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**THESIS**

**SENSITIVITY ANALYSIS OF WATER LEVELS AND  
WAVES IN THE CARMEL RIVER STATE BEACH  
TO CHANGING BOUNDARY AND MORPHOLOGICAL  
CONDITIONS IN DELFT3D: CARMEL RIVER LAGOON**

by

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June 2023

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CARMEL RIVER STATE BEACH TO CHANGING BOUNDARY AND  
MORPHOLOGICAL CONDITIONS IN DELFT3D: CARMEL RIVER LAGOON**

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## ABSTRACT

Bar-built estuaries are common worldwide along many of the coastlines in which the Navy and Marine Corp operate; however, modeling capabilities for morphologically variable systems are limited and immature in development. Climate change, major precipitation events such as severe storms and cyclones, La Niña, and human interactions can impact these bar-built estuaries and change the operating environment, both on seasonal and yearly timescales. This study uses the numerical model Delft3D to assess sensitivities of the processes driving breaching events at the Carmel River State Beach. This sensitivity analysis varies boundary conditions and morphology inputs based on in-situ environmental data from the March 2020 breaching event. Hydrological sensitivity analysis revealed that when the Carmel River experiences low river discharge, the offshore wave and tidal energy had a larger impact on the lagoon water level and conversely, when river discharge is maximized, despite the wave height, river discharge dominates the processes affecting water level in the lagoon. Both increased discharge and increased wave heights increased the mean water level in the lagoon. The morphologic analysis showed that the presence of a berm, or building sandbar, also increased the mean water level within the lagoon. Delft3D also captures simple dynamics of sediment transport and provides realistic results for sedimentation and erosion, as compared to the observations from March 2020.

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## LIST OF ACRONYMS AND ABBREVIATIONS

BBE	bar-built estuaries
CDIP	Coastal Data Information Program
CNO	Chief of Naval Operations
CRSB	Carmel River State Beach
Hs	Significant Wave Height
ICOLL	intermittently closed/open lakes and lagoons
JLOTS	Joint Logistics Over the Shore
LOCE	Littoral Operations in a Contested Environment
MOP	Monitoring and Prediction System
MPWMD	Monterey Peninsula Water Management District
NAVD88	North American Vertical Datum of 1988
NDBC	National Data Buoy Center
NOAA	National Oceanic and Atmospheric Administration
TOCE	Temporarily Opened/Closed Estuaries
UTM	Universal Transverse Mercator

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## I. MOTIVATION

The United States has been a superpower within the Global Power Competition; however, this is a critical decade as warfare transitions from a land-locked or open-ocean battles to now focusing on the littoral-based environment. The Chief of Naval Operations (CNO) emphasizes in the Navigation Plan 2022 that in order for the United States Navy to remain the most “potent, flexible and versatile instrument of military influence” during this transition, the United States (U.S.) must continue to stay ahead of our competitors in exploiting sea control, gaining warfighting advantages and projecting power while limiting theirs (Gilday 2022). This requires faster capabilities and strategic innovations delivered to the Fleet. By doing this, Joint Forces acquire freedom of maneuverability by positioning forces forward and providing logistics over the shore not only in neutral, non-defended territory through Joint Logistics Over-the-Shore (JLOTS) capability, but also amongst contested shorelines through the U.S. Marine Corps restructure for Expeditionary Advanced Base Operations (EABO) and Littoral Operations in a Contested Environment (LOCE).

The littoral environment consists of blue to green and green to brown waters. Blue to green operations include high waters/open ocean to coastal waters and green to brown include coastal waters to rivers/lakes/bays and estuaries (Department of the Navy 2021). Each section of the littoral environment presents unique challenges that require intelligence of the battlespace to allow U.S. Forces to operate and respond to. Operations in littoral zones can change overnight or be impacted seasonally based on their location. One example of rapidly changing environments includes Intermittently Closed/Open Lakes/Lagoons (ICOLLs), which are found worldwide (McSweeney et al. 2017) and have morphological and hydrodynamical impact within the littoral operating areas. What once made up a stable sandy beach could be transformed after storm passage or heavy rain event with river outflow dominating the surf zone, potentially impeding the delivery of logistics to an area and/or delivery equipment for the area. Military forces must work together using strategic sealift ships and aircraft in areas of deficient or damaged ports, or in areas of ICOLLs. JLOTS is a capability owned by U.S. Transportation Command

(USTRANSCOM) that focuses on operational maneuver of logistics and supplies in uncontested environments where access is denied or degraded during wartimes or in theatre development. This requires the Navy and the Army to work together to get supplies through a littoral environment to support forces (JP 4-01.6). The Marine Corps is working to redesign its forces to support EABO and LOCE through Maritime Mobility and Resilience which will allow forces to determine a baseline understanding before executing an array of missions against an adversary within the littoral operating area (Department of the Navy 2021).

This study focuses on modeling the morphological and hydrodynamical factors within the green and brown waters that cause these systems and areas of operations to change. The ability to model and predict morphological evolution and closings within the littoral battlespace will continue to be a point of focus. Predicting and forecasting the evolution of beach breaches and increasing ephemeral river flow will allow the U.S. Navy to exploit sea control and gain advantages over adversaries. To sustain a “combat-credible military,” this study is one step in the direction to modernizing a joint, agile, and updated warfighting force (White House 2022).

## II. INTRODUCTION

### A. BAR-BUILT ESTUARIES

Referred by multiple names, bar-built estuaries (BBEs), also known as Intermittently Closed/Open Lakes/Lagoons (ICOLLs), seasonally opened inlets, ephemeral rivers, and Temporarily Open/Closed Estuaries (TOCE), are estuarine systems characterized by the intermittent presence of a sandbar at the mouth of the estuary, sometimes creating complete closure of the systems (McSweeney et al. 2017). There are over 1,400 ICOLLs worldwide on six continents, however a majority of those ICOLLs are considered small catchment areas, classified by  $< 2000 \text{ km}^2$  and tidal prisms  $< 30 \times 10^6 \text{ m}^3$  (McSweeney et al. 2017). This estimate excludes estuaries with catchment basins  $< 100 \text{ km}^2$  which dominate many coastlines, such as California. Bar-built estuaries comprise 8–15% of the coastlines to include Australia, Africa, Mexico, both Americas, as well as Europe. Climate change, major precipitation events such as severe storms and cyclones, La Niña, and human interactions can impact these bar-built estuaries and change the littoral environment, both on a seasonal and yearly timescale (McSweeney et al. 2017; Orescanin et al. 2019). Sea-level rise, changing precipitation and temperature patterns, and growing human populations along coastal regions all impact coastal bar-built estuaries (Sherwood et al. 2014). Given the variability in environmental conditions and morphological state, the ability to predict evolution and closure at the beach is the goal for stakeholders and managers of these systems.

The dominant environmental forcing that drives morphological evolution comes from river discharge, tides, and waves (James 2005; Orescanin and Scooler 2018). A relationship between river flow and precipitation can be observed more clearly as having a larger impact on openings and closings of the ICOLLs, meaning that small inlets which experience heavier rainfall will have periods of time with longer or more openings than when the season is noticeably drier (McSweeney et al. 2017; Rich and Keller 2013). When river flow or forcing is low, the system is balanced by forcing from tidal events and large waves, depositing sediment, creating a sandbar that closes the mouth of the river from a

bay or ocean (Behrens et al. 2013; Orescanin and Scooler 2018; Velasquez Montoya et al. 2018).

In areas with ephemeral rivers, back bay lagoons, and bar-built estuaries (BBE), sediment transport leads to both the openings and closures of the system based on the processes taking place. Environmental (and sometimes human) forcing control the dynamics of BBEs (Rich and Keller 2013). A coastal explanation of a breach by Kraus (2002) is when a new opening develops in a narrow landmass, whether artificially or naturally, that allows flow from one body of water to another body of water through this channel/opening. Breaching events allow back bays and/or rivers direct access to the ocean which can dramatically change and impact the ecosystem and infrastructures around it. Waves, currents, and the resulting sediment transport are the main physical properties studied that drive nearshore coastal morphology (Komar 1998). Sediment import is done primarily through wave-driven transport, while sediment export is driven by tides and river flow (Behrens et al. 2013). Imbalances between coastal physical processes lead morphodynamical changes in the inlet resulting in breaches and closures of the lagoon to the ocean or migration of the inlet mouth (Orescanin et al. 2021).

Dynamic mechanisms that lead to ICOLL closure events include wave overtopping, storm surge, and tidal events from the ocean side and increased discharge from the lagoon side (Laudier et al. 2009; Orescanin and Scooler 2018). Wave overtopping occurs when wave heights are large enough to flow over the top of the barrier to fill the lagoon, causing the sandbar elevation to increase (Laudier et al. 2009; Orescanin et al. 2021). In some cases, such as the Carmel River State Beach (CRSB), the system will be perched (lagoon water level continuously above ocean water level), creating an offshore pressure gradient, and the closure events become a dynamic balance between river flow with the pressure gradient and wave forcing opposing each other, depositing sediment at the river mouth (Orescanin and Scooler 2018). James (2005) recognizes the river discharge being essential to physical breaches and closures for river mouth lagoons, as well as responsible for morphologically changing the state of the beach. Ranasinghe and Pattiaratchi (2003) found that cross shore transport which builds sand bars into the beach, as well as the inlet trapping along shore sediment transport are important processes leading to closure evolution within BBEs.

Morphology and the understanding of interaction of physical processes become a difficult question not only due to variations in sediment and sediment transport from size, type, densities, and their respective hydraulic behavior within the water column but also because wave and current behavior can often be unpredictable (Komar 1998).

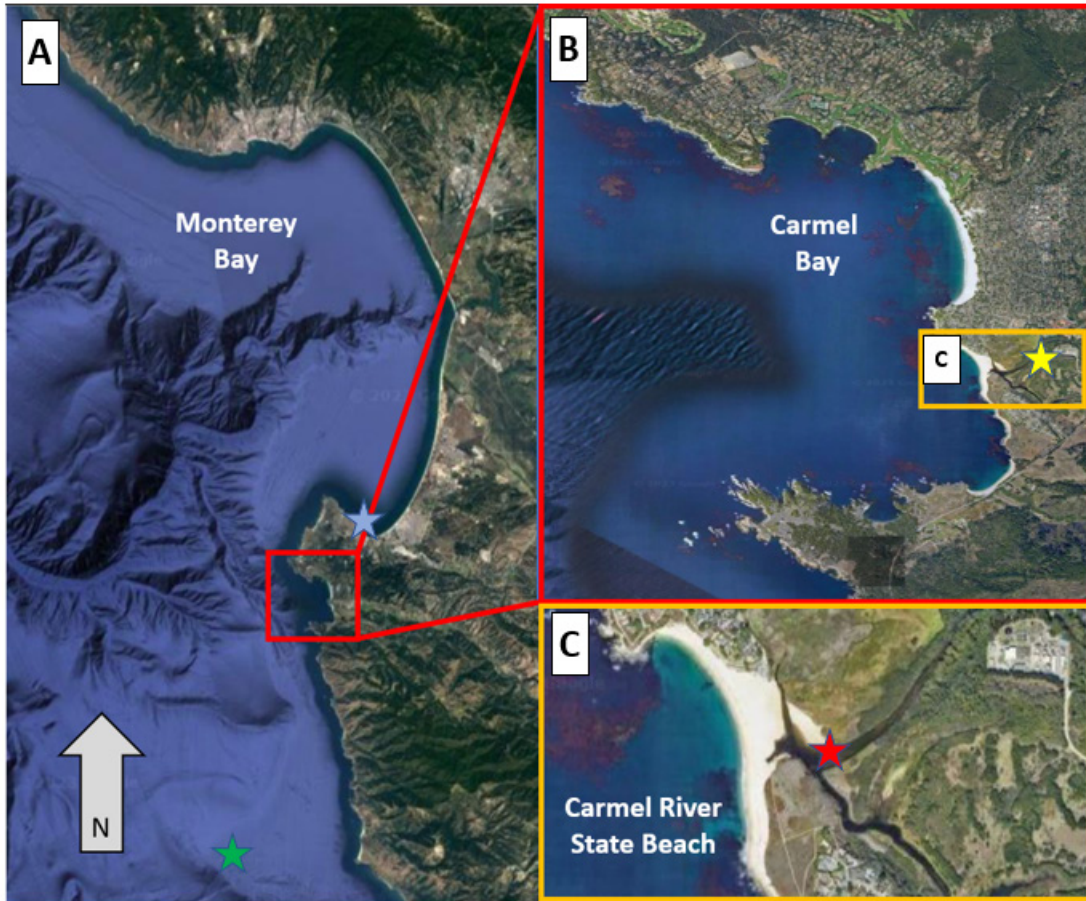
Previous modeling studies have been done to test breaching by using specific environmental data for a specific location, however, causes of breach events vary based on location (Orescanin et al. 2021; Wainwright and Baldock 2015). Velasquez Montoya et al. (2018) studied Pea Island, an ephemeral inlet on the Outer Banks, NC using Delft3D coupled with SWAN and revealed through model analysis that the spatial and temporal variability of tides and waves were impactful to Pea Island breaching process. Delft3D Model analysis helped to identify external forces in this area during major events. Another study was done by Ormond et al. (2020) using a combination of Delft3D and XBeach to produce a hindcast morphodynamical evolution of a barrier island breach caused by Hurricane Sandy and highlights sediment transport and flow processes that were unknown. Barrier island breaches along the east coast of the U.S. are more-commonly a result of storm surge from the ocean combined with wave forcing and tidal action (Velasquez Montoya et al. 2018), whereas the California coastline experiences a Mediterranean climate with active continental margins that imply river discharge drives breaching (Behrens et al. 2009). BBE breach openings and closure events occur when river discharge, wave forcing and tidal stages vary, yet predicting the location and timing of these events can be challenging. Any combination of these dynamics can lead to an opening or closure of the breach (Orescanin and Scooler 2018).

Rapid morphological changes occur in small inlets over time scales of hours to days whereas large estuaries and inlets will respond seasonally to the environmental conditions over months, even to years (Van de Kreek 2004; Velasquez Montoya et al. 2018). Behrens et al. (2013) studied and attempted to model the Russian River in northern California using a one dimensional along-channel sediment mass balance for sediment gain and losses. Wainwright and Baldock (2015) found that other models had the tendency to overestimate breach channel deepening while underpredicting breach channel widening. Wainwright and Baldock (2015) used a field data set based around Tabourie Lake, New South Wales,

during an artificial breach to test a semi-coupled two-dimensional model. This data collection dealt with parameters and sediment transport leading to improved modeling techniques for side wall erosion within the channel and enabled the development of a 2-dimensional numerical model describing shallow water hydrodynamics and morphodynamics with focus on channel bank erosion. Rich and Keller (2013) conducted a study on the Carmel River using a quasi-analytical model finding that an estuary is strongly impacted by a variety of factors that are able to be predicted using a model, however, stresses the importance of calibration.

## **B. STUDY AREA: CARMEL RIVER STATE BEACH**

This study focuses on the Carmel River State Beach (CRSB) along the central California coast. Figure 1 shows the location of Carmel Bay in reference to the location of Monterey Bay along the California Coast on the left, and then on the right, it zooms into the southern portion of Carmel Bay where the CRSB is located. CRSB separates the Carmel River from the Carmel Bay.



Panel A shows the location of Carmel Bay, denoted by the red square, in reference to Monterey Bay along the central California coast. Panel B zooms into Carmel Bay and focuses on panel C shows the Carmel River State Beach and Carmel River Lagoon System. Approximate locations for Tides (blue star), waves (green star) Lagoon water-level (red star) and River Discharge (yellow star) observations are marked.

Figure 1. Carmel River State Beach

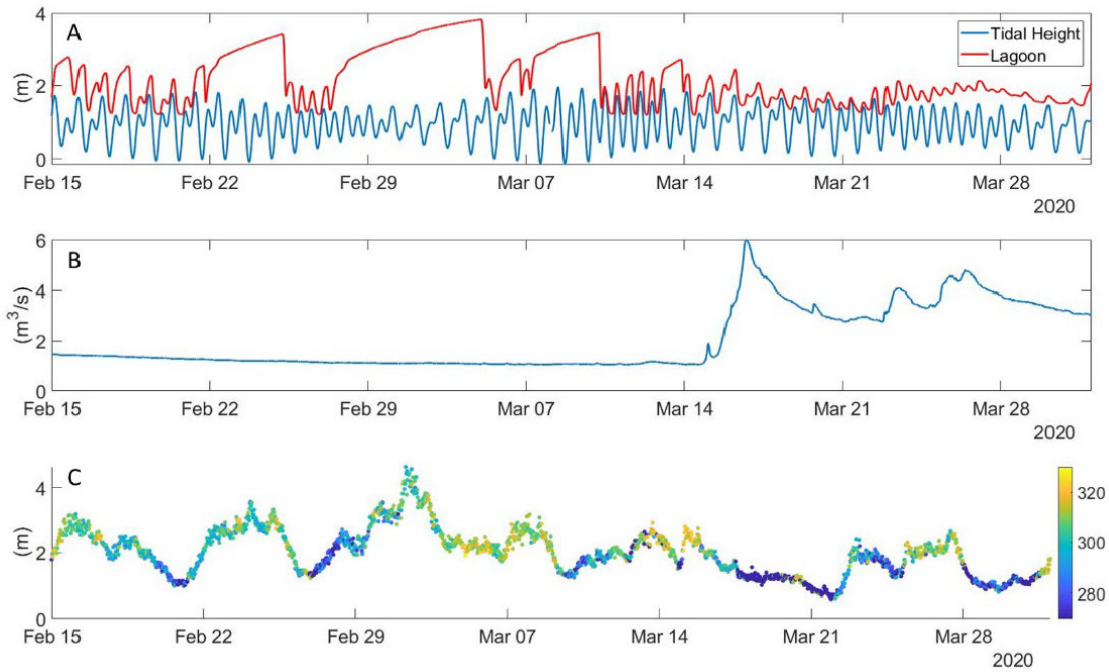
The Carmel River is an ephemeral river driven by seasonal precipitation during the winter leading to breaches. The Santa Lucia Watershed holds approximately 660 km<sup>2</sup> and feeds into the 58 km long Carmel River (Orescanin and Scooler 2018). In Figure 2a, one can see how the lagoon is a perched system as the red line, representing the water level of the lagoon is consistently above the blue line, representing the tides. The Carmel River experiences varied discharge rates throughout the year, depending on the season with 0 m<sup>3</sup>/s during the dry summer months and major flood rates above 200 m<sup>3</sup>/s. During the rainy winter months, discharge rates are considered a moderate flow at 5 m<sup>3</sup>/s (Figure 2b).

Depending on the filling rate of the lagoon, moderate rates ( $\sim 5 \text{ m}^3/\text{s}$ ) can cause a natural breaching process, where discharge rates exceeding  $200 \text{ m}^3/\text{s}$  will induce management action leading to an artificial breach by the water district management (James 2005). Lagoon filling can also occur when river discharge rates are low by wave over-topping. This normally occurs when wave heights exceed 3 meters (James 2005).

CRSB is affected by offshore wave heights (Figure 2c) ranging from 1–5m and wave directions typically between 280–300 degrees because it is constricted by rocky headlands to the North and South (Figure 2c; James 2005; Orescanin et al. 2021). James (2005) found that CRSB is 50% migratory and 50% stationary in terms of river beaching. Orescanin et al. (2021) found that during migratory years, there is a loss of sediment on the back beach and during the years of no migration (stationary), the beach builds back up due to sediment gain which leads to a low net loss or gain over time within the beach.

### **C. RESEARCH OBJECTIVE**

This study uses the numerical model Delft3D (Deltares 2014) to assess sensitivities of the processes driving breaching events for the CRSB for a March 2020 breaching event. This sensitivity analysis will vary boundary conditions and morphology inputs based on in-situ environmental data from the March 2020 breaching, as seen in Figure 2. The Carmel River Bay grid was created by Cavins in 2021 to replicate the perched estuarine system consisting of Carmel River, the Carmel River Lagoon and the Carmel Bay (Cavins 2021). The hypothesis to be tested is that river mouth morphology (bar height) is critical to the hydrodynamic “perching” of the lagoon. Furthermore, it is hypothesized that both increased offshore wave heights and increased river discharge lead to increased average water levels in the lagoon.



(A) Water level in the lagoon (River Marker) (Figure 1, red star) and tidal height (Figure 1, blue star), (B) Instantaneous river discharge rate (Figure 1, yellow star), (C) Pt. Sur NBDC wave height and direction (Figure 1, green star). CSR Environmental Forcing Parameters. Source: Cavins (2021)

Figure 2. CSR Environmental Forcing Parameters. Source: Cavins (2021)

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### III. METHODOLOGY

#### A. GENERAL MODEL SET UP

The numerical model, Delft3D, is used to test hydrodynamic and morphological variables to examine river, tide, and wave influences within the CRSB on evolution and closure event of a breach that occurred in March of 2020. This study uses the Delft3D modeling suite which specializes in both 2D and 3D computations within coastal, river and estuarine environments (Deltares 2014). Delft3D uses the full Navier Stokes system of equations in shallow water. It is comprised of several modules which interact with one another. The Delft3D-Flow module is a multi-dimensional module which conducts simulations for sediment transport, morphological development flows and waves. The Delft3D-Flow module is dynamically coupled with the Delft3D-Wave module so that processes and information is transferred between the modules. Delft3D-Wave module uses the Simulating Waves Nearshore (SWAN) model to calculate waves from a wide spectrum within the grids. Sediment Transport within Delft3D uses the Van Rijn method to calculate the combined effect of waves and currents on non-cohesive sediments, such as sand. These parameters and system of equations used by the Delft3D-Flow and Delft3D-Wave modules are further explained in Deltares (2014).

The initial hydrodynamic and wave grids (Figure 3) for Carmel River State Beach within Delft3D were set up by Cavins (2021) using multiple bathymetric data sources which were converted to Universal Transverse Mercator (UTM) Zone 10. Elevation data is recorded in meters using the North American Vertical Datum 1988 (NAVD88). Tidal boundary conditions, river discharge, and wave boundary conditions including significant wave height, direction and peak period (Figure 2) were sourced through multiple agencies including National Oceanic and Atmospheric Administration (NOAA Tides and Currents 2020) Municipal wharf in Monterey Bay, Monterey Peninsula Water Management District (MPWMD 2020), and National Data Buoy Center (NOAA NBDC 2019a; NOAA NBDC 2019b) using West Monterey Bay buoy, located approximately 41.5 km northwest of CRSB as well as the Point Sur Buoy located 27 km southwest of CRSB.

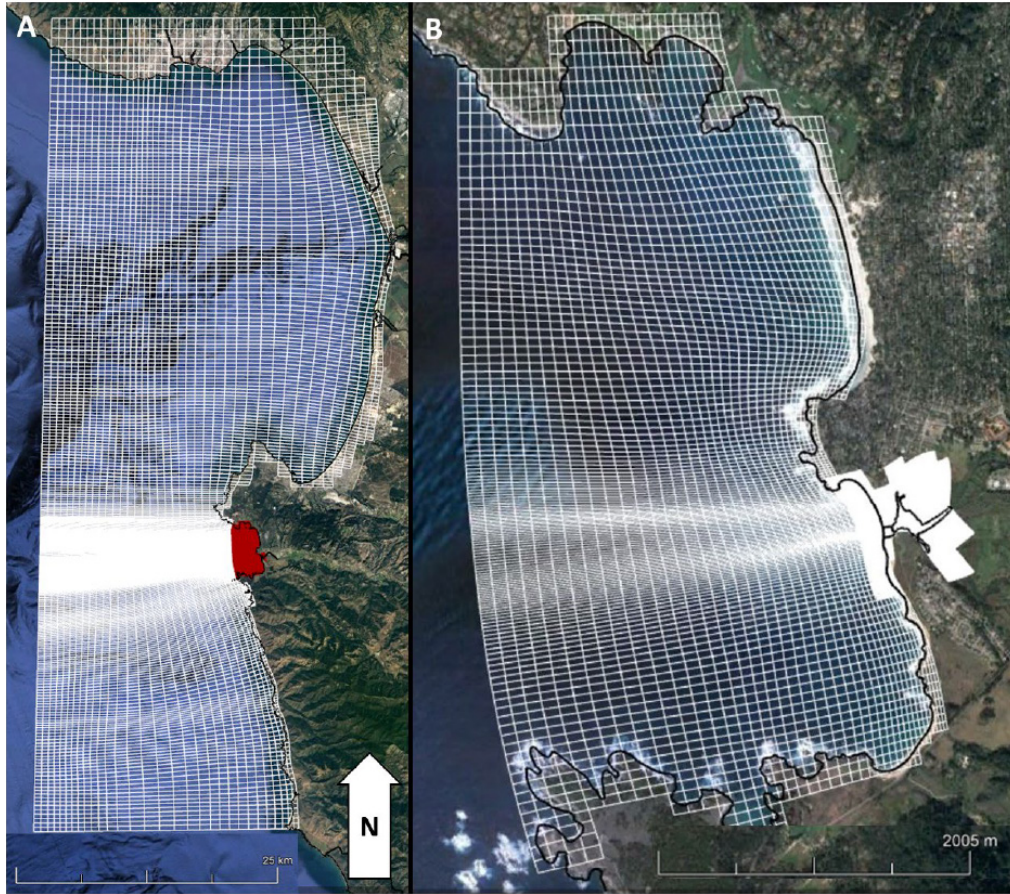


Figure 3. A) Delft3D Wave Grid (red indicates hydrodynamic grid) and B) Delft3D Hydrodynamic Grids. Source: Cavins (2021)

This Delft3D Flow model includes a large- and small-scale hydrodynamic grids with different spatial resolutions and with boundary conditions to encompass the entire testing site as shown in Figure 4. The larger scale hydrodynamic grid, Figure 3B, has a coarser resolution of 15x15 meters covering Carmel Bay and this sub grid was coupled seamlessly, through Delft3D domain decomposition, with the smaller scale hydrodynamic grid with a finer resolution of 2x2 meters. This smaller scale grid encompasses CRSB, lagoon and 100 meters up the Carmel River, cutting off prior to crossing U.S. HWY 1. Figure 3A depicts the SWAN grid in white, relative to the hydrodynamic domain in red.

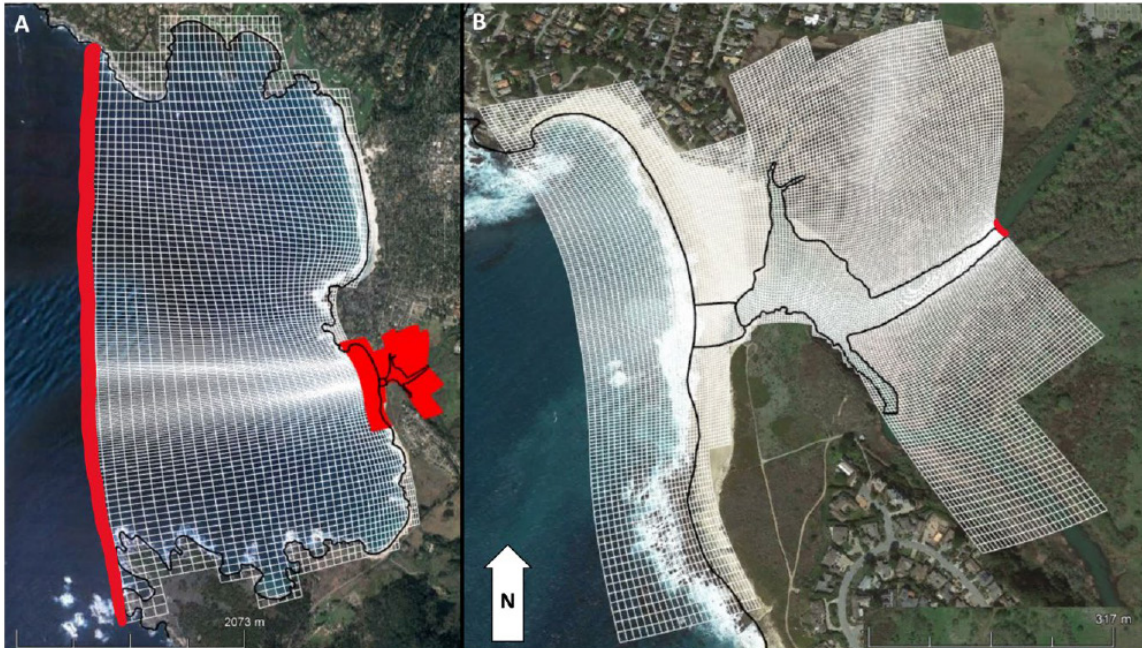


Figure 4. Hydrodynamic Sub-Grids of Carmel River Bay (A) and Lagoon (B) System in Delft3D. Source: Cavins (2021)

The initial baseline simulation in Delft3D was run by Cavins (2021) using observed discharge and observed waves during the March 15, 2020, breaching event as boundary conditions (Figure 2), without any sediment or morphology settings turned on for hydrodynamic calibration. Comparing the original model-data agreement from Cavins (2021) using water level at the River Marker (Figure 5), there were several issues in calibrating both average water level and tidal range (Figure 1C red star for site location). The model picks up the timing of high tide correctly, however it does not predict the tidal range of the observations, especially from March 24 onward. This period coincided with the neap tidal cycle with a period of increased river discharge, which increased the mean water level by almost half a meter and decreased the tidal range by the same amount, as seen in the observed data (black line, Figure 5). The water level of the modeled output consistently tends to be lower than what was recorded during the breaching event, especially towards the end of the event, which led Cavins (2021) to the conclusion that further hydrodynamic sensitivity was needed to better understand why the system increases mean water level and decreases tidal range during this period. One of the goals of this study

is to systematically vary boundary conditions and compare model outputs at the locations noted in Figure 6.

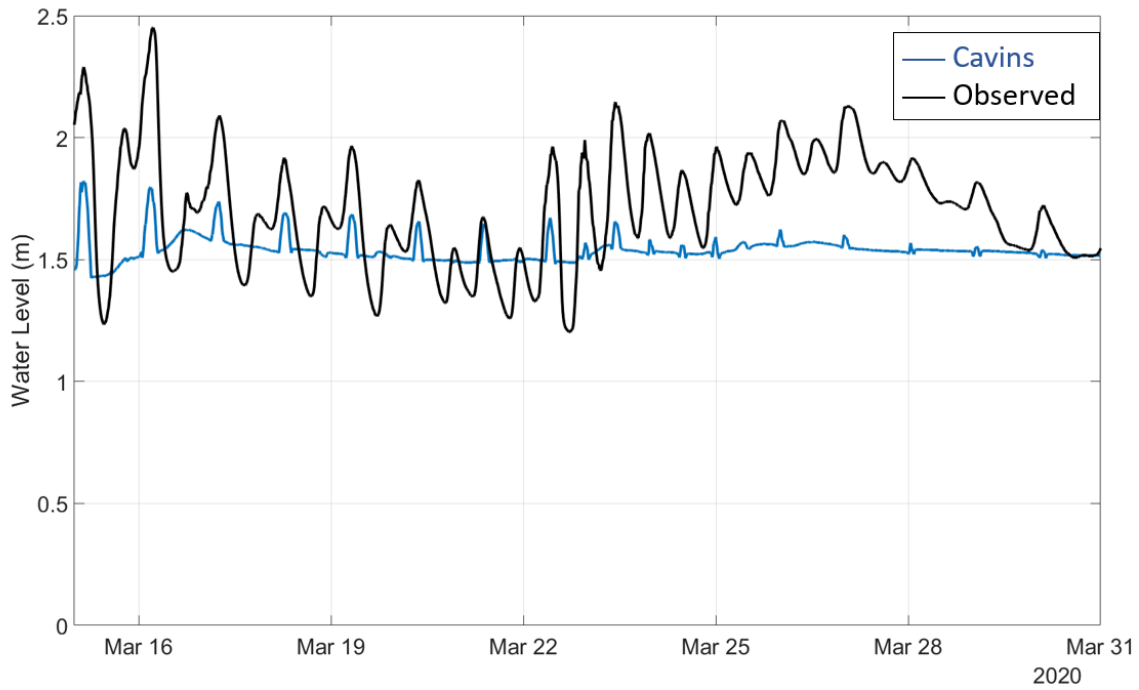


Figure 5. Baseline simulation water level comparison at River Marker location: Black line is observed water level recorded during March 2020. Blue line is baseline simulation run in Delft3D presented by Cavins (2021).

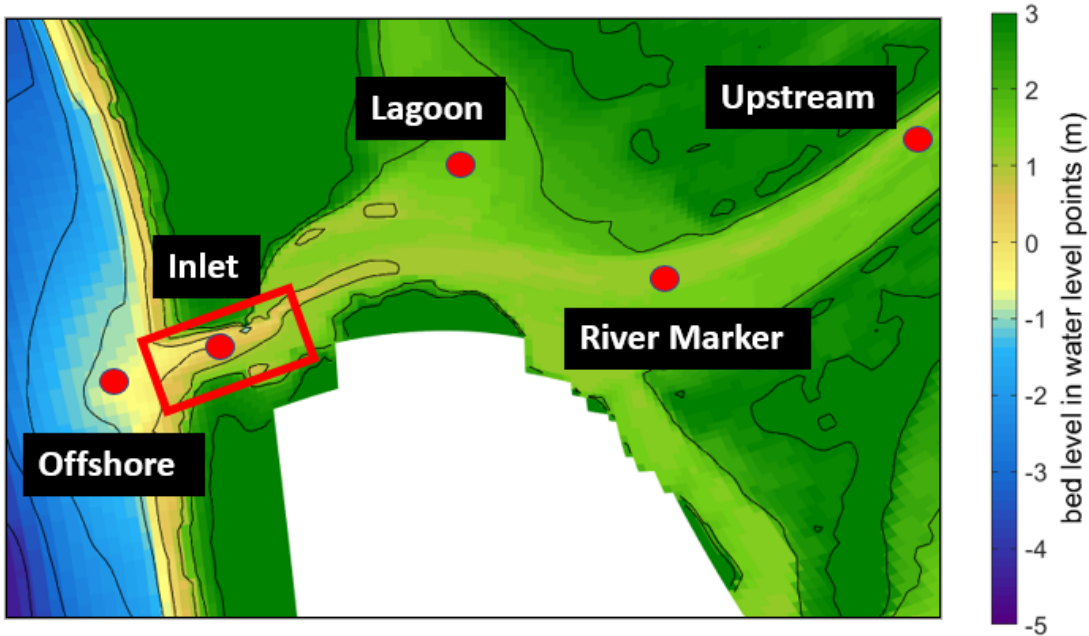


Figure 6. Carmel River Lagoon system with points of interest and model outputs locations

## B. SENSITIVITY ANALYSIS TO HYDRODYNAMICS

### 1. Variable Boundary Conditions

The first section of this analysis deals with the hydrodynamic impacts to an opened breach or Inlet and the effects waves, river discharge, and the combination of the two forcing mechanisms have on the Lagoon water levels and velocities. Model outputs are compared at four locations within the model domain: Offshore, Inlet, Lagoon, and River Marker (Figure 6). Four sets of hydrodynamic simulations were completed to assess the sensitivity of the forcing mechanisms within the Lagoon. The first two sets were used to see the impact of wave forcing and river discharge on the lagoon, while the third and fourth sets were used to understand the sensitivity that each forcing mechanism plays when one process becomes more dominant.

The first set of simulations, as seen in Table 1, uses realistic (observed) river discharge with varying wave conditions (significant wave height and peak period). A constant significant wave height ( $H_s$ ) from 5 m to 1 m was ran as the variable assessed to see the impact of wave forcing to the water level in the Lagoon based on a realistic

discharge rate from the Carmel River. All idealized wave heights have a peak direction of 270 degrees.

Table 1. Set of simulations varying significant wave height and peak period combined with realistic flow conditions.

<b>Simulation ID</b>	<b>H01</b>	<b>H02</b>	<b>H03</b>	<b>H04</b>	<b>H05</b>
<b>River Discharge (m<sup>3</sup>/s)</b>	real/observation	real/observation	real/observation	real/observation	real/observation
<b>Significant Wave Height (m)</b>	5	4	3	2	1
<b>Peak Period (s)</b>	18	16	14	12	10

The second set of simulations held river discharge constant at 1 m<sup>3</sup>/s, typical discharge rates for intermittent breaching, and again varied wave conditions from 1 m to 5 m respectively (Table 2). This modification shows the magnitude of influence wave forcing has upstream based on the size of waves entering the Lagoon.

Table 2. Set of simulations with constant low river discharge and varying wave conditions

<b>Simulation ID</b>	<b>H06</b>	<b>H07</b>	<b>H08</b>	<b>H09</b>	<b>H10</b>
<b>River Discharge (m<sup>3</sup>/s)</b>	-1	-1	-1	-1	-1
<b>Significant Wave Height (m)</b>	5	4	3	2	1
<b>Peak Period (s)</b>	18	16	14	12	10

The third set of simulations, as seen in Table 3, neglected wave action while varying the river discharge from 1 m<sup>3</sup>/s to 20 m<sup>3</sup>/s, respectively. Changing this boundary condition

assesses the influence of river discharge on water level in the Lagoon without any impact of from wave forcing countering the discharge.

Table 3. Set of simulations varying river discharge while neglecting waves

<b>Simulation ID</b>	<b>H11</b>	<b>H12</b>	<b>H13</b>	<b>H14</b>	<b>H15</b>
<b>River Discharge (m<sup>3</sup>/s)</b>	-1	-2.5	-5	-10	-20
<b>Significant Wave Height (m)</b>	0	0	0	0	0
<b>Peak Period (s)</b>	0	0	0	0	0

The last set of simulations in the hydrodynamic sensitivity analysis, as seen in Table 4, set the significant wave height to a constant 2 meters and a peak period of 12 seconds for all runs and varied the discharge from 1 m<sup>3</sup>/s to 20 m<sup>3</sup>/s respectively. This simulation, along with the no-waves simulation allows a comparison of river discharge influence on lagoon dynamics based on typical wave conditions at the site.

Table 4. Set of simulations varying river discharge with constant 2-meter significant wave height and 12 s peak period

<b>Simulation ID</b>	<b>H16</b>	<b>H17</b>	<b>H18</b>	<b>H19</b>	<b>H20</b>
<b>River Discharge (m<sup>3</sup>/s)</b>	-1	-2.5	-5	-10	-20
<b>Significant Wave Height (m)</b>	2	2	2	2	2
<b>Peak Period (s)</b>	12	12	12	12	12

For these runs, the inlet is considered open, and the boundary conditions being modeled are used to see how the coupling effects of river discharge and wave forcing affect the water level in the Lagoon.

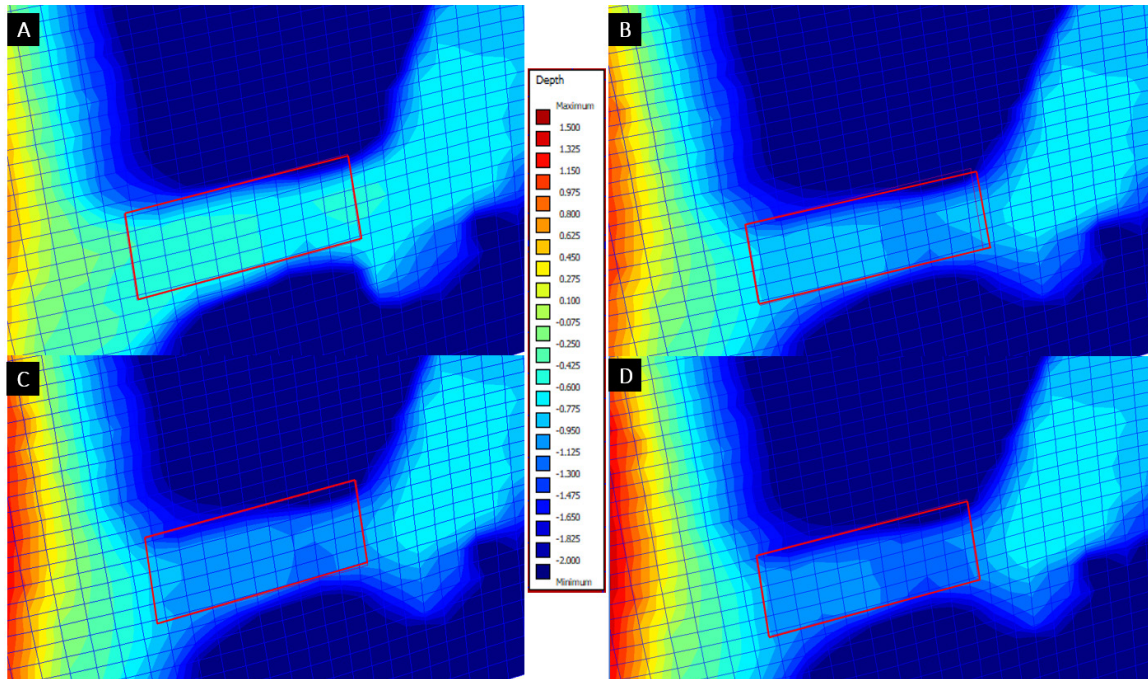
## 2. Rigid Morphology Variations

The morphological comparison of this study includes a set of simulations, in Table 5, that assesses the sensitivity between the morphology of the inlet and the control it has on the hydrodynamics in the lagoon. All simulations are built from a baseline simulation (ID B1), Figure 7A, which consists of realistic wave conditions and river discharge and a bathymetric survey collected from March 2020. The three simulations with different initial inlet bathymetries are shown in Figure 7, panels B through D, were intended to reduce the depths of the inlet relative to the baseline (i.e., creating shallower inlets). Simulation ID M01 raised the bathymetry by 0.35 m, and simulation ID M02 raised the bathymetry by 0.45 m and simulation ID M03 raised the bathymetry by 0.55 m. These comparisons were done to assess hydrodynamic sensitivity of the lagoon to the presence of a beach berm within the inlet. Observed water levels at the lagoon (River Marker) recorded during the 2020 breach were compared to the outputs of the rigid berms simulations to evaluate the performance of the model at simulating water levels in the lagoon with varying initial berm elevations (inlet depths).

Table 5. Rigid berm simulations and morphologic assessment simulations

Simulation	Rigid Berm Modification	Morphology	Simulation	Rigid Berm Modification	Morphology
<b>Baseline (B1)</b>	Baseline	Off	Baseline (B2)	Baseline	On
<b>M01</b>	Baseline + 0.35m	Off	M04	Baseline + 0.35m	On
<b>M02</b>	Baseline + 0.45m	Off	M05	Baseline + 0.45m	On
<b>M03</b>	Baseline + 0.55m	Off	M06	Baseline + 0.55m	On

These simulations keep the corresponding berm modification set up through each set of simulations where morphology is left off and then when morphology is turned on.



Panel A: bathymetry of baseline simulation (ID B1) with maximum inlet depth of 0.85 m. Panel B: bathymetry of simulation (ID M01) with depth reduced by + 0.35 m. Panel C: bathymetry of simulation (ID M02) with depth reduced by + 0.45 m. Panel D: bathymetry of simulation (ID M02) with depth reduced by + 0.55 m. Location of grid modification here is indicated by the red box in Figure 6.

Figure 7. Bathymetry modifications for variable berm height

### C. MORPHOLOGIC ASSESSMENT

Next, morphological sensitivity was tested by turning on the morphology and sediment parameters within Delft3D for each of the simulations ran within the rigid morphology section. Simulated and observed water levels were compared at the river marker and different spatial trends of morphological evolution within the system were identified after 15 days of morphological change.

The Delft3D model for the CRSB solves the depth-averaged advection-diffusion equation for suspended sediment transport and the Van Rijn TR2004 formulations for non-cohesive bed load transport. A median grain size  $D_{50}$  of 1000  $\mu\text{m}$  with a density of 2650  $\text{kg/m}^3$  was selected as it represents a typical sediment size found in the CRSB. More calibration settings are identified in Table 6. This portion was conducted to identify the effects that the initial bathymetric conditions have in the morphological response of the

Carmel River System. Reference cases A through D in Figure 7 were run, however berm heights above 0.45 m led to numerical instabilities within the model and could not be resolved during the scope of this study.

Table 6. Delft3D morphologic parameters

<b>General Set up</b>	
Morphological Scale Factor	5
Spin Up interval before Morphological Changes	29 days
Minimum depth for sediment calculation	0.1 m
<b>Sediment Transport Parameters</b>	
Van Rijn's Reference height factor	0.5
Threshold Sediment Thickness	0.050000001 m
Estimated Ripple Height Factor	2
<b>Calibration Factors</b>	
Factor for erosion of adjacent dry cells	0.8
Current-related reference concentration factor	1
Current-related transport vector magnitude factor	1
Wave-related suspended transport factor	0.15
Wave-related bed-load transport factor	0.15

## IV. HYDRODYNAMIC SENSITIVITY TO VARYING WAVES AND RIVER DISCHARGE

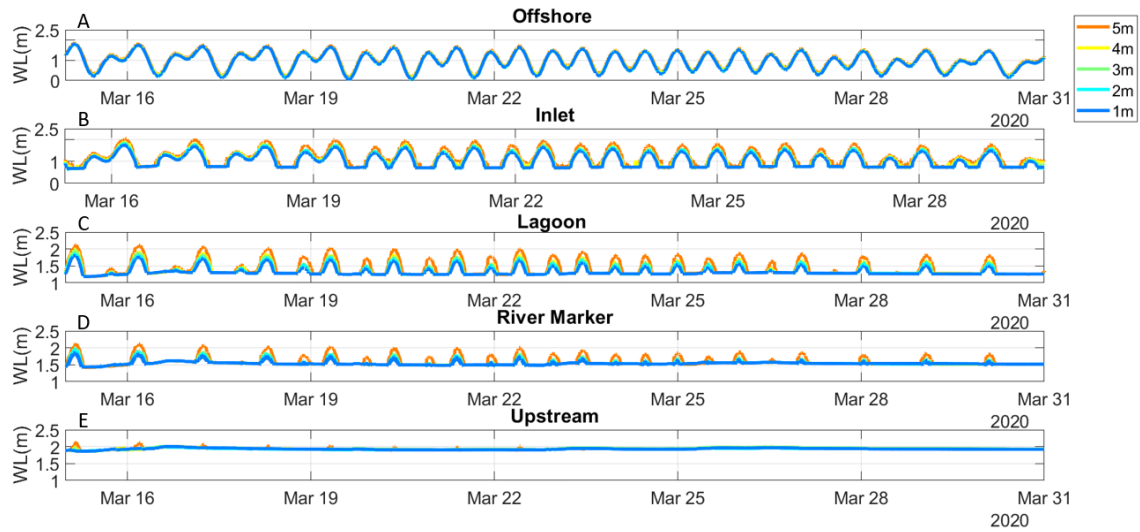
### A. RESULTS

#### 1. Realistic River Discharge with Varying Wave Conditions

Models H01-H05 assessed hydrodynamic sensitivity to ideal (constant) offshore wave heights ranging from 1m to 5m with observed river discharge during March 2020 (Table 1 from methods). To assess impacts of varying offshore waves, model outputs (Locations Figure 6) of water level (Figure 8) and significant wave height (Figure 9) are compared. It should be noted that owing to the effects of refraction along the irregular, rocky coastline, significant wave heights are decreased to a maximum of 3m at the Offshore location, even for the 5m simulation (Figure 9, panel a). Wave heights impact the water levels at the Offshore through Upstream locations, however by the time waves reach the Upstream location, the wave heights are almost negligible (Figure 8e). For a greater offshore wave height, the effect on peak water levels at high tide are greater (orange lines are always higher than blue, Figure 8). Furthermore, mean water levels from Offshore to Upstream increase from 1m (Figure 8A) to nearly 2m (Figure 8E) which is indicative of a perched system where the lagoon sits higher than the coastline. The high tides are physically higher at the locations from Offshore to the River Marker (Figure 8 A-E) as indicated by the orange lines, however, that impact tends to decrease as it reaches the River Marker and only with the higher waves, is this wave energy experienced at the Upstream location of the river system. This is supported by Figure 9, as the significant wave heights are present only on the high tides and for greater offshore wave heights. The impact of non-constant observed river discharge is evident in the variable low tides over the two-week period, especially in water levels at the Upstream through Lagoon locations (Figure 8, bottom three panels).

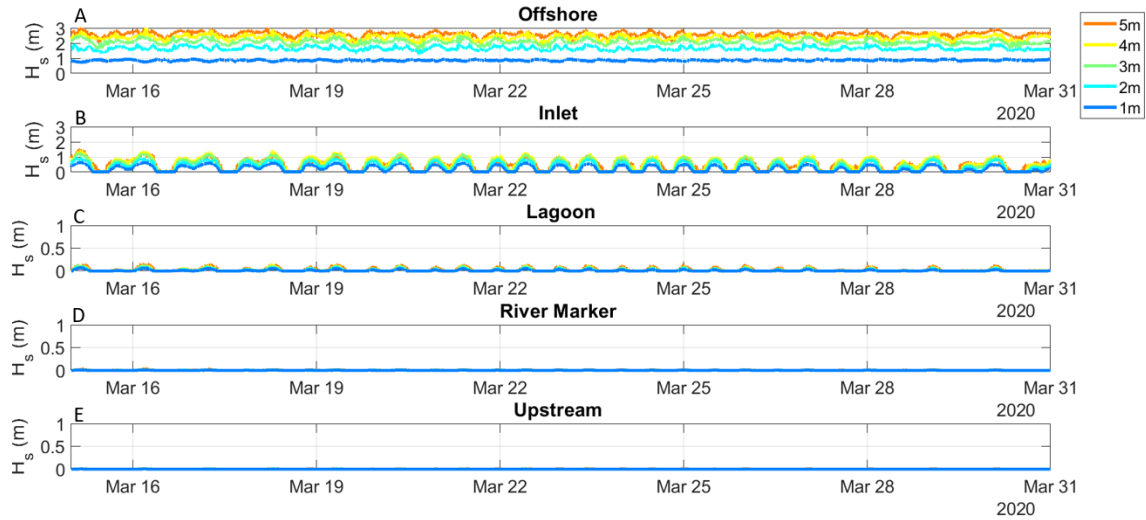
In summary, the main takeaway for all wave conditions tested, is that waves barely reached the River Marker located 250 m landward from the inlet, but they can still influence water levels as far as the Upstream station, located 450 m landward from the inlet. Wave

propagation into the lagoon and landward is highly dependent on tidal phase, with waves reaching the farthest landward distances during high tides.



Water Level of Realistic (Observed) discharge with ideal waves at the (A) offshore, (B) Inlet, and (C) Lagoon, (D) River Marker, and (E) Upstream locations as shown in Figure 6.

Figure 8. Water level of realistic (observed) discharge with ideal waves. Note the difference in the Y axis scales in the Lagoon, River Marker and Upstream panels



Significant wave height of realistic (Observed) discharge with ideal waves at the (A) offshore, (B) Inlet, and (C) Lagoon, (D) River Marker, and (E) Upstream locations as shown in Figure 6.

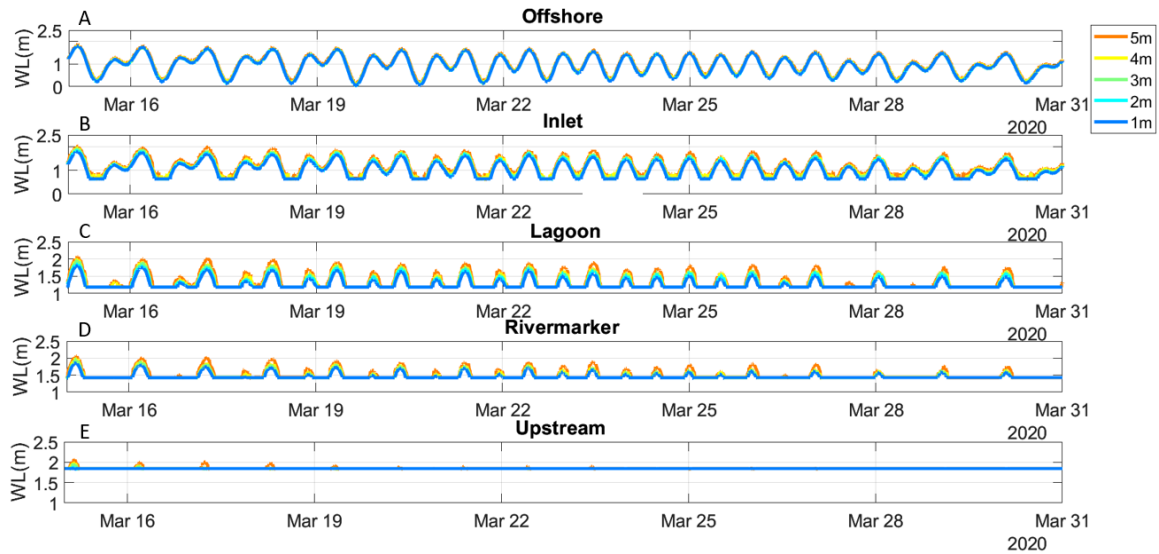
Figure 9. Significant wave height for realistic discharge with ideal waves. Note the difference of the Y axis scales for the Lagoon, River Marker and Upstream panels

## 2. Ideal River Discharge (1 m<sup>3</sup>/s) with Varying Idealized Wave Conditions

For models H06-H10 (Table 2) where river discharge is constant at 1 m<sup>3</sup>/s, similar trends to models with observed discharge (previous section) are present in both water level and significant wave heights for the high tides (Figures 10 and 11). In Figure 10, water level increases from Offshore to Inlet. Peak high tide water levels at the Inlet, in the Lagoon, and at the River Marker do not change from their respective heights in the Inlet with offshore wave height (i.e., there is no pressure gradient between the River Marker and the Inlet). Water level timeseries for the Upstream location, which is the furthest point from the wave energy, experiences water level changes only from the higher wave simulations with 4- and 5-meter waves. As expected, the larger the wave heights, the bigger the amplitude is for each location at high tide. However, each simulation has the same water level at low tide except for the Inlet where variation in water level at low tide is more apparent. In addition, this lower water level increases moving from coast to upstream river, consistent with a continuous offshore-directed pressure gradient from observations.

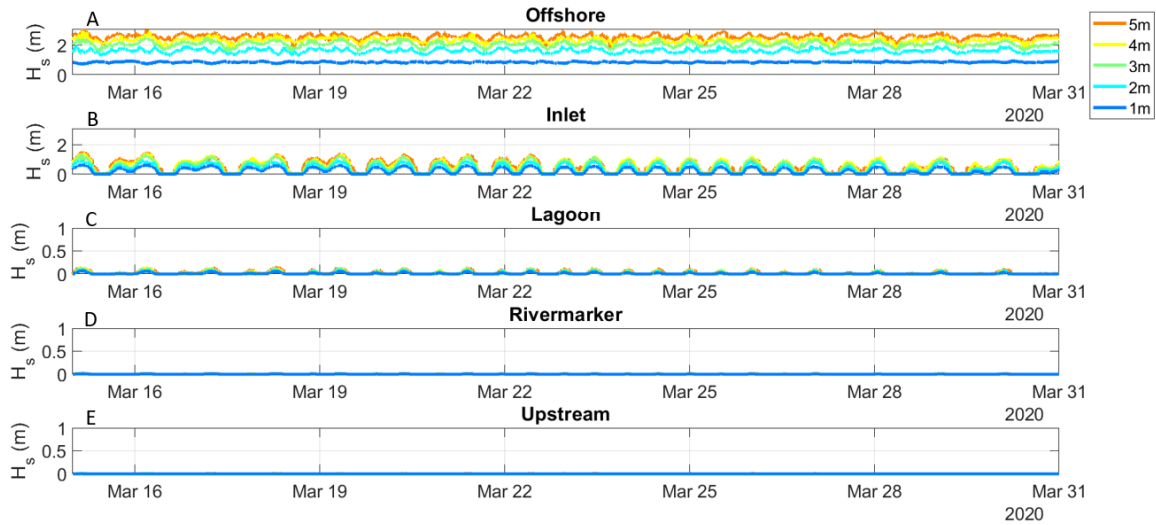
Significant wave heights (Figure 11) show that as the highest wave height offshore, wave heights diminish by a factor of 2 by the time they reach the Inlet, where only high tide leads to non-zero wave heights and low tide has no wave infiltration into the Inlet. By the time this energy reaches the Lagoon, there is little impact seen in Lagoon, River Marker and Upstream (Figure 11C/D). Only on high tide is there any wave energy at the Lagoon.

In summary, ideal varying waves against low river discharge ( $1 \text{ m}^3/\text{s}$ ) affects water level at high tide only, leaving a consistent mean water level at each location, increasing from Offshore to Upstream. Only the large waves (4- and 5-meter) have a non-zero effect on the water level in the Lagoon and further upstream.



Water level of low discharge with ideal waves at the (A) offshore, (B) Inlet, and (C) Lagoon, (D) River Marker, and (E) Upstream locations as shown in Figure 6.

Figure 10. Water level for low ( $-1 \text{ m}^3/\text{s}$ ) river discharge, with ideal waves. Note the difference in Y axis scales for Lagoon, River Marker and Upstream panels

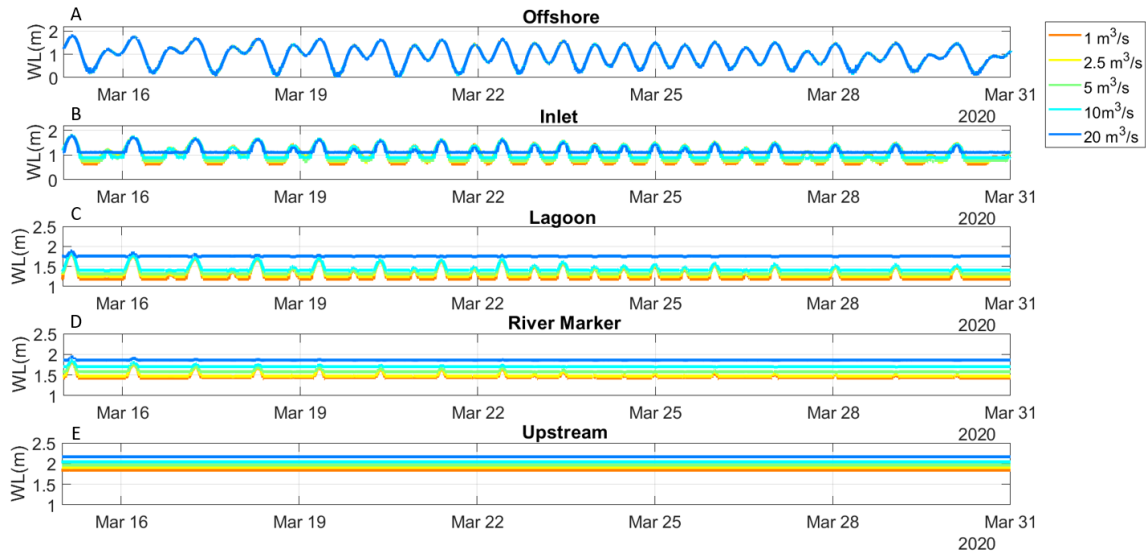


Significant wave height for low discharge with ideal waves at the (A) offshore, (B) Inlet, and (C) Lagoon, (D) River Marker, and (E) Upstream locations as shown in Figure 6.

Figure 11. Significant wave height for low ( $1 \text{ m}^3/\text{s}$ ) river discharge, with ideal waves. Note the difference of the Y axis scales for the Lagoon, River Marker and Upstream panels

### 3. Varying Idealized River Discharge without Waves

With wave height set to zero, the water level changes in the system are a function of tides and river discharge alone (Figure 12). As discharge increases, mean water levels at each station increase. With the higher discharge rates of  $20 \text{ m}^3/\text{s}$ , even at the River Marker, there was little influence of tides. However, as the river discharge rate decreases, tides became a factor in the water level rise. Within the Lagoon, tidal influence is seen at all discharge rates, however minimal at  $20 \text{ m}^3/\text{s}$  and only during the spring tidal cycle (March 15–20) were the higher high tides seen in the water level. Downstream (Inlet and Lagoon), tides continue to have impact to the water level against all discharge rates, moving Upstream, tides become less noticeable against the discharge.

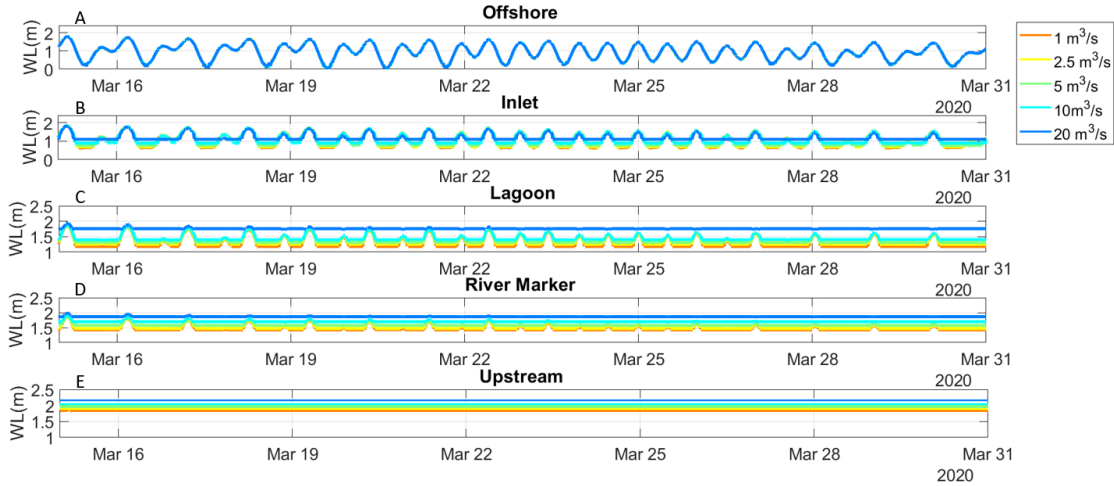


Water level for no waves with varying discharge for (A) offshore, (B) Inlet, and (C) Lagoon, (D) River Marker, and (E) Upstream locations as shown in Figure 6.

Figure 12. Water level for simulation runs with no waves (0m) and ideal varying discharge. Note the difference of the Y axis scales for the Lagoon, River Marker and Upstream panels

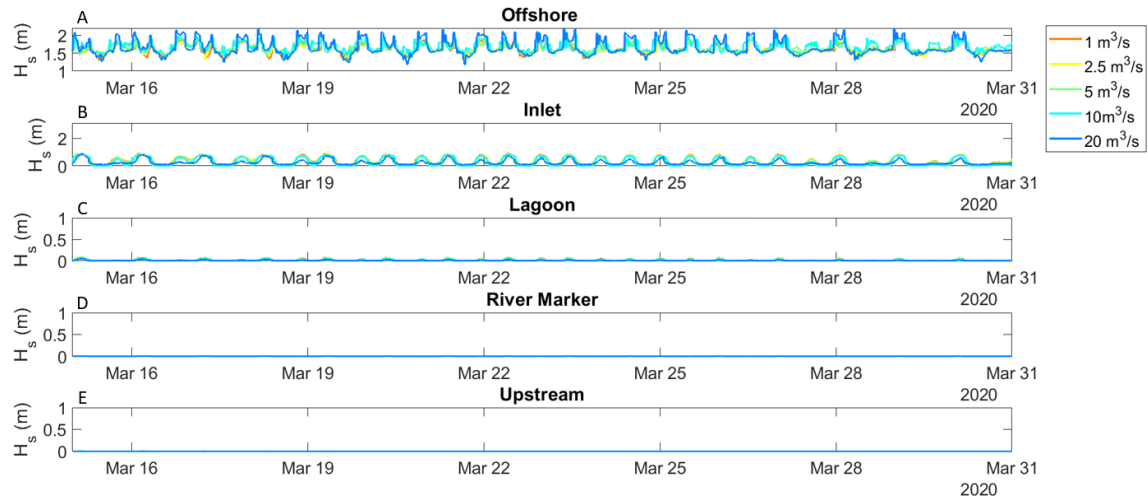
#### 4. Varying Idealized River Discharge and Typical Wave Conditions ( $H_s = 2 \text{ m}$ , $T_p = 12 \text{ s}$ )

To assess the effect of discharge on a more-realistic condition, the same models were run with wave heights set to a constant 2 meters, with varied river discharge rates 1  $\text{m}^3/\text{s}$  to max of 20  $\text{m}^3/\text{s}$ . In Figure 13, water level, with varied discharge, tends to increase from Inlet to Upstream, as in the previous simulation set. Starting at the River Marker going Upstream, the water level for the 20  $\text{m}^3/\text{s}$  is higher than those of the other discharge rates. 20  $\text{m}^3/\text{s}$  discharge rate also has the most variability and impact on the water level at both the Inlet and the Lagoon. Lower river discharge values tend to reach an average between 1 m and 1.5 m water level except for Upstream where the water level is the highest. In summary, river discharge plays a dominate role on water level dynamics from the Lagoon to Upstream. At the Inlet, discharge has a high variability due to the interaction with the waves (Figure 14).



Water level of ideal discharge and 2m waves for (A) offshore, (B) Inlet, and (C) Lagoon, (D) River Marker, and (E) Upstream locations as shown in Figure 6.

Figure 13. Water level for ideal discharge with 2m Waves. Note the difference of the Y axis scales for the Lagoon, River Marker and Upstream panels

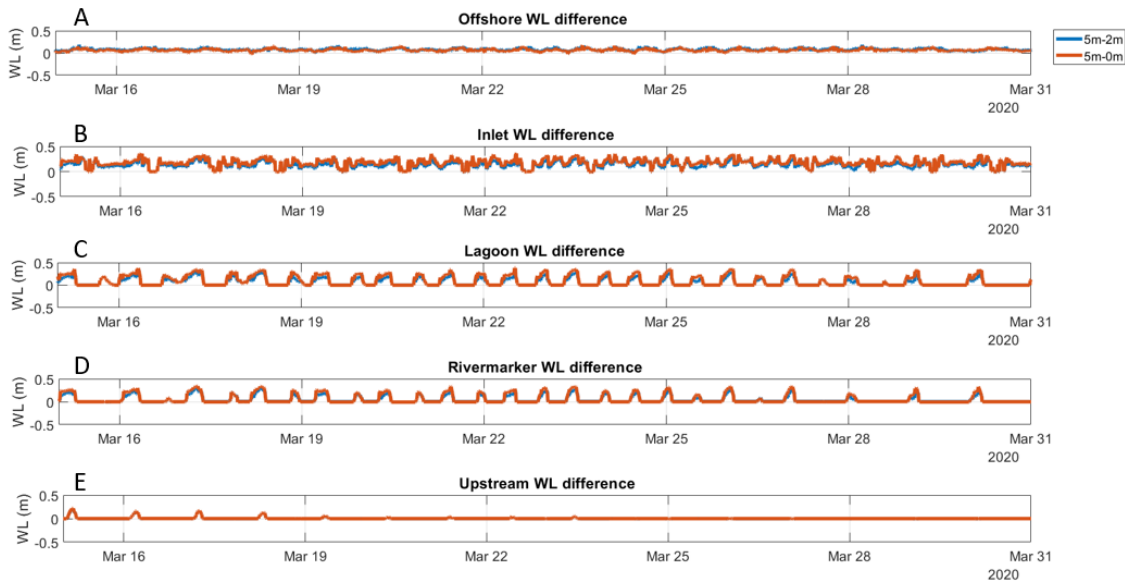


Significant wave height for ideal discharge and 2m waves for the (A) offshore, (B) Inlet, and (C) Lagoon, (D) River Marker, and (E) Upstream locations as shown in Figure 6.

Figure 14. Significant wave height for ideal discharge with 2m waves. Note the difference of the Y axis scales for the Lagoon, River Marker and Upstream panels

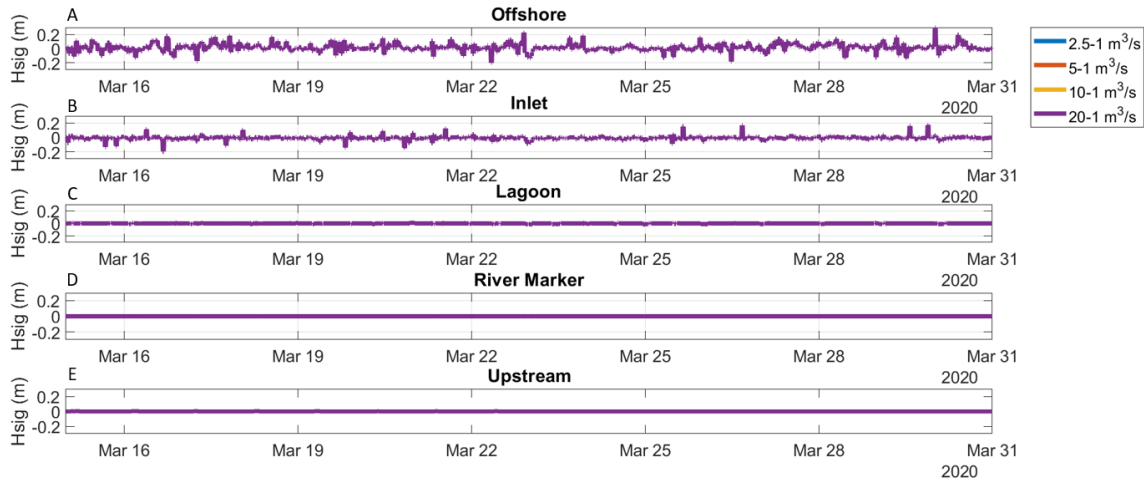
Figure 15 shows the effect of wave height on water level as a function of time. The difference between 5m wave heights and 0m wave heights with 1 m<sup>3</sup>/s discharge is larger

than 5m and 2m plot with 1 m<sup>3</sup>/s discharge. Lower wave heights, as indicated by the blue line, do not reach the upstream location. Again, this variation is seen in the peaks of high tide whereas the troughs of low tide show consistent energy at each location. As seen in Figure 16, changing the river discharge from 1 m<sup>3</sup>/s to 20 m<sup>3</sup>/s did not change the wave height at any of the locations, as all the differences are equal to each other.



Water level difference of realistic (observed) discharge with ideal waves at the (A) offshore, (B) Inlet, and (C) Lagoon, (D) River Marker, and (E) Upstream locations as shown in Figure 6. Each line represents the difference of 2 simulations where discharge is negligible, and the wave height changes. Blue line is the 5m (Sim ID H06) minus 2m (Sim ID H16) difference and the red line is 5m (Sim ID H06) -0m (Sim ID H11).

Figure 15. Water level difference plot based on 5m, 2m and 0m waves



Significant wave height difference with varying discharge at the (A) offshore, (B) Inlet, and (C) Lagoon, (D) River Marker, and (E) Upstream locations as shown in Figure 6

Figure 16. Significant wave height difference plot based on varied discharge rates

## B. DISCUSSION

James (2005) describes the typical flow rates and environmental conditions that Carmel River Lagoon experiences throughout the seasons. Winter and Spring seasons tend to be the “rainy” season with high precipitation rates driving river flow from low ( $0\text{--}2\text{ m}^3/\text{s}$ ) to moderate and heavy flow ( $8\text{ m}^3/\text{s}$ ). The water level in the lagoon will begin to increase through overtopping events by large ocean swells and with a river discharge rate around  $0.7\text{--}1\text{ m}^3/\text{s}$ , the lagoon will slowly begin to fill. High precipitation rates resulting in  $5\text{--}10\text{ m}^3/\text{s}$  river discharge can fill the lagoon within 12 to 24 hours and induce a breach if the County of Monterey has lowered the beach elevation to prevent the surrounding area from flooding. As seasons transition to summer through the fall, the “dry” season sets in and as the river discharge drops to below  $2\text{ m}^3/\text{s}$ , a sand bar will begin to build and eventually closing off the mouth of the river from the Carmel Bay. Wave induced onshore migration of sediment or overtopping is another way the lagoon system will fill and breach. Large ocean waves between  $5\text{--}7\text{ m}$  can wash over the top of the sandbar and fill the lagoon until a natural breach occurs when the lagoon water levels become too large (James 2005).

The hydrodynamic boundary conditions chosen during these tests were based on the realistic environmental conditions stated by James (2005). Waves and River Discharge values were chosen with extreme values in order to better understand the processes and dynamics that occur seasonally that results in breaches and closures at the CRSB. With a realistic discharge, as in Figures 8 and 9, wave energy does not extend far past the Inlet and river discharge tends to dominate the Lagoon water level. During a season with low precipitation, these models show the sensitivity of wave heights to the lagoon. Larger waves, such as seen by the 4 m and 5 m waves in Figures 10 and 11, tend to reach the lagoon only with the high tide indicating that river discharge dominates during low tide periods even at nearly dry riverbed. This also indicates that wave energy and mean water level in the Lagoon increase as a function of offshore wave height, as seen in Figures 15 and 16. The larger the waves offshore, the higher the mean water level will be during high tides and the further they will propagate upstream.

The second part of the hydrodynamic analysis was to determine the sensitivity of river discharge rates to the dynamics of lagoon mean water level and breaching events by keeping wave heights constant and varying discharge from a slow “dry” rate with moderate river charge (0-2 m<sup>3</sup>/s) and/or to very quick, extra “wet” with moderate river discharge (5-8 m<sup>3</sup>/s). Figures 12–14 show that a high discharge rate counters the spring tides energy from March 15–20 and only the higher high tidal energy reaches the inlet bridge location until the tidal cycles becomes neap around March 20<sup>th</sup>. Carmel River Beach is a perched system, and this is seen at the Upstream location where the water level is highest, showing deepest water level will decrease with offshore distance. River discharge tends to impact the mean low tidal water level within the Lagoon whereas the simulations H01-H10 with varying wave heights tended to impact the peak tidal flow. Unlike variable wave height simulations, the peaks of the high tide agree with consistent water level for each discharge rate at both the Inlet and the Lagoon and low tide water level varies. This location also shows that river discharge, if no waves are present, will dominate the water levels.

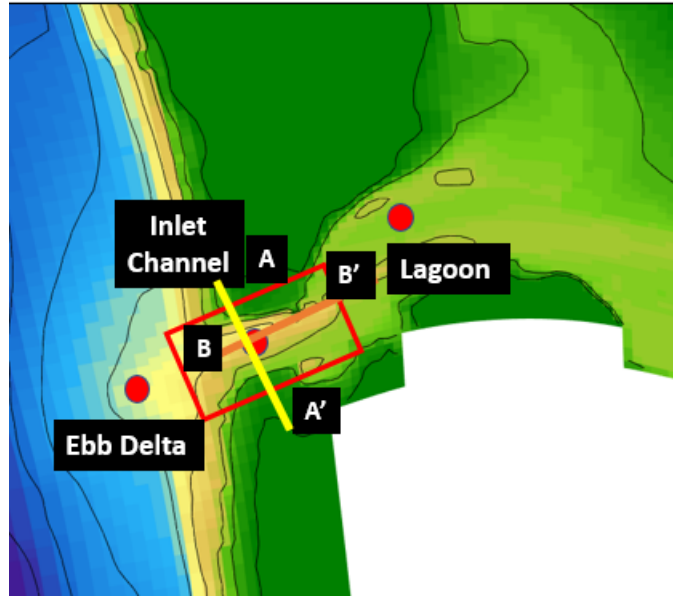
In summary, the models with constant “low” discharge (-1 m<sup>3</sup>/s) and varying wave heights from 0–5 meters showed that increased wave energy was present with increased offshore wave heights. This, in turn, resulted in increased mean water levels in the Lagoon

and increased water level range (figure 10). In contrast, with fixed offshore waves and varying upstream discharge, larger discharges were associated with smaller water level ranges, but also increased mean water levels. As the discharge increased, the tidal range decreased in the Lagoon to the Upstream, indicating that during the wet winter/fall seasons, river discharge dominates the dynamics within the Lagoon. For both larger waves and larger discharge, the Lagoon can expect increased mean water levels.

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## V. MORPHOLOGIC SENSITIVITY RESULTS

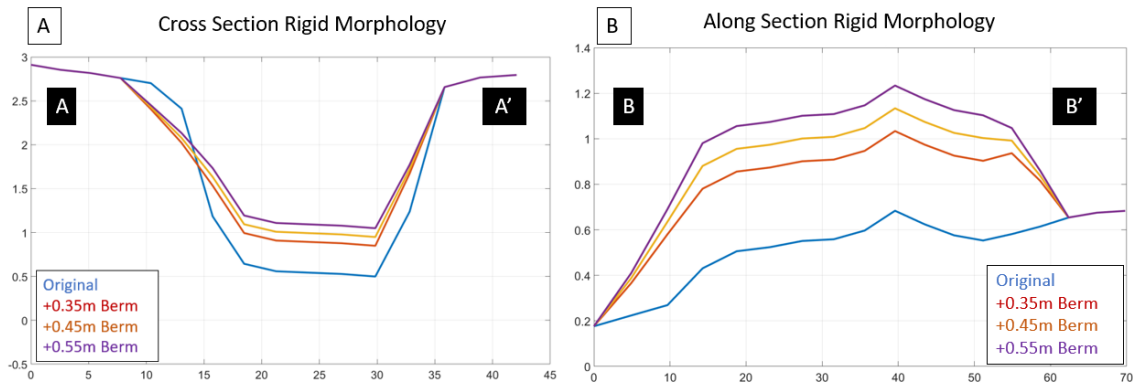
The unique morphological feature that gives systems like Carmel River State Beach the classification, bar-built estuary, is the presence of an elevated beach berm, either subaqueous or subaerial. Therefore, it is hypothesized that the presence and elevation of this berm will impact both the hydrodynamic and morphological response of the system. To test this hypothesis, two numerical experiments were conducted: 1. Rigid morphological assessment of the hydrodynamic changes owing to changes in berm height, and 2. Morphological response of these varying berm height initial conditions. The figures in the following sections include simulations with rigid morphology and morphology changes on to analyze the differences in lagoon water levels with varying initial bathymetries and with varying morphologic evolution. Creating a rigid berm is an intermediate test to assess the hydrodynamic outcome to variable rigid morphologic conditions at the mouth of the estuary. The berm simulates a sand bar that builds up owing to wave forcing from the ocean and allows for assessment of the hydrodynamic response of the model to this berm in the region outlined by the red rectangle in Figure 17. Baseline bathymetry, also referred to “Original” has an open inlet with a maximum depth of 0.85m. The original bathymetry was set up in the grid by Cavins (2021). Three regions impacted by morphology were the Ebb Delta, the Inlet Channel, and the Lagoon, shown in Figure 17.



The yellow line, A-A', is the cross section taken at the inlet while the orange line, B-B', is the along section taken through the center of the inlet to the lagoon. The Ebb Delta, Inlet Channel and Lagoon were the primary areas of interest during the morphologic sensitivity analysis

Figure 17. Morphologic regions assessed.

The Inlet cross (A-A' in Figure 17) and along (B-B' in Figure 17) sections were plotted at the beginning of the simulations (initial conditions were the same for both sets of 'rigid berm' and 'morphology turned on' simulations). The cross section was taken at the area labeled by the yellow line with A and A', indicating the orientation of the cross section with A being the northern end of the beach, which is the starting point along the X axis on Figure 18, and A' being the side with rocky headlands to the south of CRSB. Panel A shows the cross section where each bathymetry change made the inlet shallower. The blue line is the base simulation, and the berms shallow up to 0.55m respectively. Panel 18B shows the along sections of the Inlet with the shallower bathymetry and how the changes created rigid "berms." This section held the berms fixed for the rigid morphology runs, to assess the how a simulated berm affects the hydrodynamics in the Lagoon.



Panel A is the Cross Section indicating the bathymetry changes. A-A' is the orientation seen in Figure 16 with A being near the parking lot and A' ending near the rocky headlands to the south of the beach. Panel B is the Along Section with B being offshore and B' ending near the Lagoon.

Figure 18. Cross and along sections of rigid morphology

**A. SENSITIVITY OF WATER LEVELS TO CHANGES IN THE INITIAL BEACH BERM WITH MORPHOLOGICAL EVOLUTION TURNED ON AND OFF**

The water level at the Inlet (Figure 19), Lagoon (Figure 20), and River Marker (Figure 21) for both the rigid berm (morphology OFF) and morphology simulations (morphology ON) were plotted and compared to analyze the difference that morphology has on the water levels in the system. At the Inlet in the baseline simulation (Figure 19A), with original bathymetry, shows the widest range of water levels and a pronounced tidal energy influence. As the berm height increases, the tidal signal becomes less pronounced, although the mean water level increases as the berm is built up. For Morphology ON, the water level at the Inlet for the original simulation (Figure 19B) shows the widest range of water level, However, on March 16<sup>th</sup>, both berm increases (simulations M04 with berm elevation +0.35m and M05 with berm elevation +0.45 m) tend to match the original simulation closely until March 20<sup>th</sup> At this point the mean water level for both modified simulations remain higher than the original simulation.

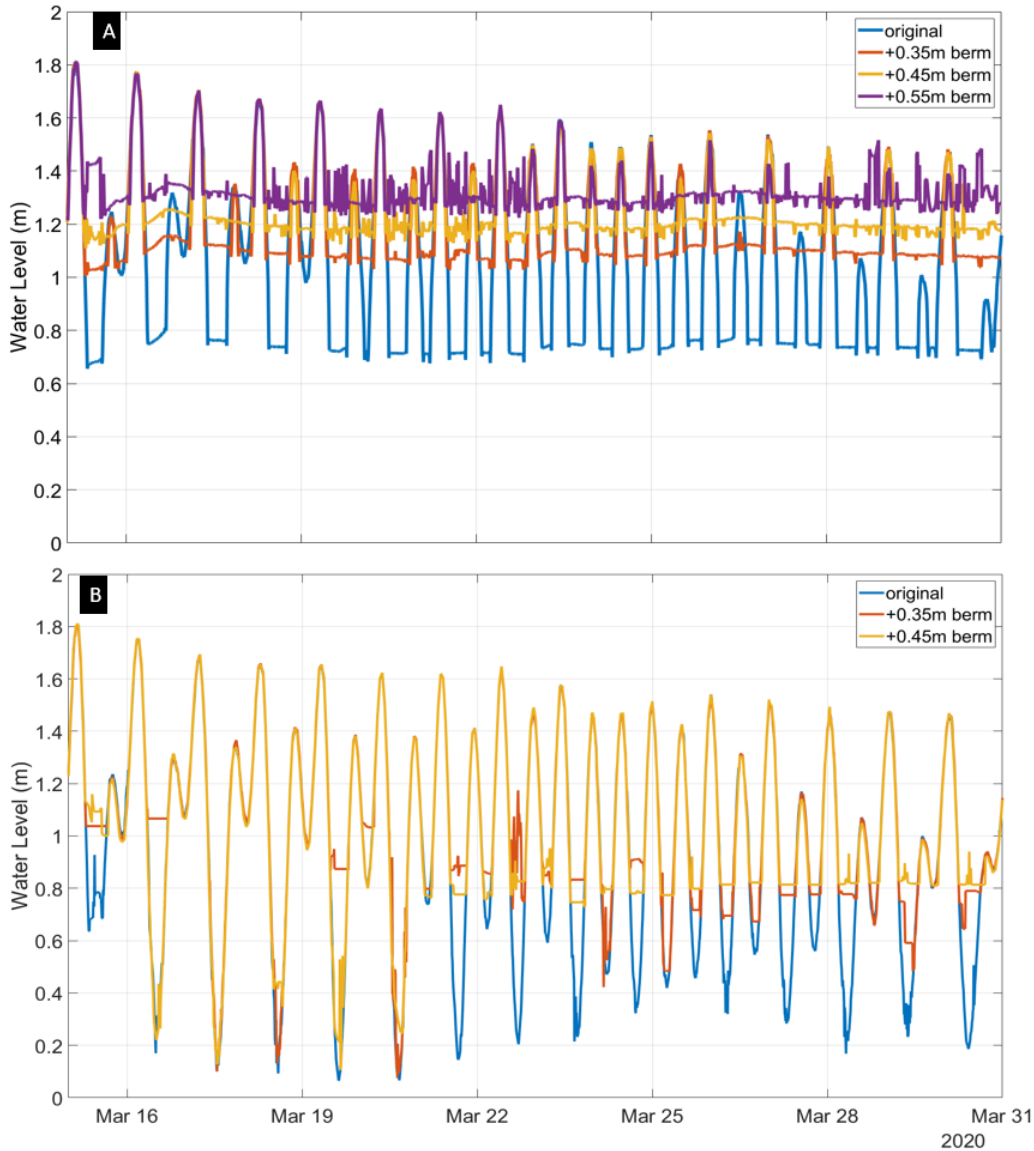


Figure 19. Water level comparison at the Inlet location for simulations with morphology off (Panel A) and on (Panel B)

In Figure 20A, the Lagoon mean water level continues to rise within each rigid berm simulation (morphology OFF) and follow the same pattern as the other rigid berm simulations. The tidal influence for each simulation decreases as the berm height increases, and the mean water level increases even above the tidal signal for the highest berm (purple curve, Figure 20A). The Lagoon water levels (Figure 20B) stay relatively stable between the simulations and follow a trend similar to the original rigid morphology (blue curve,

Figure 20A). Slight tidal variations seen in the baseline simulation are not present in the modified simulations, particularly the low tidal peak signal.

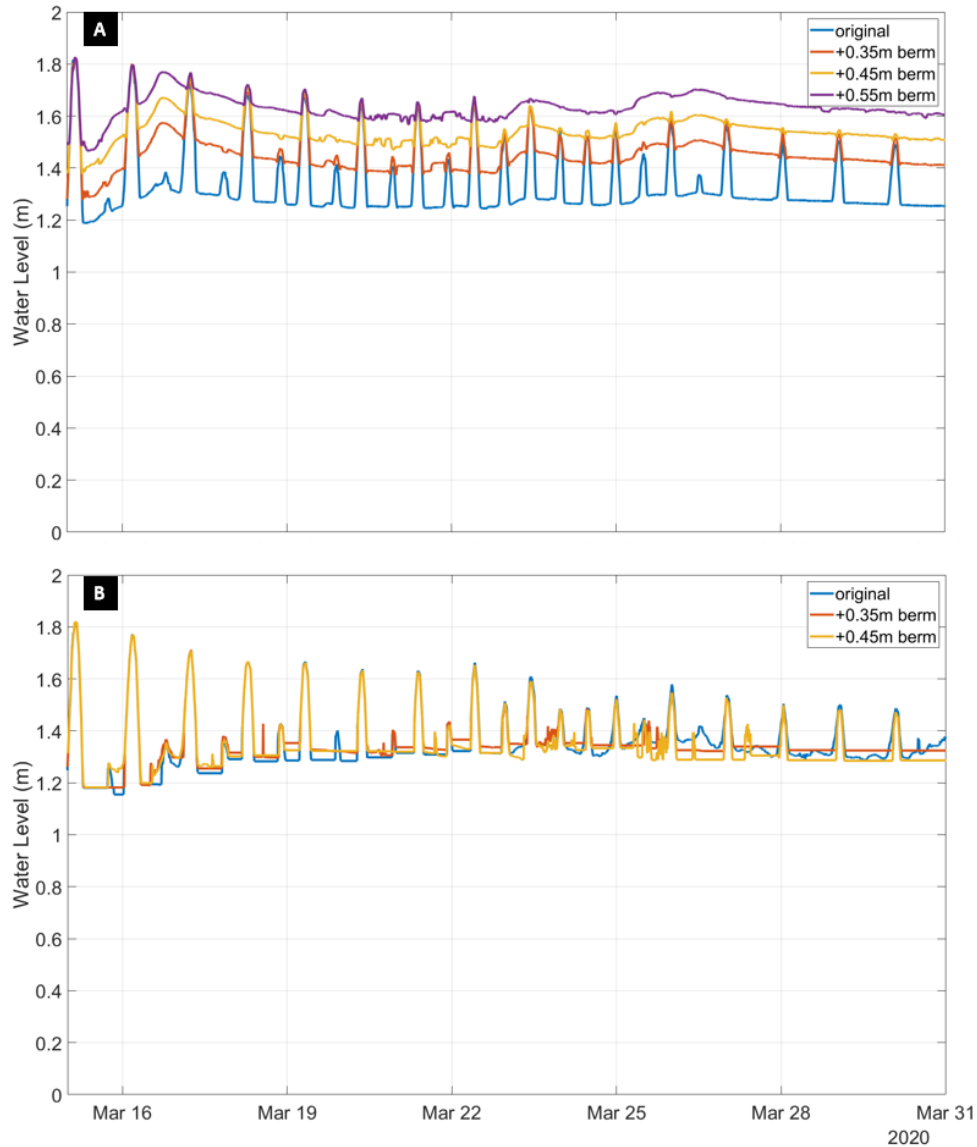


Figure 20. Water level comparison at the Lagoon location for simulations with morphology off (Panel A) and on (Panel B)

Figure 21 displays the River Marker location with the observed water level from March 2020 event. The observed water level is highly impacted by tidal energy. However, the rigid morphological runs (morphology OFF), in Figure 21A, are impacted very little by

the overall tidal range aside from the high tide. The mean water level tendency is captured by the rigid morphological runs as the mean level decreases from March 18<sup>th</sup> through March 22<sup>nd</sup>, and then begins to slightly increase through the remaining time period. With the simulations for Morphology ON, the River Marker water levels (Figure 21B) remain fairly constant at 1.5m although the observed water level begins to increase around March 25<sup>th</sup> during the neap tide. Unlike the rigid simulations, the tidal energy is present with the increased berm heights.

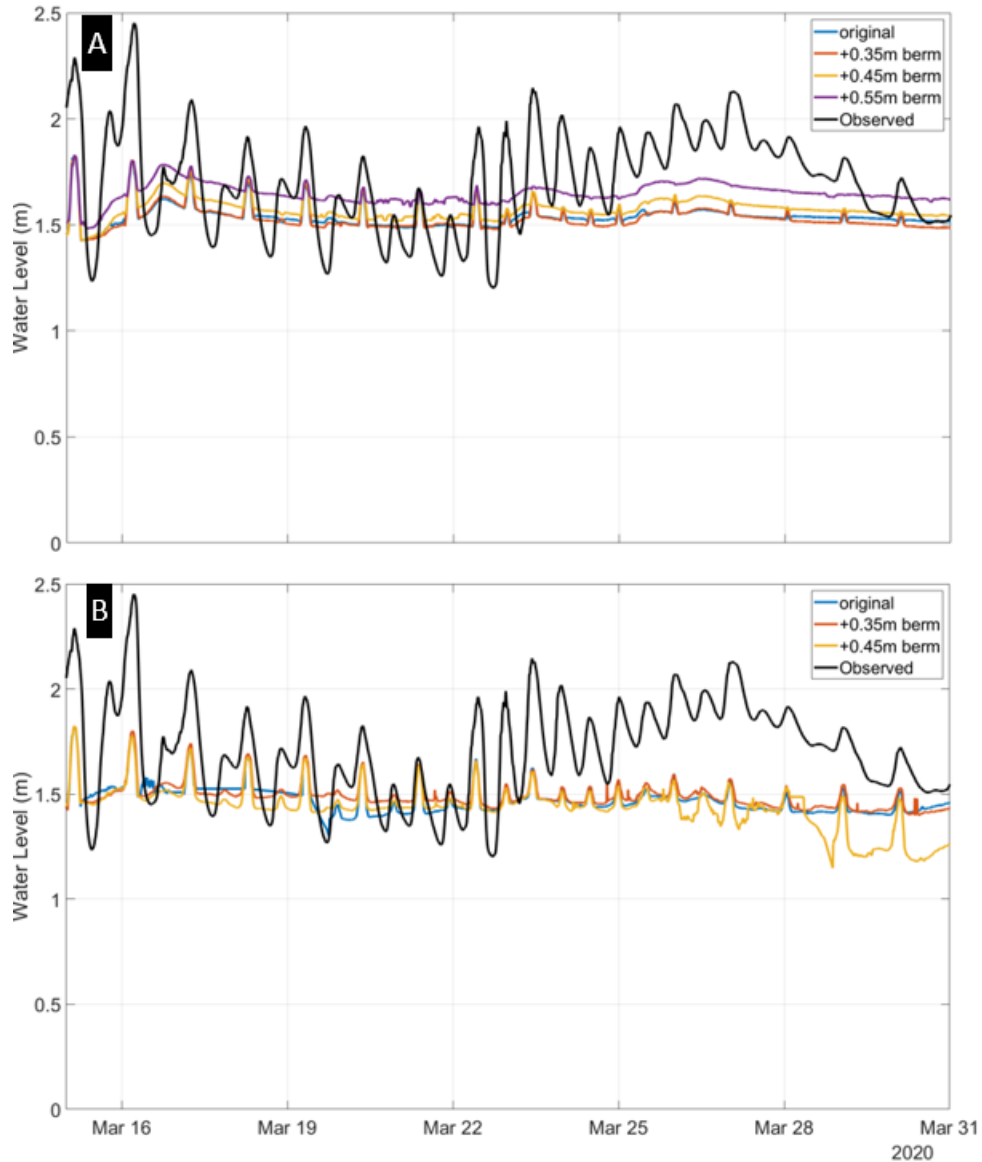
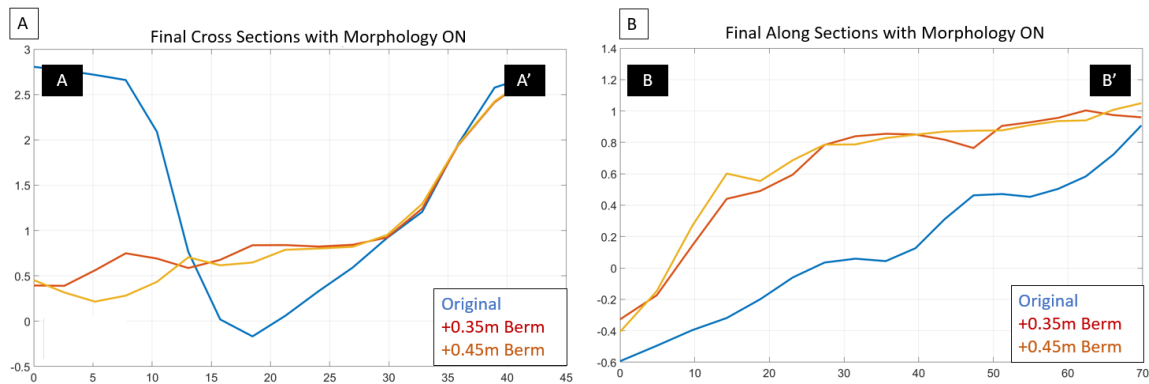


Figure 21. Water level comparison at the River Marker location for simulations with morphology off (Panel A) and on (Panel B) against observed water level from river gauge (Black line)

## B. MORPHOLOGICAL RESPONSE TO BERM HEIGHT

With morphology turned on within Delft3D, the sediment was no longer bound and was allowed to move freely to adjust to the hydrodynamic response to the increased water level within the lagoon. Figure 22 shows the final cross and along sections after both morphology and sediments were turned on after 16 days of morphological evolution. Note

the final morphology runs do not include the 0.55m berm simulation as this was a depth limitation found within Delft 3D. The difference between the initial (Figure 18A) and final cross sections within Figure 22A are quite significant. The Inlet channel erodes 2–2.5 meters on the northern end of the channel, near the rocky headland, as the initial berm heights increase. Each of the models continue to agree on the slopes of the northern edge (A) of the inlet channel. The original simulation keeps the deeper channel as expected, however as the berm heights increase, the channel becomes wider and despite the difference of 0.1m between the red and orange berm lines, they tend to agree on overall depth in the inlet channel. Same analysis occurs for the along section plots (Figure 22B). The final height of the berms shows little difference between the red and orange lines.

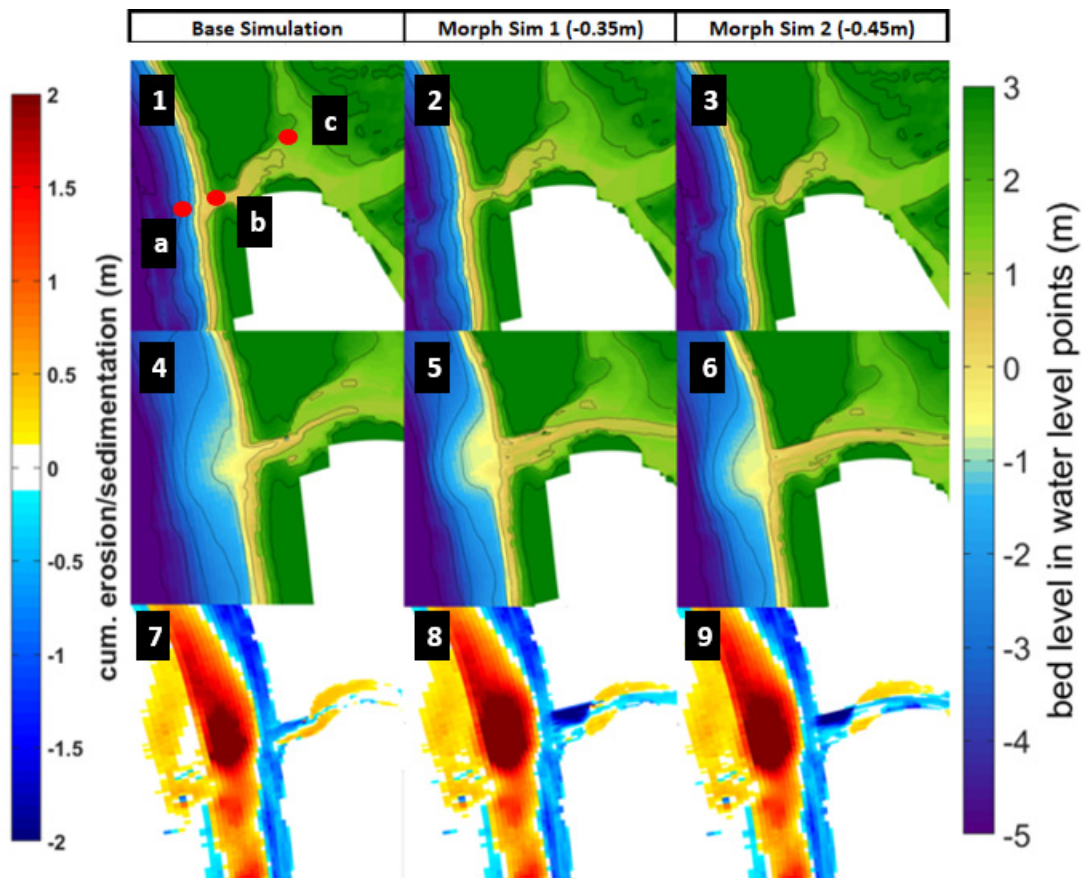


Panel A is the Cross Section indicating the bathymetry changes. A-A' is the orientation seen in Figure 16 with A being near the parking lot and A' ending near the rocky headlands to the south of the beach. Panel B is the Along Section with B being offshore and B' ending near the Lagoon.

Figure 22. Cross and along sections showing the initial bathymetry of the inlet for four simulations

A 2D view of the model morphological response is shown in Figure 22 as the initial and final bathymetry maps are compared to the model's response for sedimentation and erosion. As the berm increases, the top three panels show the disconnect of the channel (location b), respectively from original bathymetry to the shallowest channel with 0.45m berm increase. After 16 days, the final time step, Figure 22 panels 4 through 6, the elevation of the northern portion of the channel increases as the berm height increases. From the

initial bathymetry plots to the final, as morphology adjusts in the model, the channel Inlet, noted by the letter b in Figure 22, becomes more connected to the river vice elongated into the Lagoon, noted by the letter c in Figure 22. As the inlet is open, water level from the lagoon will drain to the ocean. As this process takes place, the model simulates erosion and widening of the Inlet. More erosion occurs in the northern shoulder of the inlet, that eroded sediment to builds the ebb delta (noted by the letter a in Figure 22). The riverbed seems to erode more with increased berm height. Other erosional trends are in the lower beach.



Panels 1–6 are bathymetry plots with the first three being the initial bathymetry and panels 3–6 are final bathymetry at the final time step of the simulation for March 31, 2020. Panels 7–9 are cumulative erosion and sedimentation plots where erosion is denoted by blue and sedimentation is noted by red. In panel 1, red dots labeled ‘a’, ‘b’, and ‘c’ correspond to the Ebb Delta, Inlet Channel and Lagoon regions, respectfully, from Figure 17

Figure 23. Initial (Top row) and final (Center row) bathymetries and cumulative erosion and sedimentation (Bottom row) maps

## **C. DISCUSSION**

Sediment transport resulting from the influence of winds, waves, infra-gravity waves, sediment fluxes and over wash, is highly variable per season and location and has a large influence on the coastline (Nienhuis 2021). Sediment fluxes have been tested in the laboratory but can be sensitive to barrier geometry (Nienhuis 2021). As seen at the locations above in Figures 19 through 21, changing the bathymetry (rigid berms) and turning on morphology both effect the water level as expected, yet it still does not capture the full impact of what is observed at the River Marker during the actual event. As the rigid berm simulations represent a more conceptual model sensitivity test with fewer dynamics, this shows that the Delft3D model can resolve certain aspects such as water level changes, but without adding any morphological and sediment changing factors, the model will still be unable to capture the actual event. Figure 22 captures the dynamics occurring as a breach geometry evolves. The river elongates as water flows out of the lagoon into the bay and the channel is scoured as sediment is eroded. The Ebb Delta also captures morphologic changes that as the channel is being eroded, the sediment is accumulated near the mouth of the river which will be the source of the sand bar that will build as the process reverses and wave-driven onshore sediment transport occurs, building the sand bar back up and closing the mouth of the river (Ranasinghe and Pattiaratchi 2003). During this breaching episode in March 2020, the Carmel River migrated slightly to the north. Although we do see the inlet widening, the migration morphology was not fully captured during this study.

## **D. SUMMARY**

In summary, the rigid berm simulations were designed to test whether or not the model could resolve dynamics under certain depth values. As seen, as the berm increased, indicating a sand bar building, the Delft3D outputs captured the simple dynamics of increased water level causing the lagoon water level to increase overall. The model was also able to simulate sedimentation and erosion patterns similar to those seen during the March 2020 breaching event, but not all of them. The water level plots, however, indicate that more factors are involved in breaching dynamics that were not captured by building a berm or turning on morphology.

## VI. CONCLUSIONS

Hydrodynamic sensitivity indicates that waves and river discharge play a role in governing lagoon processes. Manipulating the river discharge boundary conditions (0-20 m<sup>3</sup>/s), affected the low tidal range in the water level, whereas manipulating the wave boundary conditions, (0-5m), affected the peaks of the tidal range. Increasing river discharge and/or wave height resulted in increased mean water level through the system.

Morphology factors tested here were based on rigid bathymetry changes as well as one sediment size and morphological factor. As the initial berm height increased, the mean water level increased as well. As morphology was turned on, the tidal range increased further into the lagoon and upstream as the erosion of the channel allowed for ocean energy to travel upstream. Delft3D was also able to resolve the sedimentation and erosion dynamics within the channel and out through the ebb shoal. From these results Delft3D has the capacity to attain realistic morphological trends, however the hydrodynamic output is still far from observational data. Future work will require testing the morphologic factors in line with CRSB as well as manipulating sediment size.

From the hydrodynamic sensitivity analysis, both increased waves and/or increased river discharge can increase the water level in the lagoon. As river mouth morphology changes, as seen with different berm height simulations, it drove different water levels in the lagoon. In order for water to flow from the lagoon to the Carmel Bay, the mean water level had to increase to get over the berm. The perching set up from the lagoon to the Carmel Bay sets up a pressure gradient that creates a dynamic forcing against offshore waves when high river discharge occurs indicating that river discharge is a dominate factor in the water level of the lagoon.

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