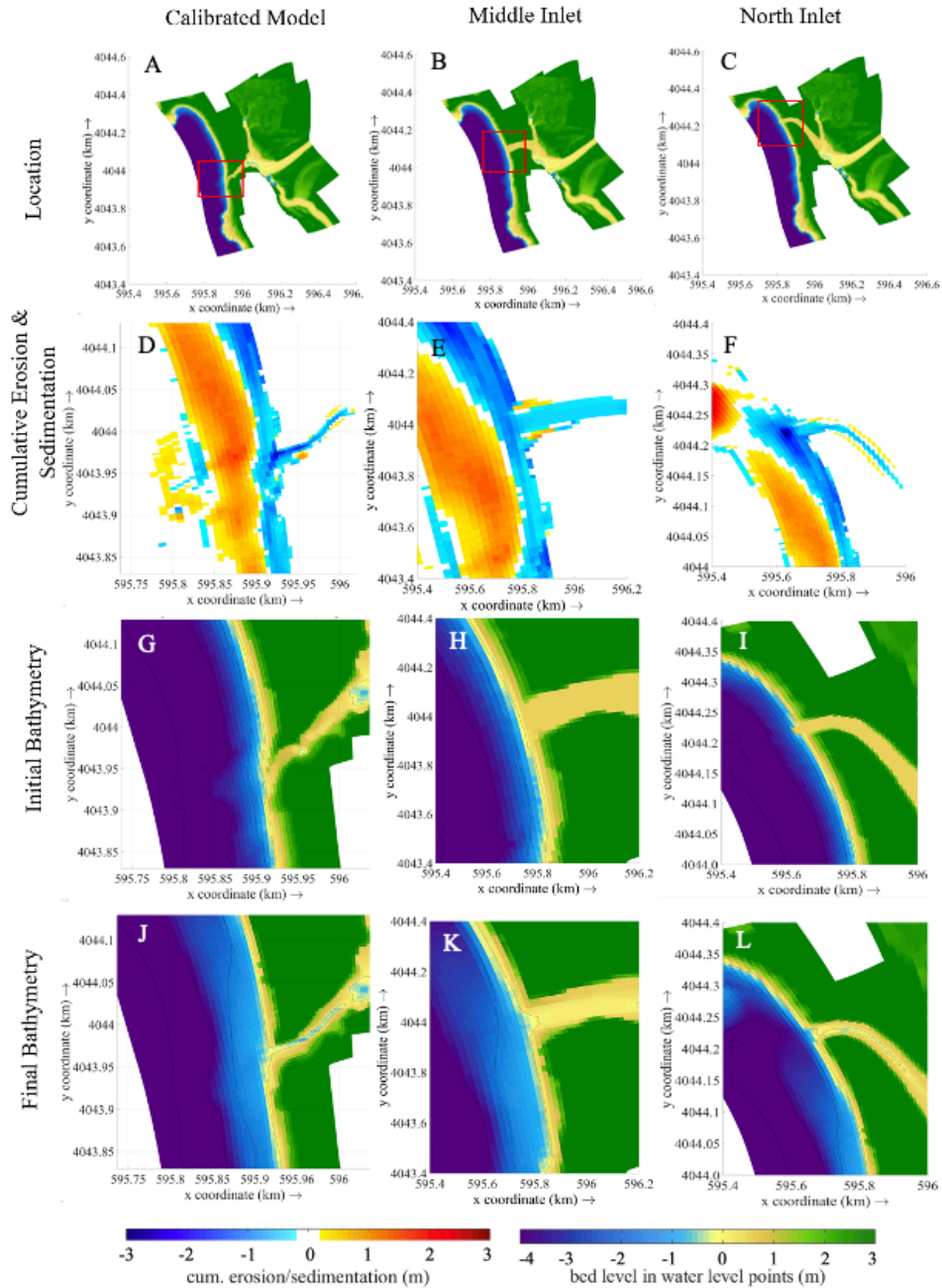
A sequential 6-hour time step of water depth (m) from low tide: 22 March 0400 (panel A) to low tide: 22 March 1000 (panel B), lower low tide: 22 March 1600 (panel C), and second high tide: 22 March 2200 2200 (panel D). Notably, the water depth at the mouth of the inlet approaches 0 m during low tide, indicating nearing closure. The blue dashed box correlates to the low tide blue dashes on the water level time series (Figure 39) and the magenta dashed box correlates to the high tide magenta dashes on the water level time series (Figure 39)

Figure 40. Analysis of modeled water depth with the tidal cycle for no river discharge.

C. INLET LOCATION ANALYSIS: NORTH AND MIDDLE

It is typical for the system to experience migration northward, and in some extreme cases, all the way to the northern border of the beach. This section will explore the model response when the inlet location is changed. Using the same approach as previous sections, this analysis evaluates the cumulative sedimentation and erosion patterns, bed level changes, cross-sectional plots, and water level response at the river marker.

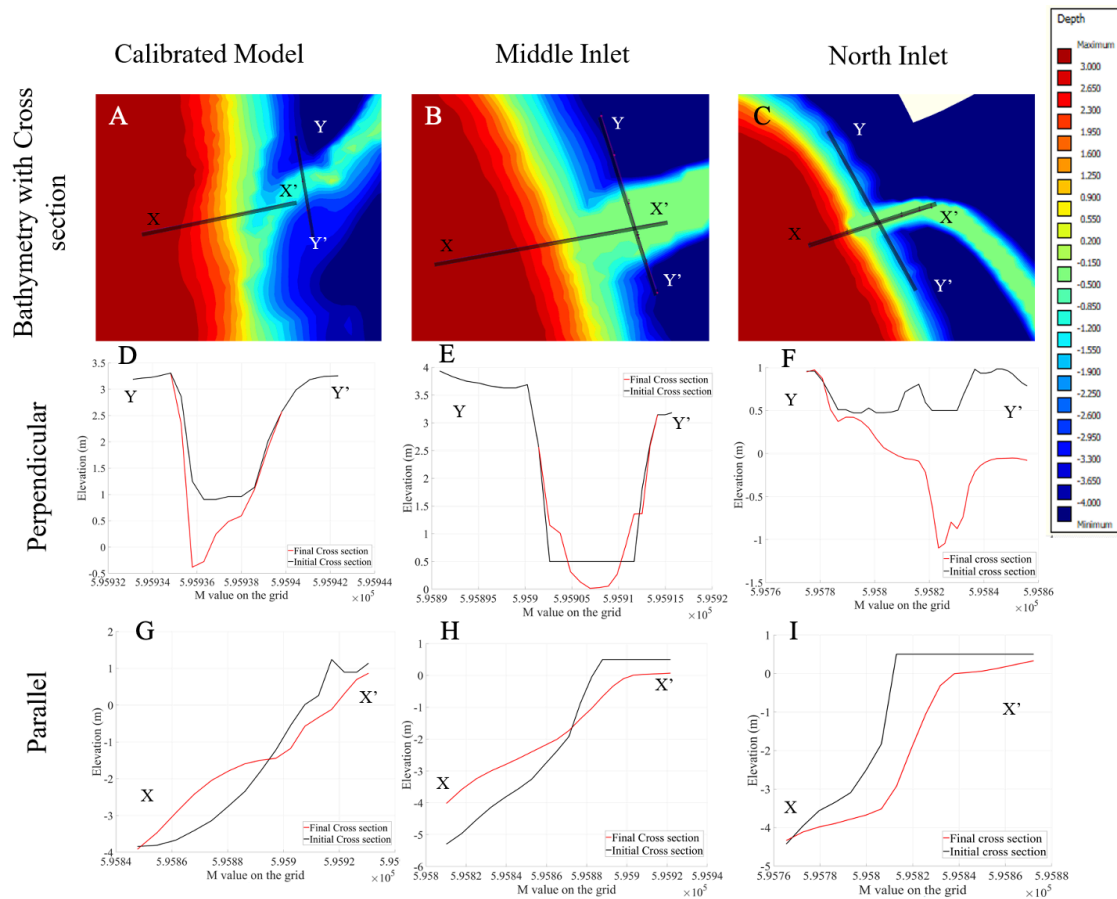
This simulation evaluates the response of an inlet that has migrated northward, close to the northern headlands. This far-north migration draws local concerns for infrastructure and safety. This analysis helps to understand the physical dynamic of a northward migrated inlet. The geometry of the inlet was created using Google Earth during a northward migration event in 2023, and the bathymetry used for this simulation was created to match the original inlet depth. This analysis will focus on the morphology surrounding the inlet using selected areas unique to the inlet location (Figure 42).



Comparing the morphology changes with the inlet location, the calibrated model: column 1, the middle channel: column 2, and north channel: column 3. Panels A-C is the initial bathymetry, where the red box is the zoomed location used for analysis. Panels D-F are the Cumulative Erosion (blue) and Sedimentation (red) around the inlet on 31 March 2020. Panels G-I is the initial bathymetry on 01 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88). Panels J-L are the final bathymetry (bed level) in meters on 31 March 2020 where yellow to green colors are elevations above 0 m (NAVD88) and blue colors are depths below 0 m (NAVD88).

Figure 41. Morphologic change analysis with varying inlet location.

There are varying morphology patterns for each inlet location. For all locations there is erosion at the inlet mouth, but spatially there is a larger area of erosion for the north inlet. The inlet geometry varies most in the calibrated model as it becomes more shore-normal in the final bathymetry. All the final bathymetries result in deeper channels from erosion within the channel. These erosion patterns are evident in the cumulative erosion and sedimentation (Figure 41 row 2). Analyzing the cross-section plots (Figure 42) there is slight northward migration in both the northward channel and the calibrated model, but it is not evident in the middle inlet (Figure 42 row 2). The inlet depth for the calibrated model and north inlet deepen about 1.5 meters, but the middle inlet only deepens by 0.5 meters. Similarly for all inlet locations, there is a reduced beach slope gradient (Figure 42 row 3). Next, this analysis compared the hydrodynamic response using the water levels at the river marker (Figure 2) for each inlet location.

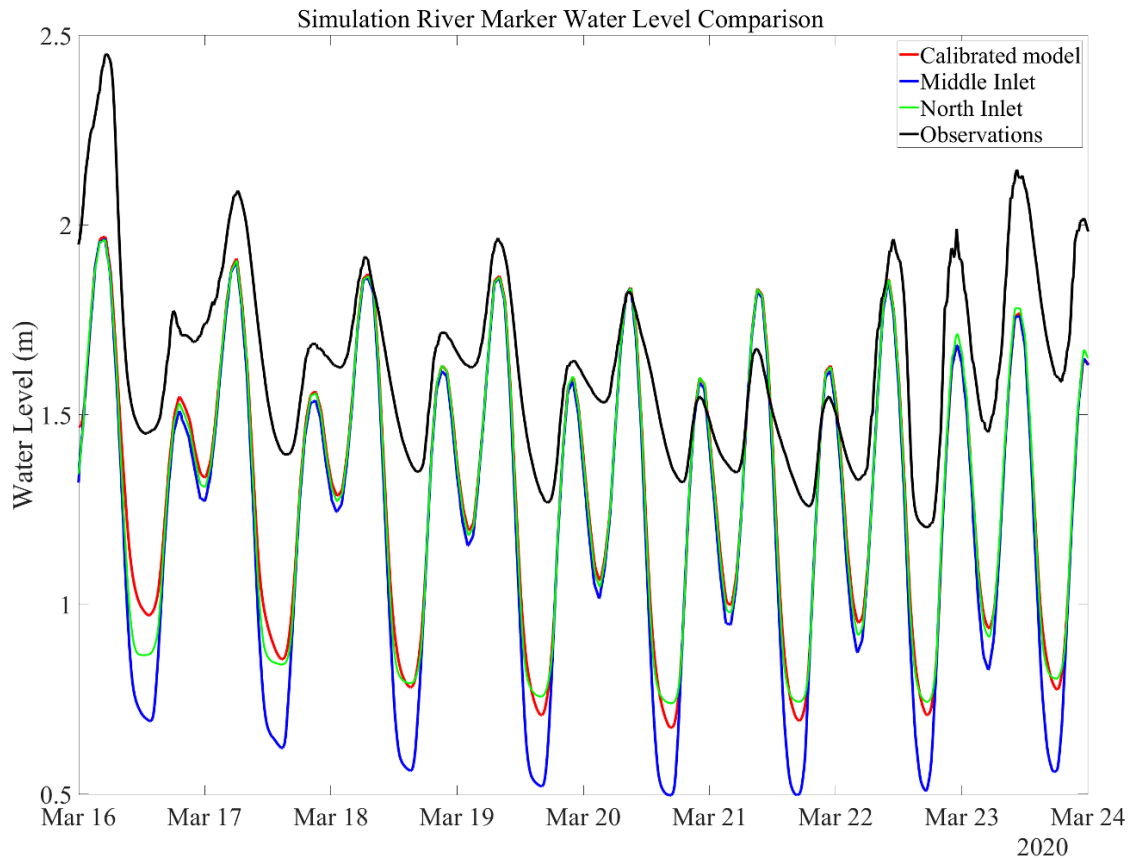


Panels A-C are the cross section locations with depth (red:3m and dark blue: -4m). Not that the “Calibrated Model” uses new cross sections to provide a comparable cross section to the other inlet locations. Panels D-F are the bathymetry perpendicular to the inlet comparing to the initial (01 March 2020) bathymetry (black) to the final (31 March 2020) bathymetry (red). Panels G-I are the bathymetry parallel to the inlet comparing to the initial (01 March 2020) bathymetry (black) to the final (31 March 2020) bathymetry (red). The locations of the cross sections are associated with labeled X & Y (the starting positions) and X' & Y' (the endpoints). Note the elevation/Y-axis scale varies for each location.

Figure 42. Cross sectional plots with varying inlet location.

The middle inlet showed the largest tidal range, where the lows were about 0.3m lower than the north inlet and calibrated model (Figure 43). All inlet locations accurately captured the tidal cycle timing with various amplitudes differing from the observed water levels. It is expected that the calibrated model most accurately models the water levels since the inlet was located at that location during the time of this observed water level. Interestingly, tidal amplitude only changed by 0.05 meters (calibrated model to north inlet) and 0.3 meters (calibrated model to middle inlet) at its largest difference with changing

inlet location. It was expected to see a more significant reduction in tidal amplitude based on longer and less hydrodynamically efficient channels.



This figure shows the water level response at the River Marker with the calibrated model with discharge set to zero. The red line is the calibrated model. The green line is the calibrated model without river discharge. The black line is the observed water level data at the River Marker (Figure 2).

Figure 43. Water level response to varying inlet location.

VI. CONCLUSION

Sedimentation and deposition around inlets of BBEs are influenced by various environmental factors that change the system on various time scales. The forces acting on the sediment can alter the geometry and beachscape, promoting an inlet breach or closure. The dominant factors that cause the inlet to breach, close, and migrate are areas of on-going research. In contrast to the simplistic 1D model analysis (Behrens et al. 2015, Davidson et al. 2009), this research aims to provide a comprehensive analysis on the physical forces acting on the system at Carmel River State Beach. Modeling can help inform the morphodynamical understanding and explore the dominance of each environmental force for various time scales. Calibrated models can also help inform coastal management planning.

Parameter calibration is a critical and tedious process for accurate model predictions. The results of this analysis proved the importance of in-situ data to verify the model outputs of various parameters, as well as forming reliable boundary conditions for the bathymetry. This research is unique in that it explores the morphologic response of a BBE over a short duration. The physical mechanisms presented in this study can be extended to modeling other BBEs in various locations and on different time scales.

The impact of bathymetry has significant impacts on the performance of the model's accuracy. Due to the constantly evolving sediment movement in these systems over a short time, the model's accuracy is enhanced with in-situ bathymetric survey data. Bathymetry had a significant impact on the water level response in the inlet.

Many factors are hypothesized to initiate inlet migration. This research tested the influence of offshore wave directions and river discharge. Off-shore wave direction did not influence sediment movement at the inlet because the waves refract to follow the coastline with a wave forcing normal to the coast, regardless of offshore direction. River discharge indicated an inlet closure and showed slight migration but not enough to indicate that migration is a fully river-driven phenomenon.

Future work should use a calibrated model with morphology turned on to model a full year and further understand the limitations for modeling a systems migration. The modeled time frame should include a breach and closure to inform model performance against the system's response.

Using this analysis from Delft3D, it would be informative to compare how the performance differs with other coastal morphodynamic models, like Xbeach. In Xbeach long wave (infragravity) effects are accounted for, which could inform tidal influences on inlet closures compared to Delft3D.

APPENDIX

SEDIMENT GRAIN SIZE CALIBRATION

All parameter modifications did not effectively model the tidal fluctuation seen in the observational water level data. Simulations using various grain sizes were run to capture the impacts of grain size on the model outputs. The morphology settings for all parameter testing were calibrated using D50 1000 μm . Using previous work and field measurements from CRSB, this calibration analysis modified the grain size to complement a range of sizes from fieldwork. The starting values were selected from a littoral sediment collection done every 10 m alongshore in the swash zone at CRSB (Storlazzi and Field 2000). This determined that the Mean ϕ for CRSB is 0.68. Using the numerical measurements base on the Wentworth scale the grain size was determined using $\phi = -\log_2(d) = -\ln(d)/\ln(2)$, resulting in 624 μm diameter. This study compared D50 and grain sizes 200 μm , 625 μm , 1000 μm , and 1375 μm . There were instabilities that required further evaluation for 200 μm , 625 μm , and 1375 μm . To further explore potential causes of the instabilities, simulation using a smaller threshold depth, 0.01m, was tested to ensure that the previous 0.1m depth for drying and flooding is not set too large. This proved ineffective for resolving the model instabilities. Simulations tested the influence of the added headlands to ensure the modified bathymetry in those regions were not causing the instabilities. This also was not found to be the cause of the instabilities. This concluded that the most appropriate grain size for this study is 1000 μm and the influence of threshold depth and modified headland bathymetry were negligible in stabilizing the model with various grain sizes. This determined that grain size did not significantly enhance the tidal fluctuation in the water levels; the influence of bathymetry requires further understanding and is the subsequent test.

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