Matilija Dam Removal Ecosystem Restoration Project

Estuarine and Coastal Modeling

Prepared for
Ventura County Watershed Protection District
800 S. Victoria Ave, #1610
Ventura, CA 93009

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ACRONYMS AND ABBREVIATIONS

µm	micrometer(s), microns
BOR	U.S. Bureau of Reclamation
cfs	cubic feet per second
CMWD	Casitas Municipal Water District
COAST	Coastal One-line Assimilated Simulation Tool
CoSMoS	Coastal Storm Modeling System
DEM	digital elevation model
DREAM-2	Dam Removal Express Assessment Model 2
NOAA	National Oceanic and Atmospheric Administration
ppt	parts per thousand
RV park	Ventura Beach RV Resort
SWAN	Simulating WAves Nearshore
USGS	U.S. Geological Survey

EXECUTIVE SUMMARY

The Matilija Dam removal ecosystem restoration project has been developed with the goal of restoring river flow and sediment load to improve habitat in the Ventura River, Ventura River estuary, and the nearby Coast of Ventura County. The restored river flow and sediment loading is anticipated to benefit the physical and ecological health of the region through enhancement of the connectivity between the local stream, riparian, estuarine, and coastal habitats for the California steelhead trout and sustain high quality habitat for many other species. Some of the biggest concerns have been about how the released sediment currently trapped behind the Matilija dam could impact sensitive species, future flood potential in the river, and the estuarine and coastal processes. Modeling of the estuary and local coast described in this report provides high fidelity tools for characterization of both the initial sediment pulse released from the dam removal and the subsequent restored river sediment loads to address these concerns.

The Integral team has conducted an assessment of the relevant physical processes over short- and long-term time scales to characterize the potential impacts to the Ventura River estuary and coastal ocean for the range of dam release scenarios. This technical report details a multi-model approach to evaluate potential sediment impacts at two time scales: short-term impacts to the estuary and coast immediately following dam release and long-term effects of restored sediment loading to the estuary. The current modeling study evaluates the effects of dam removal on the estuary, inlet, and nearshore coast and leverages prior analysis and modeling conducted by the U.S. Bureau of Reclamation, Stillwater Sciences, and AECOM to characterize upstream dynamics. Throughout this study, evaluation of impacts associated with dam removal relied on characterization of "worst-case" scenarios. The worst-case scenario for evaluating estuary impacts was the dam removal scenario which resulted in the largest sediment trapping percentage within the estuary which could have adverse impacts on existing habitats. The selection of scenarios for estuary and coastal habitat impacts is described in more detail in the report and provides a method for characterizing the largest potential change in the system due to dam removal. The modeling analysis in the present study considers physical processes and sedimentation changes that may affect habitats, including sediment erosion, deposition, and grain size; water depth and inundation; water velocities; and water quality.

Key findings resulting from increased sediment loads in the Ventura River Estuary associated with the dam removal project are as follows:

- The worst-case scenario for estuary impacts was associated with medium to high initial flows arriving in the estuary during a king high tide, which resulted in the highest trapping efficiency of sand sized particles.

- Following initial dam removal, approximately 10 to 16 percent of the total sediment load remains upstream of the estuary mouth based on estuary modeling of five dam removal scenarios.
- Silt particles comprise the largest fraction of sediment loading during dam removal, but are readily transported through the estuary to the coastal ocean. Between 7 and 15 percent of the silt load remained upstream of the estuary mouth during dam removal scenarios and the remainder was transported to the coast.
- Of all of the sediment grain sizes modeled, more than 70 percent of the mass of sediment deposited and trapped within the estuary during the release scenarios was sand. Gravel and cobble contributed less than 1 percent of the total load to and deposition within the estuary following dam release, largely because the coarser grains took much longer to move down river.
- Following the worst-case dam removal scenario that resulted in some sand deposition in the estuary, subsequent flood events were modeled to evaluate potential erosion of deposited sediment in the estuary. While smaller events mobilized some sediment, a 10-year return period event was required to remove significant fractions of deposited sediment within the estuary.
- Potential changes in habitat caused by sedimentation were evaluated quantitatively by the changes in hypsometry (volume of water at different elevations). Compared to pre-dam removal conditions, the changes due to dam release sedimentation are relatively small and likely to be eroded over subsequent flow events following the dam removal.
- The long-term inlet modeling suggests that changes to the breaching (open vs. closed) duration within the estuary and the inlet breaching frequency over the next 50 years due to dam removal are expected to be relatively small. Additional water level data collection would improve the modeling calibration. In the longer term, sea level rise is likely to increase the occurrence of open estuary conditions due to inundation.

Ventura coast findings regarding sediment loads associated with the dam removal project are as follows:

- Silt particles constitute the largest mass fraction of sediment delivered to the coastal ocean, but these small silt particles are readily transported offshore and do not deposit in the estuary or nearshore.
- The largest potential deposition impact to the coastal ocean is associated with the initial sediment release following dam removal and occurs just offshore of the estuary mouth. The residence time of the sand in the river mouth deposition area depends heavily on subsequent wave conditions.
- The long-term effect of restored sediment loading to the system is minimal (only 7 percent increase in estimated pre- and post-dam removal total sediment load). The

initial pulse of sediment following dam removal has the potential to benefit local areas (e.g., river mouth) in the near-term but has negligible effect downcoast (e.g., the harbor).

- Over the long term, sea level rise will have a larger impact on coastal processes and shoreline position downdrift of the river mouth than the dam removal.
- The restored sediment loading will not provide enough sediment to the nearshore system to avoid long-term shoreline erosion projected from sea level rise if wave conditions stay similar to historical conditions.

1 INTRODUCTION

The Matilija Dam, built in 1947 on the Ventura River for water supply and flood control, had impounded an estimated stored sediment volume of approximately 6–7 million cubic yards by 2005 and become ineffective as a flood control and water supply reservoir (BOR 2006; AECOM and Stillwater 2016). Sediment trapping and dam modifications reduced the reservoir water storage capacity from 7,018 acre-feet to ~500 acre-feet and reduced the peak flows and sediment delivery to the Ventura River, estuary, and nearshore coast. Construction of Highway 101 has also cut off the sediment supply to the coast. Water flow diversions and alterations to the river channel and estuary have further modified dynamics. The reduction in coarse-grained coastal sediment delivery has resulted in a shrinking of the Ventura River delta, causing erosion at upcoast Emma Wood State Beach and erosion downcoast at Surfers Point and the Ventura Promenade (Revell 2007). The sediment reduction has also contributed to the need for nearby Pierpont groins; however, erosion was compounded by updrift littoral impacts and a sediment deficit moving downcoast caused by the construction of the Santa Barbara Harbor in the 1920s (Revell 2007; Revell et al. 2008; Barnard et al. 2009).

Removal of the Matilija Dam has been proposed with anticipated benefits to the physical and ecological health of the watershed, estuary, and nearshore coast. Prior analysis and modeling studies have evaluated watershed dynamics, impounded sediment characteristics, and several dam removal approaches (BOR 2006; AECOM and Stillwater 2016; Stillwater 2019). Dam removal alternative evaluations included structural evaluation of the dam with and without orifices, detailed dam release sediment transport modeling, hydraulic studies of changes to flood elevations based on sediment transport change analyses, and assessment of the predictability of the first sediment flushing storm event. Based on these evaluations (AECOM and Stillwater 2016), the dam removal concept that has been advanced is concept 2A/2B, which involves installing two orifices in the dam, implementing fine sediment evacuation during a flushing storm event, and eventual demolition of the dam following sediment flushing. This dam removal concept includes optional gates in the event that the design flood event does not fully erode impounded fine sediment from behind the dam. Fluvial analysis was recently conducted to evaluate the coarse sediment (gravel and cobble) transport through Ventura River following dam removal (Stillwater 2019).

While prior studies have significantly advanced the understanding of sediment transport from Matilija Dam through the Ventura River system, no analysis had been conducted on the potential dam removal impacts on the downstream estuary and nearshore coastal habitats. Estuaries and nearshore coasts are considered to be among the most valuable habitats on the planet (Costanza et al. 1997) but are also among the most vulnerable to anthropogenic influences such as sea level rise, coastal construction, and habitat modification (Kennish 2002). Bar-built coastal estuaries, including the Ventura River estuary, are an important subset of these estuaries and are ubiquitous along the southern and central California coast. The natural dynamism associated with estuary size, shape, and drainage patterns helps support a multitude of endangered and threatened species such as Southern California steelhead, tidewater goby, western snowy plover, and the red-legged frog. This study leverages prior analysis and modeling results to evaluate potential short- and long-term changes to estuary and coastal habitats associated with sediment transport following dam removal.

The estuary and coastal modeling study outlined herein was guided by the County of Ventura Watershed Protection District and key stakeholders to evaluate the impact of dam removal concept 2A/2B (uncontrolled orifices with optional gates) on the Ventura River estuary and the nearby coastal ocean. The primary goals of this study were to improve the overall understanding of dam removal effects on the Ventura River estuary, inlet, and nearshore coast and included:

- Evaluation of short-term effects of dam removal on Ventura River estuary and nearshore coastal habitat
- Evaluation of long-term (50 years) effects of dam removal, with the inclusion of sea level rise, on inlet breaching dynamics and shoreline position

This study focused on improving the understanding of the dispersal of the full range of sediment grain sizes (silt, sand, gravel, and cobbles) following the dam removal scenarios in the estuary and nearshore coast to assess of the potential habitat impacts to the Ventura River estuary and nearshore coast. Modeling of relevant physical and sediment transport processes required accurate and system-wide assessment of riverine sediment inputs and flows, estuary circulation and trapping efficiency, inlet breaching dynamics, and coastal wave driven transport processes. This project evaluated the effects of dam removal on the estuary and coastal habitats using a coupled estuary, inlet, and coastal ocean modeling approach to evaluate both short- and long-term changes in the Ventura River ecosystem.

1.1 APPROACH

The processes driving sediment transport in the Ventura River ecosystem vary over a wide range of time scales. On short time scales (e.g., hourly to daily), the sediment transport following Matilija Dam removal has the potential to cause rapid changes to water quality and sedimentation in the river, the estuary, and nearshore coastal habitats. On longer time scales (e.g., yearly to decades), sediment supply from the Ventura River to the estuary and nearshore region is expected to increase, necessitating an evaluation of shoreline and nearshore habitat evolution in response to the sediment loading and future sea level rise. To address changes in the system over time scales ranging from days to decades, short- and long-term modeling was conducted and linked to potential habitat changes to inform dam removal decisions.

The coastal estuary and nearshore environment are dynamic and governed by complex processes. The range of physical processes and system responses in the Ventura River estuarine and coastal systems necessitated a multi-pronged modeling approach. The primary processes considered in the hydrodynamic and sediment transport modeling include the time-varying flow and sediment load from the Ventura River to the estuary, variability in the transport of different sediment grain sizes (fine silts, sand, gravel, and cobblestones), sediment deposition and morphodynamic changes within the estuary, potential changes to the periodic breaching of the bar-built estuary, and the wave-driven littoral transport in the nearshore littoral cell. To improve understanding, each of these processes and dynamics was modeled.

The modeling approach relied on a well-developed conceptual site model to describe the system, forcing conditions (river discharge and sediment loading, wave and tidal conditions, and sea level rise projections), site-specific parameters (estuary and shoreline geomorphology and sediment grain size distribution), and data for model validation (shoreline and estuary observations) to accurately characterize sediment transport in the system. Key aspects of the modeling approach included the following:

- An estuary model driven by upstream river discharge and sediment loading with episodic seasonal coastal exchanges through the estuary and inlet
- An inlet model that predicts the conditions under which there is connectivity between the estuary and the littoral zone
- A coastal sediment transport model that replicates littoral sediment transport processes associated with storm events
- A shoreline change model to evaluate long-term sediment transport patterns and shoreline position along the Ventura coast
- Evaluation of physical process modeling for key habitat metrics which include water quality, connectivity, and habitat quantity and interpretation of potential impacts on sensitive and endangered species.

The multi-model approach provided predictions of sediment transport processes across multiple spatial and temporal scales. The estuary and coastal ocean models were used to characterize sediment transport over short-term, event-based time scales (days to weeks) using high-resolution and high-fidelity modeling to accurately resolve observed transport events and provide confidence in future model projections. These event-based models allow for high-fidelity modeling of all components of the Ventura River system including the estuary, inlet, and coastal ocean. In contrast to the event-based estuary and coastal ocean modeling, the long-term dynamics (50 years post-dam removal) were predicted using an empirical inlet model and shoreline change model, which incorporate simplified transport processes as well as sea level rise. The combination of short- and long-term modeling allow for high fidelity simulations of complex processes (event-based modeling) to inform both event-based and long-term simulations (years to decades).

A key component of model development was the validation of model predictions with observed data. For the Ventura River system, limited quantitative information (e.g., water levels, currents, sediment loads) existed for typical model calibration and validation in either the estuary or coastal regions. Therefore, qualitative model validation provided the best method for evaluating and validating model behavior given the lack of available instrumented data collection. This process included sensitivity analysis and what-if simulations designed not for projecting future conditions (prognosis), but for understanding model behavior (diagnosis) in relation to observed site conditions. Validating that the models could reproduce combinations of scenarios consistent with the conceptual site model, historical information, observations, and anecdotal information provided confidence in the ability of each of the modeling components to evaluate such dynamics. Using this approach, the models have been qualitatively validated and peer reviewed by the County and local experts to ensure model predictions were consistent with the conceptual site model as described in more detail in Appendix A.

Throughout the analysis presented in this report, model scenarios were chosen to evaluate potential worst-case dam release sedimentation impacts. For example, the worst-case estuarine ecological impacts evaluation scenario was defined as the dam removal discharge scenario during king high tide with the largest sedimentation within the estuary. In contrast, the worst-case coastal ocean impacts were evaluated using the dam removal scenarios that resulted in the largest total sediment loading to the coast. As described in further detail below, these worst case scenarios were selected to conservatively evaluate potential impacts of large sediment loads associated with a dam release on the estuary and coastal habitats. In addition, model scenarios were carefully chosen to bound anticipated future dynamics, acknowledging that there is both inherent model uncertainty and uncertainty about future conditions. The combination of carefully chosen model scenarios and sensitivity analysis was used to diagnostically understand the system and predict the range of anticipated impacts. As with all models, additional data collection and observations could improve model development and calibration, but the sensitivity analysis conducted by evaluation of multiple scenarios highlights key results, which are robust across multiple modeling scenarios.

1.2 REPORT ORGANIZATION

The first section of the report provides pertinent background information, summarizes the conceptual site model of the system from the Ventura River to the coastal ocean, and describes relevant previous work that this study built upon. The first section also includes a description of sediment loading and development of pre- and post-dam removal rating curves, which were a critical input for the estuarine and coastal modeling.

Results of the estuary modeling are presented in Section 3. This includes the short-term event modeling of dam releases and large discharge events using the 2-dimensional hydrodynamic and sediment transport (Delft3D) model and the long-term empirical inlet model. Results of the estuary and inlet modeling are presented, and the impact to estuary habitat and critical species are discussed.

Section 4 of this report describes the impacts to the coastal ocean and includes a discussion of the short-term coastal ocean model (Delft3D/SWAN) and the long-term shoreline change model (COAST). This is followed by a summary of results and key findings in Section 5.

Appendix A describes data sources relied upon as well as model development, setup, and validation for each of the model components described in this report. While there is some description of model setup and data in the main document, additional information can be found in Appendix A. Supplemental results not shown in the main document are provided in Appendix B.

2 BACKGROUND

This section provides background information pertinent to the estuary and coastal modeling. A description of the conceptual site model includes a description of the river, estuary, inlet, and coastal ocean dynamics. This is followed by a description of sediment loading and rating curves developed to estimate sediment delivery to the estuary and a summary of habitat metrics.

2.1 CONCEPTUAL SITE MODEL

Sediment delivery to the Ventura River estuary and nearshore coastal region (Figure 1) is governed by upstream river discharge and sediment loading, estuarine dynamics and sedimentation, inlet processes, and coastal hydro- and morphodynamics. The following provides an overview of the river, estuary, inlet and coastal ocean processes.

2.1.1 Ventura River

The Ventura River discharges into Ventura River estuary and is fed by Matilija Creek (above Matilija Dam), North Fork Matilija Creek, San Antonio Creek, and Coyote Creek (below Casitas Dam). The river is characterized by episodic flow events during the winter and spring months followed by relatively low-flow conditions in the summer and fall. While average summer discharge at the Ventura River near Ventura (Station 11118500) can be around 10 cubic feet per second (cfs) or less, peak discharges can exceed 36,000 and 46,000 cfs for a 10- and 20-year return period flow, respectively (BOR 2006; Appendix A). The floods in 1992 and 1969 were approximately 20- and 50-year flood events, respectively, and resulted in extensive flooding and sediment loads in Ventura (Keller and Capelli 1992). The river is also characterized by significant interannual variability with multiyear droughts and wet periods. The Ventura River is therefore a highly episodic system with extreme, short-duration flood events and dry periods with nearly no flow.

Sediment loading to the Ventura River estuary is proportional to river discharge and is supplied by Matilija Creek (above Matilija Dam), North Fork Matilija Creek, and San Antonio Creek.[1] Currently, the Matilija Dam traps a portion of the Matilija Creek suspended sediment load and approximately 100 percent of the coarse sediment load (sand, gravel, and cobble) (Stillwater 2019; BOR 2006). However, the trapping efficiency of the dam is diminishing as the reservoir volume decreases. While the total trapping efficiency (fine/coarse) was approximately 45 percent in 2006, it is estimated to decline to 14 percent in 2020 and 0 percent by 2038 (BOR

[1] There is negligible sediment loading from Coyote Creek because the confluence with Ventura River is below Lake Casitas and Casitas Dam, which traps nearly all sediment.

2006). Therefore, the long-term sediment loading downstream of the Matilija Dam will become independent of whether or not the dam removal occurs once the reservoir has completely filled in (BOR 2006; AECOM and Stillwater 2016).

2.1.2 Ventura River Estuary

The Ventura River drains to the coastal ocean through the Ventura River estuary, which serves as important habitat to a range of species, including Southern California steelhead and tidewater goby. Bar-built estuaries such as the Ventura River estuary are typically small and shallow and are common in mediterranean climates on wave-exposed coastlines where there are strong seasonal differences in wave energy and river flow (Figure 1). These systems are intermittently open or closed. Depending on seasonal river discharge and wave conditions, these bar-built ecosystems cycle between open to tides and saltwater influence, perched with primarily freshwater flows into the ocean backwatered during high tides, and closed by a supratidal sand bar or beach berm. In the Ventura River estuary, inlet conditions and breaches of the beach berm are dynamic features in both time and space, highly dependent on physical processes that move sediment (river discharge and wave swash) as well as on sediment supply. These small bar-built estuaries often form in locations with seasonally variable river flow where episodic, event-based river discharges are typically the largest source of sediment loading to the nearshore region. The natural dynamism associated with estuary size, shape, and drainage patterns helps support a multitude of sensitive estuarine dependent species such as southern steelhead (endangered), tidewater gobies (endangered), and the red-legged frog (threatened), as well as riparian bird species including the least Bell's vireo (endangered), western snowy plover, and western yellow-billed cuckoo.

For a small bar-built coastal estuary like that of the Ventura River estuary, many factors control conditions in the estuary, including river flow, tidal prism, wave processes (wave-swash and overtopping), groundwater seepage, evaporation, and erosion across the inlet. The estuary depends primarily on flow from the Ventura River for its opening or breaching. The natural river flow to the estuary has been reduced over time as a result of the Robles diversion, construction of Lake Casitas on Coyote Creek, and groundwater extraction from both the Upper and Lower Ventura River basins (Turner 1971). The Robles diversion provides a substantial portion of the water supply for the City of Ventura. Subsequent wastewater from the City of Ventura is treated in the Ventura Wastewater Reclamation Facility and discharged into the Santa Clara River estuary. The alteration of the hydrograph from Matilija Dam and the trapping of approximately 6 million cubic yards of sediment has altered the habitat in the Ventura River, the estuary, and the coast. Sediment loading to the Ventura River has been modified not only by Matilija Dam, but also by modifications to the river channel and construction projects. The construction of Highway 101 has disrupted sediment supply to the estuary, and downstream reaches of the estuary have been channelized and modified for flood control.

The connection between the estuary and coastal ocean is governed by conditions of the inlet, which intermittently opens and closes depending on estuary and coastal conditions (Figure 1). Periods of high streamflow can result in breaching of the estuary fronting beach berm, sufficient to allow for a tidal exchange of water masses between the estuary and the ocean. Subsequent wave-driven sediment deposition often results in closure of the bar, which then remains closed with episodic wave overtopping until such time that high stream flows breach or open the estuary–ocean inlet. As such, the periodic breaching and subsequent rebuilding of the bar fundamentally govern estuarine dynamics. Historically, during wet periods, the inlet stays open for most of the year, and during drought periods, the inlet can close for most of the year.

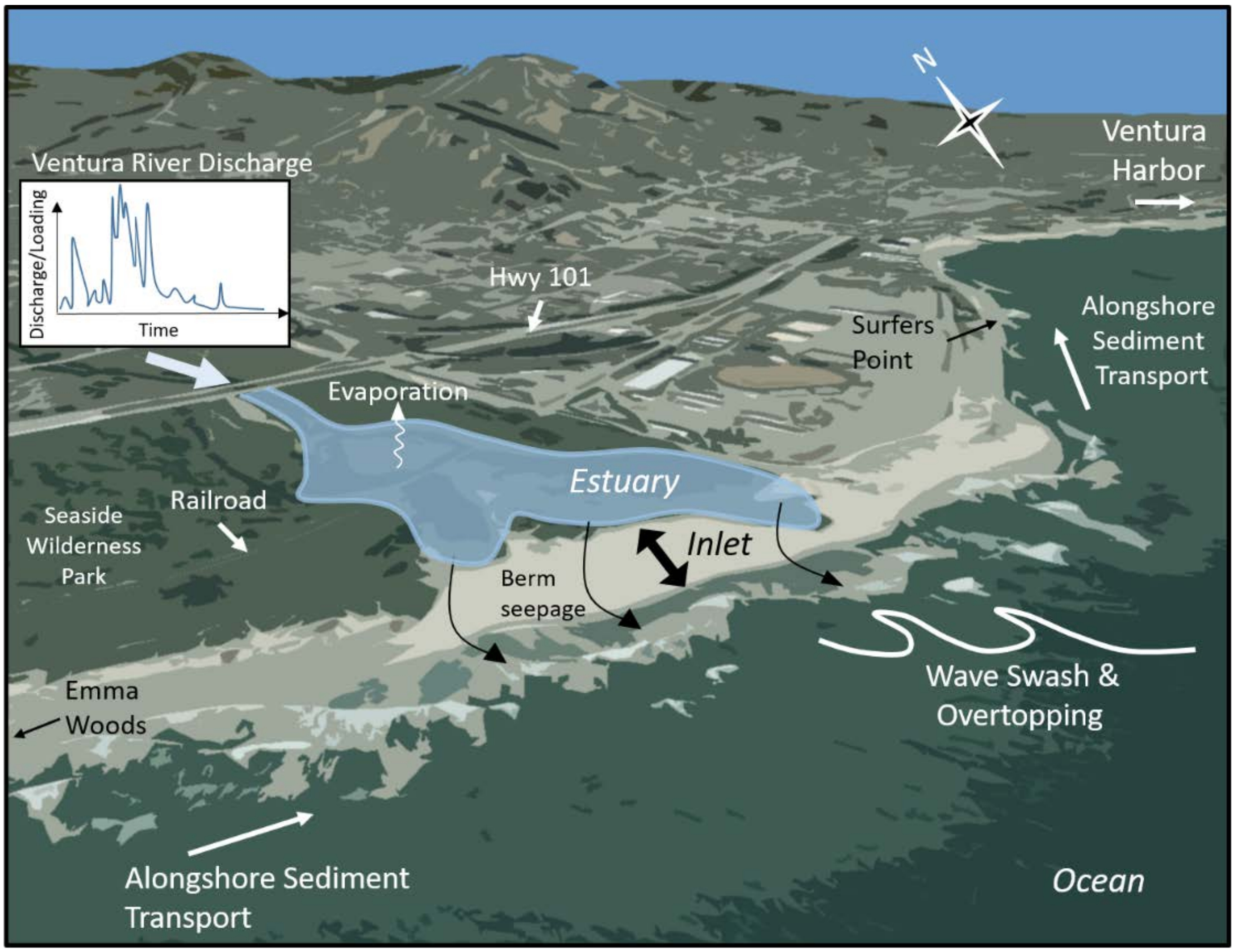

Figure 1. Estuarine, Inlet, and Littoral Processes in the Ventura River Estuary and Coastal Ocean.

By understanding and characterizing changes in river flows, sediment transport, and coastal geomorphology, one can assess the estuary habitat in terms of physical characteristics (e.g., water depths, sediment quantity and character, water velocities), all of which affect habitat. The changes in river flow due to diversion of fresh water for irrigation and potable water, modification of sediment loads to the estuary due to historical impoundment of sediment by dams and subsequent release of sediment by dam removal, and the construction of upcoast harbors, coastal armoring, and beach groins have and will affect littoral sediment transport and associated habitat.

2.1.3 Coastal Ocean

Located within the Santa Barbara Littoral Cell (Figure 2), sediment transport processes near the mouth of the Ventura River ecosystem are highly dynamic and depend on the relative magnitudes of wave events and riverine inputs, coastal orientation, and proximity to seasonal rivers. Sediment sources are scarce, and primarily consist of occasional discharges from the rivers during high-flow events and littoral (wave driven) transport of sediment from upcoast reaches. The magnitude, rate, and composition of sediment discharge to the coastal ocean depend on the highly dynamic coastal inlet, which can be intermittently breached when upstream flows result in estuary water levels exceeding that of the beach berm crest elevation.

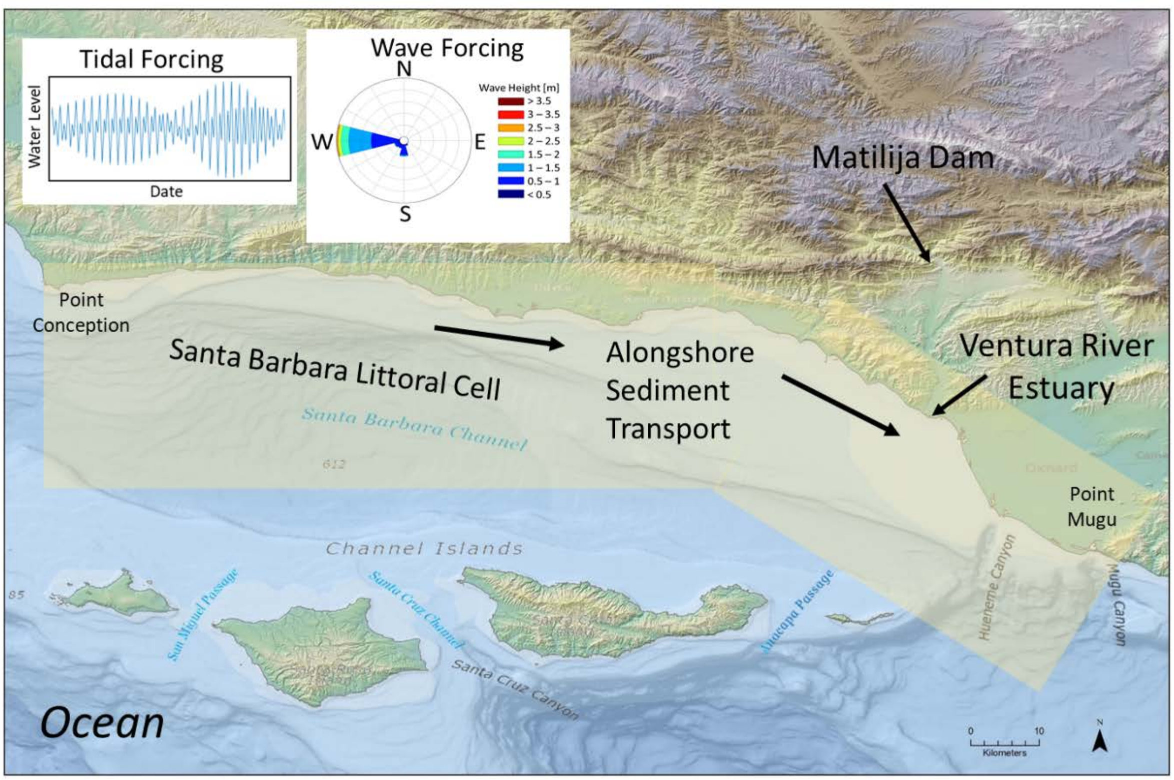

Figure 2. Overview of the Ventura River Estuary Site Setting with Coastal Ocean Forcing and Discharge from the Ventura River.

The Santa Barbara Littoral Cell (Figure 2) extends from Point Conception in the northwest to Mugu Canyon in the south. The littoral region of interest includes the portion of the Santa

Barbara Littoral Cell immediately affected by the Ventura River, primarily from Emma Wood State Beach to the Ventura Pier (Figure 1). The Ventura River provides cobble, sand, and fine sediment to the Santa Barbara Littoral Cell. Overall, sediment supplied to the coastal system comes from erosion of the coastal area and watershed delivery. The ultimate sink of the sediment is the Mugu Submarine Canyons where the littoral sediment is transported offshore into the deep water (Barnard et al. 2009).

Within the Santa Barbara Littoral Cell, westerly swell drives alongshore sediment transport from west to east (Patsch and Griggs 2008). The Ventura coastline is generally sheltered from extreme north Pacific wave events, and the transport of sediment along the coast is nearly unidirectional from west to east. Within the Santa Barbara Littoral Cell, two man-made harbors (Santa Barbara and Ventura) lie on either side of the Ventura River mouth, and the changes in annual dredge volumes required to maintain safe navigational depths provide an estimate of sand volumes supplied to the littoral system between the two harbors. Of the approximately 282,000 cubic yards per year increase in annual dredged volumes between the two harbors, the Ventura River is thought to contribute the largest volume of sediment to the coastal ocean, even with Matilija Dam in place (Patsch and Griggs 2006; Revell 2007; Barnard et al. 2009). The dynamism of a nearby system was demonstrated during post-flood monitoring of the delta-shaped sediment bulge at the mouth of the Santa Clara River, which showed significant rates of change with depth (Barnard and Warrick 2010). This study highlights the importance of occasional high-volume sediment discharges—such as can be expected following the removal of Matilija Dam—on coastal sediment supply over multiple time scales.

Long-term dynamics of the estuary and coastal ocean will also be influenced by sea level rise. Regional projections of sea level rise from a variety of sources (Sweet et al. 2017; OPC 2018) were considered. All of these estimates take into account global mean sea level rise as well as regional effects of ocean circulation, ice melt redistribution, and local vertical land motion. The final sea level rise assumptions selected for modeling came from the Sweet et al., 2017 projections due to proximity of the Rincon Island station to the Ventura River mouth. Decadal sea level rise estimates at nearby gage stations are available for five relative sea level rise scenarios (low, intermediate, intermediate-high, high, and extreme; Sweet et al 2017; Figure 1). The projected sea level rise estimates are from 2000, and, are consistent with projections adopted in the State of California Sea Level Rise Guidance (OPC 2018) for Santa Barbara (Table 1). The Rincon Island extreme sea level rise estimates bound the potential range of sea level rise projections at the Ventura River mouth. Throughout this report, the low, intermediate-high, and extreme sea level rise projections at Rincon Island (Figure 3 and Table 1) were used for all long-term modeling of the inlet and shoreline position.

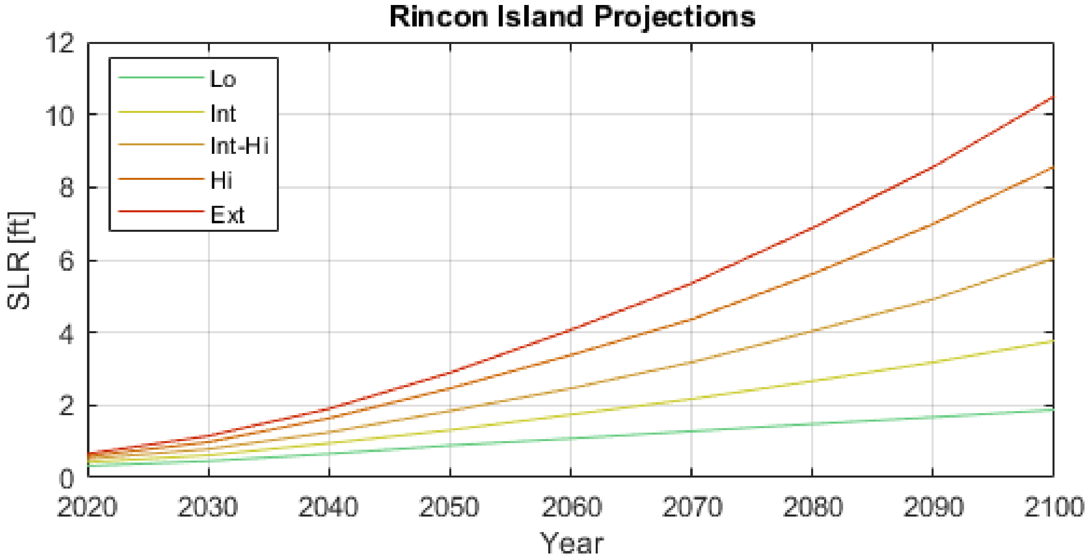

Figure 3. Sea Level Rise Projections for Five Scenarios (low, intermediate, intermediate-high, high, and extreme) from Sweet et al. (2017) at Rincon Island Water Level Station.

Table 1. Decadal Sea Level Rise Projections at Rincon Island from Sweet et al. (2017) with Projections from OPC 2018 at Santa Barbara Indicated in Parentheses[1].

Sea Level Rise Projections	Lo [ft]	Int-hi [ft]	Ext [ft]
2020	0.33	0.52	0.66
2030	0.46 *(0.4)*	0.79 *(0.7)*	1.15 *(1.0)*
2040	0.66 *(0.7)*	1.25 *(1.1)*	1.9 *(1.6)*
2050	0.89 *(1.0)*	1.84 *(1.8)*	2.89 *(2.5)*
2060	1.08 *(1.0 – 1.3)*	2.46 *(2.2 – 2.5)*	4.07 *(3.6)*
2070	1.28 *(1.3 – 1.7)*	3.18 *(2.8 – 3.3)*	5.35 *(4.9)*
2100	1.87 *(2.0 – 3.1)*	6.04 *(5.3 – 6.6)*	10.5 *(9.8)*

[1] OPC 2018 sea level rise projections are included for low-risk aversion, medium-high risk aversion, and extreme risk aversion estimates at Santa Barbara. A range is shown where both low and high emission scenarios were reported (OPC 2018).

2.1.4 Habitat

The primary goal of the estuary and coastal modeling effort was the characterization of physical stressors caused by sediment from the dam to habitat and species within the estuary and coastal ocean. Current habitat mapping within the estuary is limited so the team relied on a detailed mapping effort from 1990 to begin to evaluate sedimentation impacts on estuary habitats habitat (Ferren et al. 1990). A digitized map of the habitat survey (Figure 4) was used to evaluate potential habitat stressors due to sedimentation within the estuary following dam removal. More current habitat mapping that coincided with recent elevation data would improve this analysis and may be warranted in future work.

Coastal habitats ranging from sand to cobble beaches provide diverse flora and faunal resources in the area such as giant kelp and lobsters that could also be potentially impacted by the Matilija Dam removal (Hunt et al. 1992). Anthropogenic disturbances in intertidal marine habitats have been investigated in Sousa (1979) and documented by others in southern California (for example Klose et al. 2015).

Figure 4. Digitized Map of Habitat from Ferren et al. (1990).

The removal of the Matilija Dam provides an opportunity to increase steelhead spawning and rearing habitat in the Ventura River watershed over existing conditions by reconnecting habitat upstream of the dam (Capelli 2004; Allen 2016). The Southern California steelhead Distinct Population Segment is federally endangered and important to California coastal ecosystems. Southern Steelhead are an anadromous *Oncorhynchus mykiss*, which like other salmonids transitions from freshwater to the ocean during its life cycle, and then returns to their natal rivers to spawn. Estuaries form an important link in this life cycle by providing juveniles habitat to grow and physiologically adapt to saltwater prior to their oceangoing life stage. Steelhead upstream migration can be impeded by barriers particularly during low-river flow periods. Significant changes to the estuary depth from sedimentation may cause additional challenges to their survival. Estuary opening and closure duration as well as wave overtopping and freshwater inflows may impact steelhead and estuary water quality conditions. Timing of inlet open versus closed conditions also has impacts on fish passage and water quality (CMWD 2017). Although steelhead rely on the estuary for a critical period of their life history, steelhead also spend most of their life cycle outside of the estuary. However, further north in central California, juvenile steelhead that rear in bar-built estuaries (versus upstream freshwater habitats) have faster growth rates, attain a larger size for their age, and have a higher ocean survival rates (Hayes et al. 2008); whether this life history strategy occurs in southern California estuaries is not known. In addition, bar-built estuaries that remain connected to their freshwater tributaries allow juvenile steelhead to move upstream if estuary water quality conditions become less suitable (Hayes et al. 2011).

The tidewater goby is another federally threatened species that is completely reliant on the estuary for all aspects of its life history/life cycle. This sensitive species prefers low velocity conditions with sandy substrate for spawning. When Matilija dam is removed, changes to physical factors may temporarily or permanently affect the habitat morphology due to changes in sediment erosion, deposition, and sediment properties; water depth and duration of inundation; water velocities; and water quality. Based on the unique life history of the species, the tidewater goby was selected as a key species for analysis because it represents the most sensitive indicator for the habitat and ecology of the Ventura River estuary.

In addition to steelhead and tidewater goby, a wide range of other species utilize the Ventura River estuary seasonally or peridodically, including Pacific lamprey (Reid and Goodman 2016), forage fish such as topsmelt, and flatfishes. A wide array of species has been documented within the estuary (Yoklavich and Cailliet 2006); however, many of these species do not entirely rely on the estuary for completion of their life cycles. In contrast, the tidewater goby is almost completely reliant on the estuary for all aspects of its life history/life cycle (see Appendix A for more detail).

The tidewater goby population in the Ventura River estuary is likely a source population to the LA/Ventura Recovery Unit, and is, therefore, important for maintaining metapopulation dynamics (USFWS 2013). The physical and biological features essential to the conservation of tidewater goby consist of persistent, shallow (in the range of approximately 0.3 to 6.6 ft [0.1 to 2 m]), still-to-slow-moving lagoons, estuaries, and coastal streams with salinity up to 12 parts per thousand (ppt), which provides adequate space for normal behavior and individual and population growth, that contain (i) substrates (e.g., sand, silt, mud) suitable for the construction of burrows for reproduction; (ii) submerged and emergent aquatic vegetation, such as *Potamogeton pectinatus*, *Ruppia maritima*, *Typha latifolia*, and *Scirpus* spp., which provides protection from predators and high flow events; or (iii) a sandbar(s) across the mouth of the estuary during the late spring, summer, and fall that closes or partially closes the estuary, thereby providing relatively stable water levels and salinity. Many of these same habitat features support juvenile steelhead that may rear in the estuary; however, extreme high temperature or low dissolved oxygen levels could be harmful, especially if juveniles cannot move upstream where temperatures and dissolved oxygen levels may be more suitable (Hayes et al. 2008).

2.2 SEDIMENT LOADING

Sediment loading to the estuary will govern the potential impacts associated with dam removal and restored sediment loading; therefore, the transport of silt, sand, gravel, and cobble is a critical modeling input to the estuary and coastal modeling. For each sediment grain size (silt, sand, gravel, and cobble), a sediment rating curve was developed for pre- and post-dam removal conditions to characterize the sediment loading associated with discharge magnitudes. In addition, the pulse of sediment following dam removal was estimated so that the short-term effects of the dam removal on the estuary could be evaluated.

The sediment rating curve and dam removal loading analysis, described in more detail below, relied heavily on prior analysis and modeling studies. In particular, prior studies conducted by the U.S. Bureau of Reclamation (BOR), AECOM, and Stillwater Sciences (BOR 2006; AECOM and Stillwater 2016; Stillwater 2019) were leveraged to develop a robust understanding of sorted sediment loading to the estuary. The BOR (2006) sediment analysis included characterization of impounded sediment, sediment yield both with and without the dam in place, and sorted sediment rating curve analysis.

The range of sediment loading analysis (BOR 2006; AECOM and Stillwater 2016; Stillwater 2019; Cui et al. 2017) within the system are used in concert for estimates of sediment delivery and loading to the estuary and the coastal ocean. Each of the four sediment grain sizes (silt, sand, gravel, and cobble) are treated individually in the estuary and coastal models. The following summarizes available sediment loading associated with dam removal as well as the development of sediment supply curves for the Ventura River with and without the dam in place.

2.2.1 Sediment Supply Rating Curves

Sediment rating curves can be used to estimate sediment loading for a particular grain size based on river discharge at a given location within a watershed. To estimate the sediment loading to the estuary from the watershed (i.e., not associated with the erosion of impounded sediment following dam removal), sediment rating curves were developed pre- and post-Matilija Dam removal from prior studies (BOR 2006; AECOM and Stillwater 2016; Stillwater 2019).

The sediment loading for each grain size class (silt, sand, gravel, and cobble), Q_s, can be estimated using the equation:

$$Q_s = a\, Q_w^b$$

where a and b are coefficients, Q_w is the river discharge, and both sediment loading and discharge are in m^3/s. The b coefficients depend on dynamics of the watershed, the sediment grain size, and general transport characteristics, and the a coefficients modify the magnitude of the sediment load and can be scaled to appropriately account for sorted sediment loading pre- and post-dam removal based on annual sediment supply estimates.

Sediment rating curves were developed under current conditions (i.e., dam in place) for silt, sand, and gravel based on sediment concentration data and long-term sediment supply estimates at multiple gage stations (BOR 2006). While it is acknowledged that the concentration data do not capture bedload and gravel material not in suspension, a key assumption is that the concentration data can be reasonably used to determine the shape of the sediment rating curves (b coefficients). The magnitude of the total load is then based on watershed estimates of annual loading using the a coefficients. The b coefficients were derived at the Ventura River gage station for silt, sand, and gravel loading as 1.6, 2.4, and 3.0, respectively (BOR 2006). For silt and sand sediment loading, annual estimates of loading were used to develop the rating curves. For gravel and cobble, however, the DREAM-2 model outputs were available at the upstream end of the estuary to develop the rating curves.

Estimated pre- and post-removal equilibrium (i.e., no sediment trapping behind Matilija Dam) sediment loading to the Ventura River from Stillwater (2019) is shown in Table 2. For transparency, the pre- and post-dam removal estimates developed by BOR (2006) are also shown (Table 3) and indicate similar total magnitude estimates of sediment loading. However, the Stillwater (2019) estimates assume zero trapping of silt sediment by Matilija Dam and suggest much smaller annual sand loading to the estuary. Differences between the two estimates may be due to differences in the assumptions regarding trapping of sediment grain sizes in the system. It is also worth noting that the BOR (2006) post-dam removal estimates applied a constant trapping efficiency across all sediment grain sizes. In reality, coarser grain material is more likely to be trapped behind the dam compared to fine-grained material as indicated in the Stillwater estimates. Because the primary focus of this study is to evaluate the effect of dam removal relative to current conditions, the difference between pre- and post-removal sediment loading is of primary importance. Fortunately, since the goal of this study is to evaluate the change in sediment load, the pre-removal total sediment load still allows for the evaluation of changes in total load relative to current conditions. Therefore, while there are differences in the magnitude of estimated sand loading to the estuary from Stillwater (2019) and BOR (2006) reports, the increase in sand loading ranges from approximately 16,000 to 21,000 m^3/yr for both cases.

Table 2. Estimated Annual Sediment Delivery at the Estuary from Stillwater (2019).

	Sediment Loading (m^3/yr)			
	Silt	Sand	Gravel	Total
Total Pre-removal	344,210	12,190	7,600	364,000
Total Post-removal Equilibrium	344,210	28,190	17,600	390,000
Percent Increase Post-removal	0%	131%	131%	7%

Table 3. Estimated Annual Sediment Delivery to the Ocean from BOR (2006).

	Sediment Loading (m^3/yr)				
	Silt	Sand	Gravel	Cobble	Total
Total Pre-removal	237,000	104,000	7,200	400	349,000
Total Post-removal Equilibrium	285,000	125,000	8,600	480	419,000
Percent Increase Post-removal	20%	20%	20%	20%	20%

For silt and sand, sediment rating curves were developed from the estimated annual load of sediment in Table 2 based on the Stillwater (2019) work as the most up to date system description. The b coefficients, as described above, are based on measured sediment concentration in the Ventura River at Station 11118500 (BOR 2006) to best approximate the loading curve given the available data. The coefficients for silt and sand at the gage station are 1.6 and 2.4, respectively. Using the total estimated annual sediment load, the a coefficients were computed for both the current loading as well as the long-term post-removal equilibrium sediment loading based on the 15-minute discharge data measured at Station 11118500 over the 30-year period of available data.

The DREAM-2 modeling study evaluated coarse sediment (diameter > 2 mm; gravel and cobble) transport through the watershed under current conditions (Runs 1a, 1b, 1c, 1d, and 1e) and following dam removal (Runs 2a, 2b, 2c, 2d, and 2e) using five discharge scenarios (a–e). Stillwater Sciences provided the Integral team with daily discharge and sorted coarse sediment loading across all 10 scenarios at the West Main St. Bridge (just upstream of the estuary) over the entire 68-year simulation period. The loadings across all 10 scenarios were used to estimate the sediment rating curve coefficients for coarse grain material (> 2 mm) for pre- and post-dam removal conditions. The best fit between total gravel and cobble loading and discharge across the 10 scenarios was computed to estimate the rating curve coefficients. Coefficients were computed for each of the 10 scenarios and all but two of the cases (Runs 1c and 2c) generated identical *a* and *b* coefficients (Table 4).

Importantly, there was no difference in the gravel and cobble loading for the cases with and without dam removal based on the DREAM-2 modeling. This is because the coarse grain material will likely take decades to travel from the dam to the coastal ocean. Therefore, while gravel and cobble are important features of the watershed, the dam release and removal are not expected to appreciably modify coarse grain transport in the system appreciably. There are also significant gravel and cobble contributions from other tributaries, primarily, San Antonio Creek. In addition, there are other significant gravel and cobble sources to the Ventura River that are not impacted by the Matilija Dam (North Fork Matilija Creek and San Antonio Creek) such that the total change in gravel and cobble loading post-dam removal is small. Another likely reason that the predicted gravel and cobble loading at the estuary are equivalent pre- and post-dam removal is due to uncertainty in DREAM-2 model predictions, particularly in regions where the river channel slope flattens out. Near the estuary, the river channel slope decreases and the DREAM-2 model correspondingly predicts large sediment deposits.

To ensure that the dam removal impact on estuary habitat was conservatively predicted in the present study, sensitivity of the model results on the estimated gravel and cobble loading was evaluated. Additional modeling studies were conducted that incorporated a 20 percent increase in the post-dam removal gravel and cobble sediment loading. This increase is consistent with the BOR (2006) predicted increase in gravel and cobble loading from pre- to post-dam removal conditions.

Table 4. Rating Curve Coefficients for Silt, Sand, Gravel, and Cobble.

Rating Curve Coefficients	Silt (0.03 mm)	Sand (0.2 mm)	Gravel (16 mm)	Cobble (100 mm)
b	1.6	2.4	3.0	3.0
a (pre-removal)	4.07E-04	1.21E-07	6.80E-10	5.40E-11
a (post-removal equilibrium)	4.07E-04	2.80E-07	6.80E-10	5.40E-11

Based on the derived sediment rating curve coefficients shown in Table 4, the rating curves for silt, sand, gravel, and cobble in the Ventura River post-dam removal are shown in Figure 5. The sediment grain sizes used throughout this analysis for silt, sand, gravel, and cobble are 0.03, 0.2, 16, and 100 mm, respectively. These rating curves are used throughout the analysis.

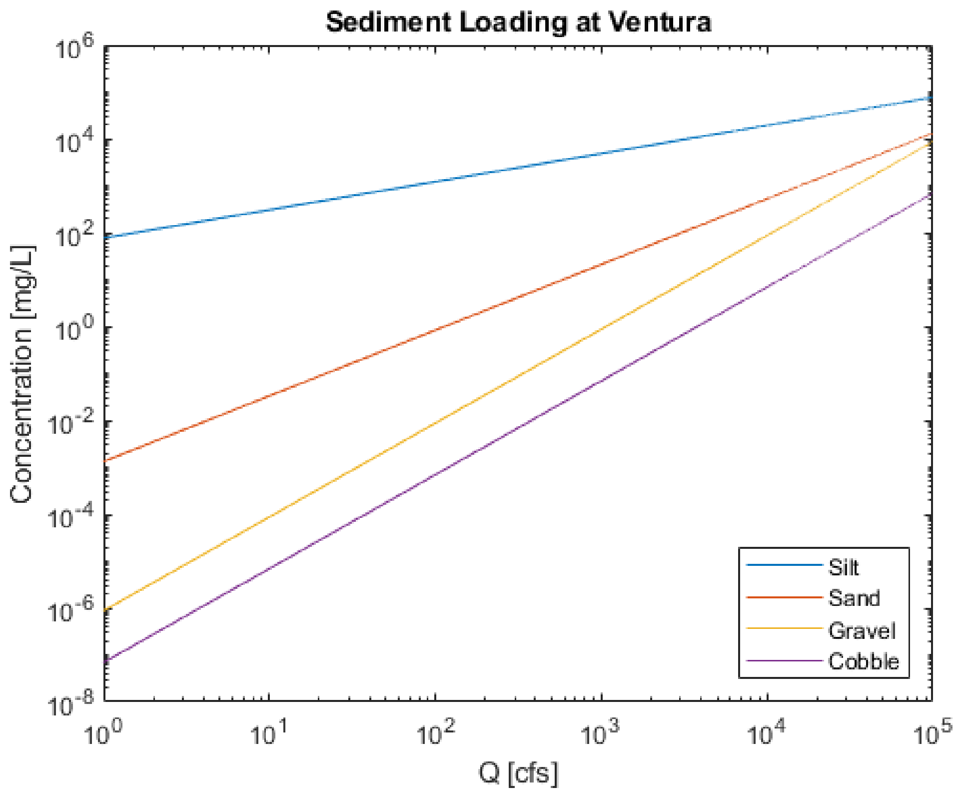

Figure 5. Post-removal Sediment Rating Curves at Ventura Gage Station (11118500) Developed for the Four Sediment Size Classes.

2.2.2 Dam Removal Sediment Loading

The dam removal concept 2A/2B (uncontrolled orifices with optional gates) would involve blasting open boring tunnels when a high-flow event occurs to erode significant portions of fine sediment deposits in the reservoir. Based on analysis from AECOM and Stillwater (2016), the design high-flow event on Matilija Creek would need to exceed 1,700 cfs[2] to sufficiently erode accumulated silt and sand from behind the dam (AECOM and Stillwater 2016). If the observed flood event is not adequate to remove accumulated fine sediment from the reservoir, gates might be installed that allow the reservoir to refill until the next high-flow event occurs. The

[2] The design high-flow event on Matilija Creek of 1,700 cfs is approximately a 4-year return period event (AECOM and Stillwater 2016).

dam would then be removed when a sufficient amount of fine impounded sediment has been eroded from the reservoir (AECOM and Stillwater 2016).

The character of the sediment behind the Matilija Dam has been used to estimate grain size distributions and sediment loading to the system during dam removal (AECOM and Stillwater 2016; Stillwater 2019). The DREAM-2 model output from the first design flow-event (in the 68-year simulations) was used to specify the gravel and cobble loading to the estuary for the five dam removal modeling scenarios. While the DREAM-2 scenarios are used to specify coarse sediment (>2 mm) loading to the estuary, a separate approach had to be used for fine (silt and sand) sediment transport. Silt and sand sediment transport following dam removal has been estimated in Cui et al. (2017) using an empirical approach. The total mass of sediment to be eroded following a design event was estimated between 850,000 and 1,170,000 metric tons. The range of sediment is based on estimates of channel formation and is supply limited based on the available sediment in the reservoir. The total mass of fine sediment eroded from Matilija reservoir during dam removal release was used to specify the sediment load to the estuary over a dam removal event. The erosion of impounded silt and sand following dam removal was added to the post-dam removal sediment supply rating curves to account for silt and sand originating from other regions of the watershed.

A summary of the dam removal sediment loading is shown in Table 5. The total sorted sediment load anticipated during the initial release following dam removal as well as the restored annual sediment loading in Table 5 are used throughout the analysis to evaluate the effect of dam removal on the estuary and coast.

Table 5. Sorted Sediment Loading to the Estuary Associated with Initial Dam Removal and Restored Loading Post-Dam Removal.

	Silt (0.03 mm)	Sand (0.2 mm)	Gravel (16 mm)	Cobble (100 mm)
Initial Dam Removal (m^3)	607,000	124,000	-	-
Post Dam Removal Annual Loading (m^3/yr)	344,000	28,200	3,200	260

3 VENTURA RIVER ESTUARY

The impact of dam removal on habitats within the estuary was evaluated using a combination of a high-resolution numerical hydrodynamic and sediment transport model and a long-term empirical[3] inlet model. Similar modeling of the coastal ocean over short and long time scales is discussed in the next section. The two models (numerical and empirical) provide a method for evaluating both the short- and long-term impacts of dam removal on the estuary.

A 2-dimensional hydrodynamic and sediment transport estuary model was developed in Delft3D and used to evaluate the impact of the initial sediment load following dam removal as well as the restored sediment loading on habitat within the estuary. The high-resolution model (the estuary model) resolves sediment transport over individual flow events and allows for sediment transport deposition within the channel, across the floodplain regions, and to the coastal ocean. The dam removal model scenarios and results are discussed below, and setup and validation of the estuary model can be found in Appendix A.

An empirical inlet model was developed to evaluate potential changes to opening and closure of the estuary, which may affect habitats. The empirical inlet model specifically predicts the inlet condition (open, closed, or tidally open) over long periods (years to decades). The timing and duration of inlet breaching is an important seasonal process that many species within the estuary rely on for access. The inlet model was used in the present study to evaluate the long-term impact of modified conditions (discharge, sedimentation, and sea level rise) on the inlet breaching. The empirical model uses a water balance approach whereby various inputs and outputs of water are computed over hourly time steps. The model includes inlet erosion via river discharge and accretion via wave swash. The model was validated with observations of inlet conditions provided by Casitas Municipal Water District (see Appendix A for further details on model development and validation). Improved estuary water level data collection would improve this model. The following describes the results of the estuary and inlet modeling and the impact on habitat within the estuary.

3.1 SHORT-TERM DAM REMOVAL SCENARIOS

To evaluate the short-term effect of dam removal on the estuary, the 2-dimensional Delft3D hydrodynamic and sediment transport estuary model was employed. The validated Delft3D estuary model domain extends from the ocean to approximately 1 mile upstream of the coastal inlet and from the southern extent of Emma Wood Beach to the east and beyond the levee to the west (Figure 6; see Appendix A for more detail). This area captures the extents of the estuary, the beach along the coast adjacent to the estuary, as well the floodplain regions (the agriculture

[3] A numerical model relies on mathematical descriptions based on mechanistic processes in a system to predict behavior, and an empirical model relies on parameterizations developed from data and observations.

field, the Ventura Beach RV Resort [RV park], and the trails and vegetation to the northwest of the estuary) that are known to periodically flood during large events (Keller and Capelli 1992).

The 2-dimensional estuary model grid has 5 m horizontal resolution throughout to resolve key bathymetric features and allow for accurate engagement of the floodplains. The Ventura River discharge and sediment loading are specified at the upstream boundary of the domain, and the offshore water level is specified at the southern boundary of the domain. The estuary model was validated with observed flood extents from an approximately 5-year return period event in February 2019, a well-documented high flow that occurred during the course of this study (see Appendix A for further details on model development and validation). The validated estuary model was used to simulate five dam removal scenarios (based on the five discharge scenarios defined in Stillwater 2019) to evaluate the effect of dam removal on sedimentation and habitat within the estuary. The following section describes the model setup, results, and the habitat implications of the initial sediment release following dam removal.

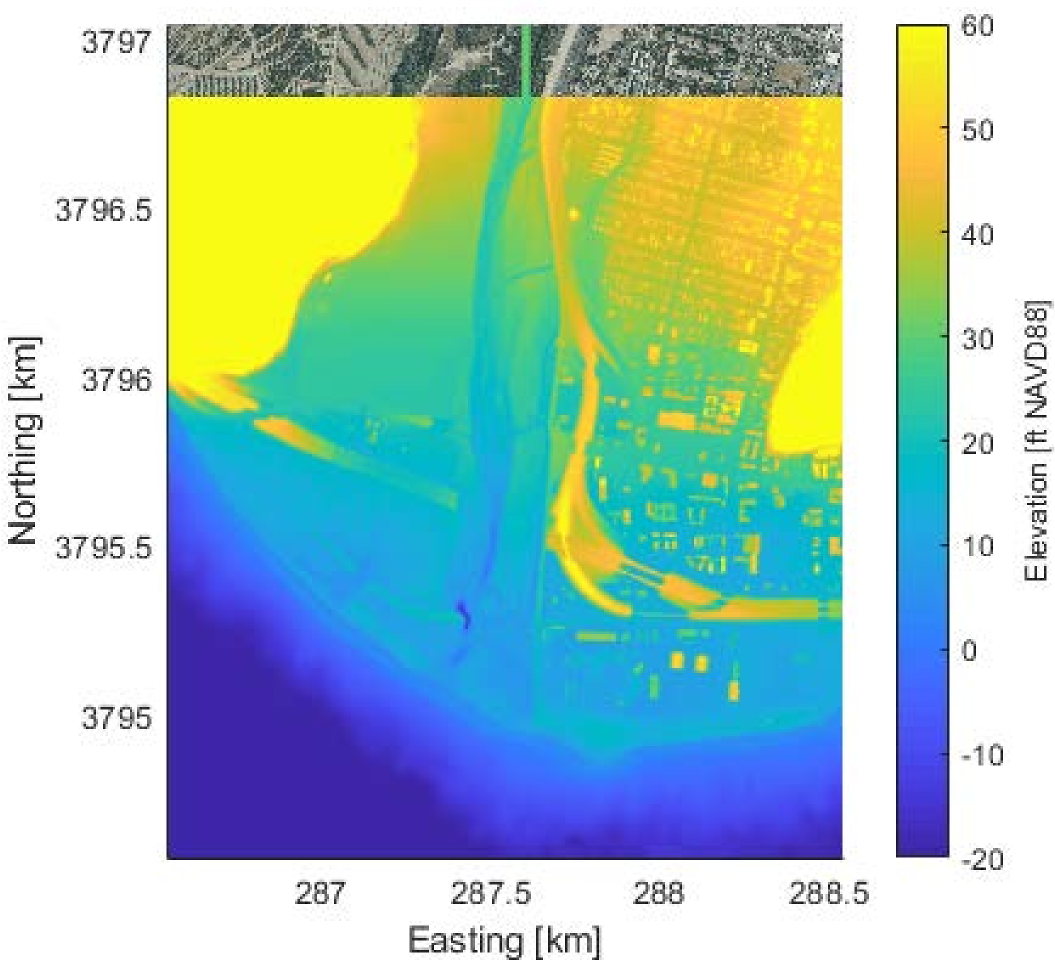

Figure 6. Estuary Model Domain with Elevation Data.

3.1.1 Model setup

For inputs, the estuary modeling relied on the previous analysis of sediment transport loading from the dam to the estuary (Stillwater 2019). As described above, 10 sediment transport simulations were conducted pre- and post-dam removal. The daily discharge and coarse sediment loading at the West Main St. Bridge over the 68-year study was provided to the Integral team by Stillwater Sciences (as described in Section 2.2 above). The dam removal scenarios developed by Stillwater Sciences (Run 2) include scenarios 2a through 2e (Stillwater 2019). The initial event at the beginning of each simulation was specified to meet the design discharge constraint of greater than 1,700 cfs daily average flow on Matilija Creek. Runs 2c, 2d, and 2e are approximately 4-year return period events although the daily average discharge for the first event in Run 2c is slightly smaller (1,260 cfs) than the design constraint. The smaller discharge scenario examines the case in which the observed flood event following dam removal fails to reach the desired design flow. The first event for Runs 2a and 2b are approximately 10-year return period events. The daily average discharge and sorted coarse sediment (gravel and cobble) loading predicted at West Main St. Bridge was provided by Stillwater Sciences for the five scenarios (Table 6).

3.1.1.1 Discharge

To generate higher resolution boundary conditions for the estuary model, 15-minute discharge data from the U.S. Geological Survey (USGS) gage station (11118500) were used. The date of the first discharge event for each scenario was identified and the 15-minute USGS discharge data were used. However, 15-minute discharge data were not available for Runs 2b and 2c because these events occurred prior to 1988 when only daily discharge data were available. For these two cases, an exponentially modified Gaussian curve characteristic of the local hydrograph was used to specify variability of discharge over the event. The modified Gaussian curve is useful for representing an asymmetrical hydrograph, where, for instance, the ramp-up to peak discharge is followed by a more gradual decrease. The asymmetrical curve allows for more realistic characterization of a watershed hydrograph. The discharge is given by the equation below:

$$q = \frac{\lambda}{2}\exp\left(\frac{\lambda}{2}(2\mu + \lambda\sigma^2 - 2t\right)\operatorname{erfc}\left(\frac{\mu + \lambda - t}{\sqrt{2}\sigma}\right)$$

where λ, σ, and μ are curve fitting coefficients, t is the time in days, *exp* is the exponential function, *erfc* is the error function, and q is the normalized discharge time series. The curve fitting coefficients were selected by comparing normalized observed discharge events and estimating a characteristic hydrograph for the watershed.

The high-resolution discharge curve was generated to match the daily average discharge provided by Stillwater Sciences. The resulting high-resolution (15-minute) discharge over the first flow event for each of the five dam removal scenarios is shown in Figure 7. While Runs 2c, d, and e have a similar daily discharge (approximately 4-year return period flow) the peak 15-minute flow varies across the scenarios depending on the shape and duration of the event. Therefore, the five scenarios provide a range of potential design flow events. For all dam removal scenarios, the peak discharge occurred on day 1 of the simulation (Figure 7).

Table 6. Discharge for the Five Dam Release Scenarios at West Main St. Bridge.

Run	Date of Initial Event	Maximum Daily Average Discharge (at Highway 101) from DREAM-2 (cfs)	Peak 15-Minute Discharge (cfs)
2a	1992	8,670	45,800
2b[a]	1969	6,800	38,550
2c	1958	3,350	8,140
2d	2017	4,770	18,500
2e	1991	2,990	11,300

Source: BOR (2006).

Note:

[a] The first dam removal event is followed by a larger flow of approximately 58,000 cfs that corresponds to a 50-year flood. For the purposes of the dam removal modeling, the first event was used.

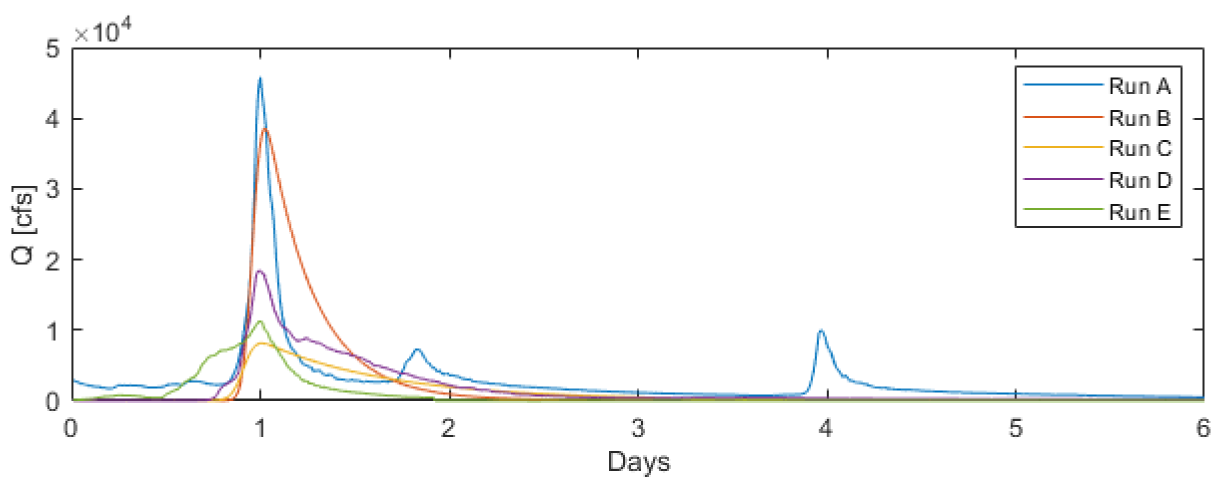

Figure 7. 15-Minute Discharge of the First Flow Event Following Dam Release for the Five Scenarios Identified by Stillwater (2016).

3.1.1.2 Offshore Water Level

The offshore tide levels were specified using measured tidal elevations from nearby Santa Barbara (Station 9411340). The time series was shifted such that a king high tide[4] water level

[4] Highest predicted tide of the year.

occurred immediately following the peak discharge (similar to the conditions observed during the February 2019 validation event described in Appendix A). A king high tide following the high flow event would be expected to generate the largest impact due to sedimentation (relative to low water level) in the estuary by inhibiting flow to the coastal ocean and significantly altering benthos. The king high tide affects sedimentation, flood extents, and water quality because the high tide pushes water into the estuary, backwatering river flows, elevating estuary water levels, and dropping large sediment loads. Therefore, the scenarios developed provide a worst-case scenario for potential sedimentation impacts to the estuary following the dam release event (Figure 8).

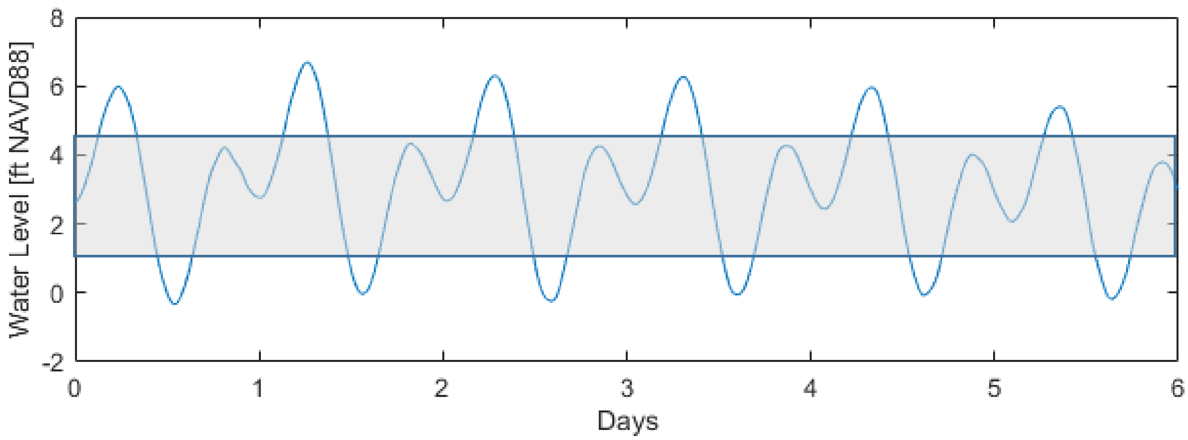

Figure 8. Offshore Water Level for Dam Release Scenarios. Normal mean high water to mean low water tide range shown in gray.

3.1.1.3 Sediment Loading

To conservatively evaluate any impacts of dam-released sediment on the estuary, we assume that the total mass of eroded sediment from behind the dam will be delivered to the Ventura River estuary in a single event at the same time. It is anticipated the some fraction of sediment (particularly coarser grain sand, gravel, and cobbles) will deposit near the channels and in floodplains along the length of the river, staggering the timing of the load for each sediment size delivered to the estuary following an initial dam removal event; therefore, the use of the total load is a conservatively high sediment loading assumption for the assessment here. As discussed previously, the sediment grain sizes used for modeling silt, sand, gravel, and cobble are 0.03, 0.2, 16, and 100 mm, respectively. Each of these size classes is treated discretely in the model and the loadings are described here.

Gravel and cobble loadings over the five dam removal events are based on results from the DREAM-2 model at the estuary. The coarse (> 2 mm) sediment loading associated with the dam removal events has been taken from the daily average DREAM-2 model results at the Highway 101 Bridge. The total loading over the first event provided by Stillwater Sciences was then distributed across the event based on discharge (Figure 7).[5] While the DREAM-2 model was developed and validated for higher gradient river reaches, the model is not intended for use in low-gradient estuarine environments that are also influenced by oceanic water levels; therefore, an estuarine model sensitivity analysis was conducted to evaluate the effect of a 20 percent increase on gravel and cobble loading during the dam removal scenarios.

Fine sediment loading for the impounded sediment erosion immediately following dam removal was specified using analysis from Cui et al. (2017). The total mass of fine sediment eroded from the reservoir was based on sediment supply and two possible post-erosion channel geometries (Cui et al. 2017). From their analysis, the total mass of fine sediment anticipated to erode during a dam release event (4-year return period event) was between 880,000 and 1,170,000 metric tons. The absolute maximum fine sediment erosion estimated from the total mass of impounded silt and sand is 2,830,000 metric tons (Cui et al. 2017). Cui et al. (2017) assumed that this initial phase of sediment erosion would occur over 1 to 2 days and that sediment concentrations would rapidly decrease to background levels.

For the purposes of estuary modeling of the dam-released fine sediment, we distributed the total eroded mass (1,170,000 metric tons) over the dam release event using the sediment rating curves for silt and sand (b is 1.6 and 2.4 for silt and sand, respectively). The coefficient a was derived for each event based on the total magnitude of eroded sediment such that the sediment loading varied with discharge across the event. The fraction of silt and sand was based on distribution of fine sediment in the reservoir (83 percent silt and 17 percent sand). The total silt and sand loading over the dam release events was equal to the background sediment supply with no Matilija Dam (from Table 4) plus the eroded impounded sediment behind the dam (1,170,000 metric tons). The sediment delivered to the estuary therefore takes into account the eroded reservoir impounded sediment in addition to the background sediment supply from Matilija Creek, North Fork Matilija, and San Antonio Creek.

The sediment loading for each grain size class (silt, sand, gravel, and cobble) is shown in Figure 9 for all five dam removal scenarios. Eroded fine sediment from the impounded sediment constitutes between 52 and 86 percent of the total sediment load over the five scenarios. An example of the sediment loading for each grain size class is shown for Run 2d in Figure 9. The loading curves (bottom panels) follow the discharge curve (top panel) closely with the majority of the sediment pulse occurring in the first 2 days.

[5] The coarse sediment loading was assumed to follow the functional rating curve relationship ($Q_s = a\,Q^b$), where b is defined in Stillwater (2019), and a was computed such that the total loading over the event was equivalent to the DREAM-2 predicted loading.

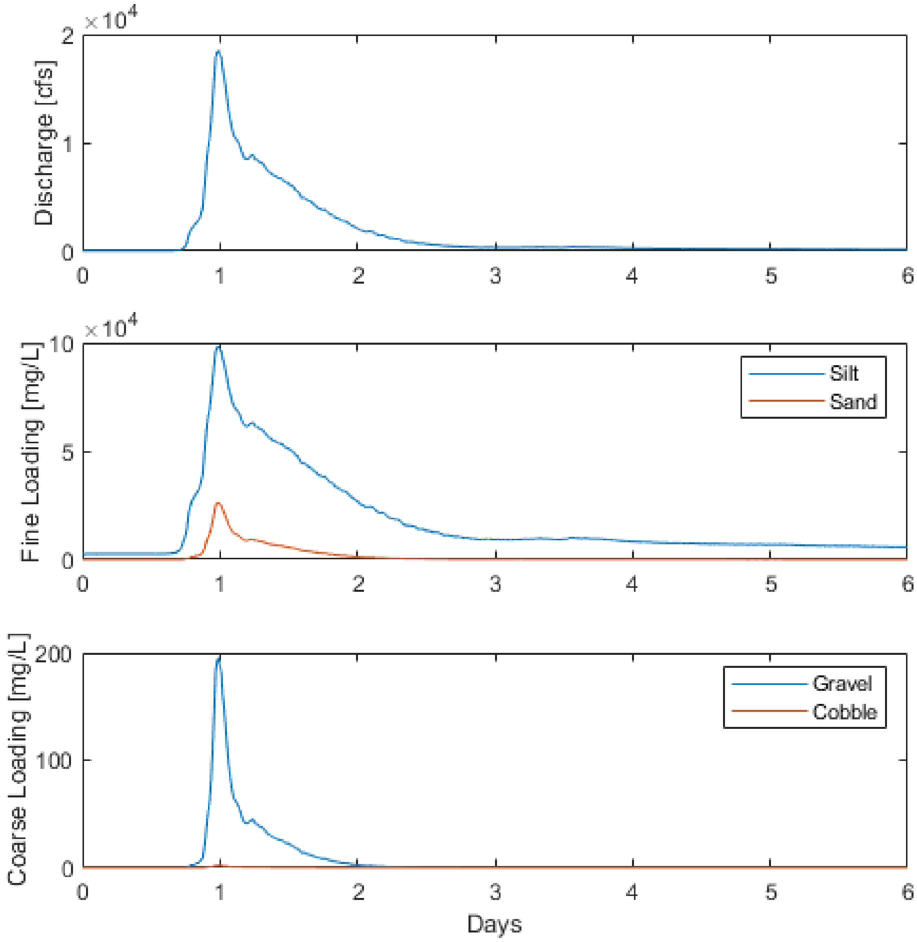

Figure 9. Sediment Loading for Dam Release Run 2d for Silt, Sand, Gravel, and Cobble.

3.1.2 Results

Simulations were conducted using the estuary model for the range of conditions described above. The total sediment load released to the estuary and nearshore coastal ocean has been characterized using water quality (based on suspended sediment concentration), sedimentation deposition thickness, and grain size distribution. These metrics provide the basis for quantification of potential impacts to the habitat in the estuary and nearshore coast.

3.1.2.1 Water Quality

Increased suspended sediment concentrations could pose a short-term water quality concern in the system. The values presented here provide the basis for future impact assessment work. The suspended sediment concentration is shown for all scenarios in the center of the estuary over the 6-day simulation period (Figure 10). In all cases, the suspended sediment concentration increases substantially during the dam removal flow event. Due to the erosion of more than 1 million metric tons of impounded silt and sand from behind the dam, the suspended sediment concentration within the estuary is high (on the order of 150 g/L) during the dam removal event. As the dam removal event wanes, the turbidity rapidly decreases in nearly all scenarios after a few days. Notably, there is a secondary and tertiary event following the initial event in Run A, which results in additional peaks in suspended sediment concentration at 1.9 and 4 days post-release. In general, however, the suspended sediment concentration in the estuary decreases rapidly at the cessation of the discharge event. This finding is consistent with analysis conducted by Stillwater Sciences evaluating anticipated duration of the initial impounded sediment erosion (Cui et al. 2017).

The deposits of silt and sand within the estuary during the dam removal event have the potential to affect the estuary during subsequent flood events as the fine sediment deposits can be readily mobilized. The most mobile sediment fraction, silt, is the largest contributor to the observed suspended sediment concentrations and, as shown in the results in the following section, approximately 90 percent of the silt fraction is transported through the estuary to the coastal ocean during the dam removal event. While the remaining deposits of silt in the estuary can effect turbidity within the estuary beyond this acute event, the largest impacts to water quality in the estuary are observed over a few days following dam removal.

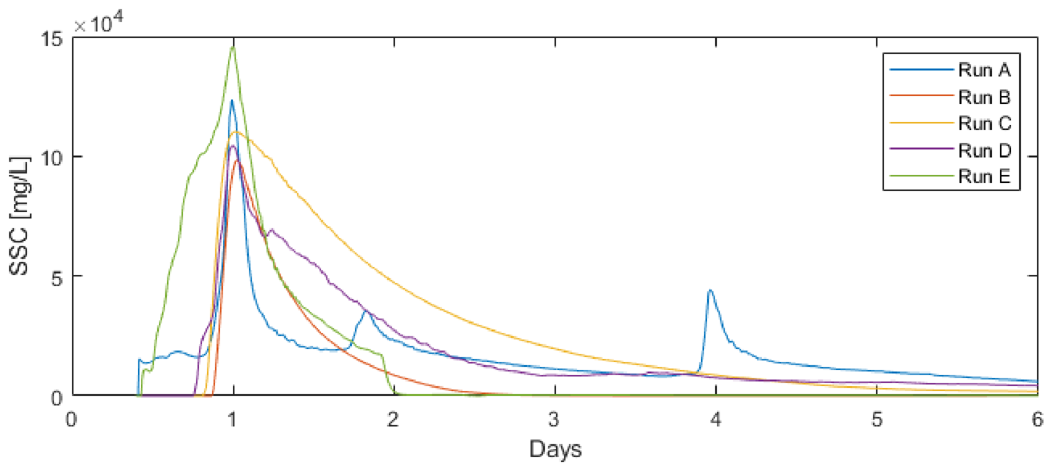

Figure 10. Suspended Sediment Concentrations Within the Estuary for the Five Dam Release Scenarios.

3.1.2.2 Estuary Trapping Efficiency

The percent of the total load that deposited within the estuary was computed for each dam release scenario for each grain size class. The vast majority of silt particles was readily transported through the estuary and out to the coastal ocean, with between 7 to 15 percent of the total silt load depositing in the estuary. A larger percent of total sand load (between 61 and 90 percent) deposited within the estuary. In general, the trapping efficiency of sand within the estuary decreased as the discharge increases (Runs 2a and 2b represent approximately 10-year return period events, while Run 2c was the smallest discharge event). The total loading of silt and sand the dam removal scenarios increases with discharge based on the sediment rating curves.[6] Despite these differences, the trapping efficiency is relatively consistent across the range of simulated dam removal events, indicating the estuary response to discharge events is consistent across the scenarios.

Table 7. Percent Mass of Total Sediment Load Deposited Upstream of the Estuary Mouth.

Run	Max Discharge (cfs)	Silt (%)	Sand (%)	Gravel (%)	Cobble (%)	Total (%)
2a	45,800	15.7	69.9	99.7	100.0	12.6
2b	38,550	9.3	61.8	99.9	100.0	11.0
2c	8,140	7.9	88.4	100.0	100.0	16.7
2d	18,500	12.3	89.7	100.0	100.0	17.5
2e	11,300	7.6	84.0	100.0	100.0	14.4

For all five scenarios, 100 percent of the total gravel and cobble load remained in the estuary. The trapping efficiency for the coarser sized sediment loads within the estuary is therefore, tied to the delivery of coarse material to the estuary. For the smaller discharge events (Runs c and e), the vast majority of the coarse grain material remains upstream of the estuary within the river channel, highlighting the fact that these coarser grain materials move incrementally down river only during intermittent large flow events. There are existing relic deposits of gravel and cobble throughout the Ventura River system, such that these flood events will incrementally move gravel and cobble throughout the system. Based on the small incremental movement of coarse grain material, coupled with results from Stillwater Sciences DREAM-2 modeling of the Ventura River, the impact of dam removal on gravel and cobble transport is unlikely to be felt by the estuary (over 20 km downstream) for many decades. The timing of gravel and cobble delivery from Matilija Dam is outside the scope of this study and is evaluated in Stillwater (2019). The following section, however, addresses the potential coarse grain transport through the estuary and to the coastal ocean over various return period flood events.

Overall, and as expected, the trapping efficiency decreases as discharge increases with Run 2b having the lowest trapping efficiency. Of the three approximately 4-year return period dam removal scenarios, the case that resulted in the highest sediment trapping percentage within the estuary was Run 2d. Run 2d represents the balance of a high enough sediment loading and flow to allow for high trapping percentage, but not a very high flow, as in Runs 2a and 2b, which

[6] The silt and sand loading during dam removal scenarios is based on the estimated erosion of impounded sediment behind the dam (from Cui et al. 2017) as well as background sediment loading from the watershed estimated using the sediment rating curves.

limit the capacity for trapping the incoming flow. Given this important finding that the characteristics of Run 2d represents the largest percent trapping event in the estuary, the remaining discussion of results and potential impacts focuses on Run 2d while results from the other four dam release events can be found in Appendix B.

3.1.2.3 Estuary Sedimentation

The sedimentation thickness deposited within the estuary at the end of the 6-day simulation for Run 2d is shown in Figure 11.[7] The most significant deposition within the estuary occurs under the railroad bridge largely because during the bathymetry survey of the estuary, this area was characterized by a deep scour hole.

The resulting grain size distribution within the estuary after the dam release is shown in Figure 12 using the percent of total deposited mass that is finer than 65 μm and 2 mm (left and right panels, respectively). More than 70 percent of the sediment deposited within the estuary during this event was sand (green regions in the left panel) with most of the remaining deposition comprising silt particles (gravel and cobble contributed less than 1 percent of the total deposition within the estuary; green regions in the right panel).

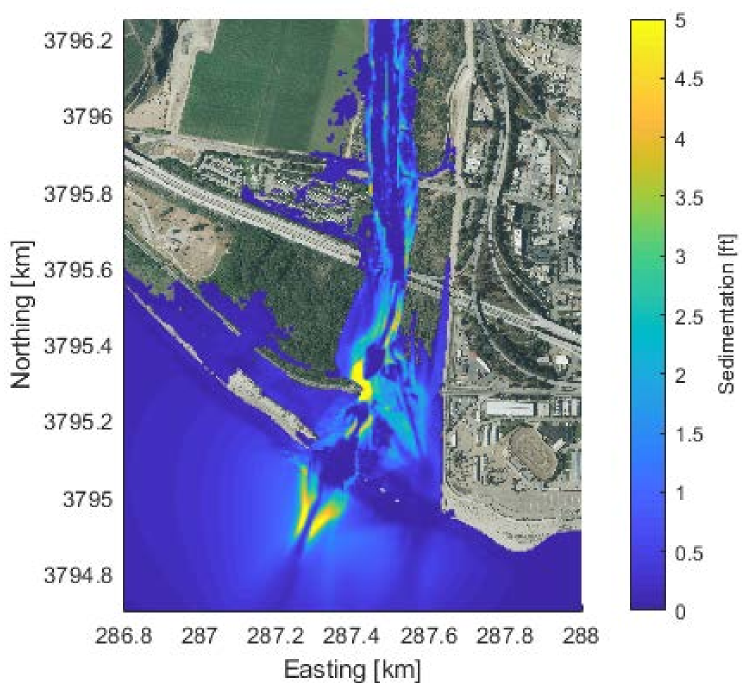

Figure 11. Total Sedimentation Thickness of Silt, Sand, Gravel, and Cobble Deposited from Run 2d Dam Release.

[7] Run 2d demonstrated the largest total sedimentation within the lagoon of the three approximately 4-year return period dam release scenarios.

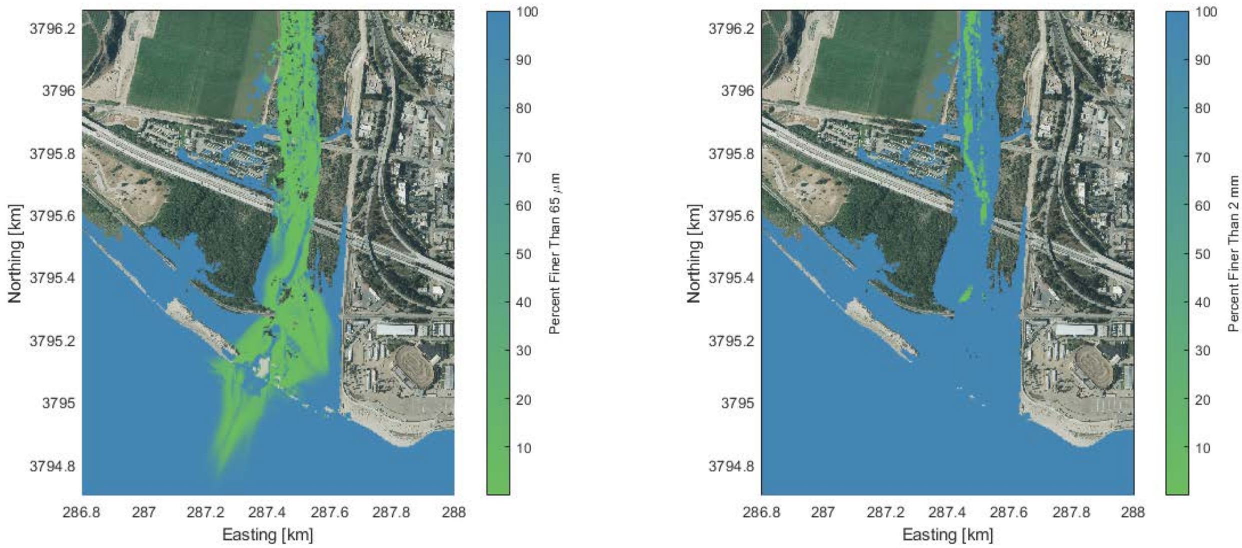

Figure 12. Sediment Grain Size Distribution for Run 2d Indicated by the Percent of Deposited Material Silts (Less Than 65 µm) (left panel) and the Percent of Deposited Material Sand (Less Than 2 mm) (right panel[8]).

3.1.2.4 Model Sensitivity

The design flow (4-year) dam removal scenario with the maximum sedimentation (Run 2d) was also simulated with modified offshore boundary conditions to evaluate the effect of tidal forcing on sediment transport and trapping in the estuary. The offshore water level was shifted such that the peak discharge occurred just before the daily low tide during the neap tidal cycle (approximately –0.3 ft NAVD88). A second scenario was also considered where the discharge occurred during king high tide (6.5 ft NAVD88), which represents the highest annual predicted water level. The simulations with modified offshore water level forcing provide a comparison of dam removal scenarios across the full tidal range (low, high, and king tide).

Across the three offshore water level conditions (low tide, high tide, and king tide), the trapping efficiency for silt ranges from 8 to 12 percent (for low and high tide, respectively) for dam removal scenario Run 2d. The trapping efficiency of sand above the estuary mouth ranged from 81 to 90 percent. Therefore, the offshore water level does influence the dynamics in the estuary. However, the range of trapping efficiency values for silt and sand based on offshore water level are comparable to the range observed across the various dam removal scenarios (a–e).

This comparison indicates that the timing of peak discharge relative to offshore tidal water level will modify flooding and deposition of silt and sand in the estuary. However, as Run 2d was

[8] Gravel and cobble deposition was less than 1 percent of total sediment deposition.

identified as potentially the most problematic to estuary habitats and conditions due to high sediment deposition, other implications of this model run at a high tide are continued below.

3.1.3 Subsequent Flow Events

To evaluate the persistence of dam-released sediment within the estuary that may cause potential channel avulsion or exacerbate flooding due to this sedimentation, subsequent flow events were simulated after the worst-case dam release event (Run 2d) was simulated. The resulting sedimentation for each grain size at the end of Run 2d was used to specify an initial bed condition for subsequent return period river flow events. The modeled bathymetry was updated to account for sedimentation associated with the dam release and Run 2d. The upstream discharge for each subsequent return period event was equivalent to the return period events described below (see Section 3.2.1) without any upstream sediment loading to estimate the persistence of dam release deposits within the estuary. As a diagnostic case here, the influence of upstream sediment is assumed not to have an effect on estuary deposit erosion.

Events with return periods of 2, 5, and 10 years were simulated without upstream sediment loading to estimate the persistence of sediment associated with dam removal within the estuary. The percent of the previously estuary-deposited dam release sediment mass that was further delivered to the ocean over the events was 8, 10, and 37 percent for the 2, 5, and 10 year events, respectively. While there was some modeled erosion across all events, significant flood events, such as a 10-year return period event were required to transport significant fractions of deposited sand within the estuary. This may indicate that the initially deposited sand may have some additional residence time depending on the sequence of subsequent river flow events, which could result in persistent sediment deposits and, potentially, water quality impacts. The small fractions of silt that deposit in the estuary during the dam removal event are readily transported during subsequent flood events. This mobilization will have an effect on turbidity and water quality in the estuary; however, the small fractions of silt associated with dam removal do not persist in the estuary. Subsequent events have the effect of continuing to move the small gravel and cobble fractions through the estuary and to the coastal ocean. A 10-year flood event has the potential to move gravel and cobble from the upstream reaches of the model domain out to the coast (a distance of approximately 1 mile). In contrast, smaller flood events result in more incremental movement of coarse sediment downstream.

3.1.4 Summary of Dam Removal Results

The dam removal scenarios estimated the short-term impact of both background sediment loading and eroded silt and sand from behind Matilija Dam. The scenarios represent a conservative approximation of estuary water quality and deposition impacts because we assumed that the total fine impounded sediment load from behind Matilija Dam was delivered to the estuary during a high tide. In reality, sand grain sizes are more likely to deposit along the length of the Ventura River. These combined effects were chosen to conservatively predict the impact of sedimentation on the estuary in what are considered worst-case scenarios.

Across all five dam removal scenarios, similar patterns emerged. Silt particles are readily transported to the coast with between 4 and 7 percent trapping of silt particles within the estuary. The silt deposits largely occur in the floodplain regions, side channels, and offshore. The biggest impact on the estuary across all five runs was driven by sand grain-sized particles. Approximately 61 to 90 percent of sand particles was deposited within the estuary along the edges of the main river channel and within the scour pit under the bridge. Coarser grain material (gravel and cobble) had a minimal impact on the estuary (<1 percent of total sediment) because the larger grain sizes are less mobile than smaller grain size sediment. Large portions of the coarse grain material remain upstream of the estuary and are likely to do so for many years. This is consistent with results from Stillwater Sciences, where the coarse grain material delivery to the estuary does not change between the dam in place and dam removed scenarios when modeled over 68 years.

Of the three design (approximately 4-year return period) dam removal events, the largest mass of sedimentation within the estuary occurred during Run 2d. This case was considered the worst-case scenario for estuarine habitat impacts. The persistence of deposited dam-released sediment within the estuary was evaluated by simulating subsequent flow events with the modeled sediment deposition from the dam removal scenario Run 2d. Results show that with subsequent flows at the 2-, 5-, and 10-year return period events, sediment was moved offshore in all cases; however, larger flow events were required to mobilize and transport significant fractions of deposited sediment.

3.2 POST-DAM REMOVAL RETURN PERIOD EVENTS

To evaluate the effect of restored sediment loading to the system after the initial dam release, the 2-dimensional estuary model was used to simulate subsequent return period flood events. The subsequent flood events were used to evaluate the effect of post-dam removal sediment loading relative to current loading conditions.

3.2.1 Model Setup

The characteristic return period events are based on return period analysis at Shell Road (approximately 3 miles upstream of the Ventura River mouth) (BOR 2006). The peak discharge used for the return period events is shown in Table 8. The average winter and summer discharge values were computed based on the 30 years of available 15-minute discharge at the Ventura River gage station (11118500) approximately 6 miles upstream.

Table 8. Return Period Scenarios.

Return Period (years)	Discharge (cfs)
2	5,080
5	12,250
10	41,300
20	52,700
50	67,900
100	78,900
500	105,500
Average Winter	200
Average Summer	10

Source: BOR (2006)

To develop a time series of discharge based on the peak discharge provided by the return period analysis, an exponentially modified Gaussian curve was used (equation above). A subset of discharges is shown in Figure 13, which range from 2- to 20-year return period events. The characteristic hydrograph shown was given by the equation with coefficients λ, σ, and μ set to 4, 0.05, and 0.95, respectively.

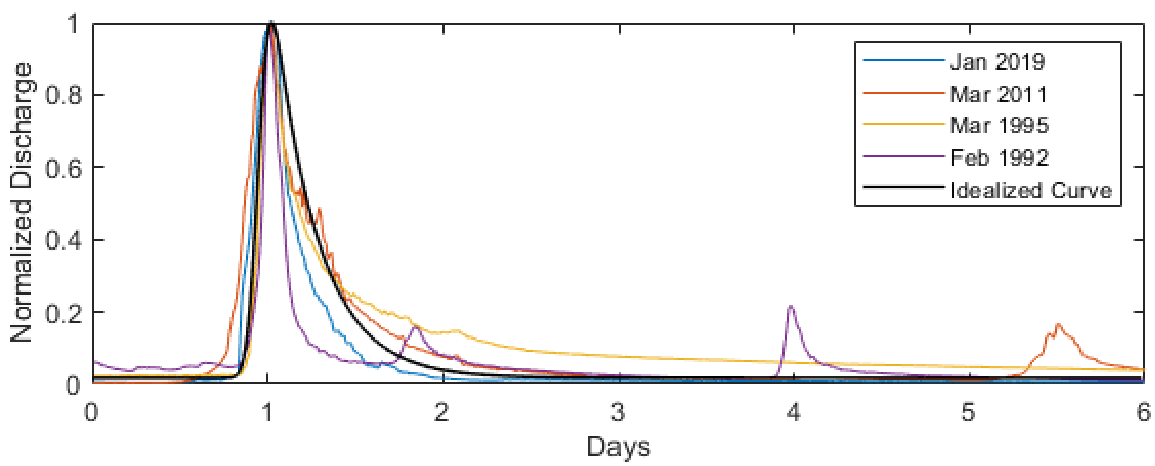

Figure 13. Normalized Discharge with Fitted Idealized Discharge Curve.

The return period events were generated by multiplying the normalized discharge q by the peak discharge for each scenario specified in Table 8. The resulting return period discharge events are shown in Figure 14. The average winter and summer conditions used constant discharge rates because these scenarios are intended to be representative of background discharge conditions in the absence of a large flood event.

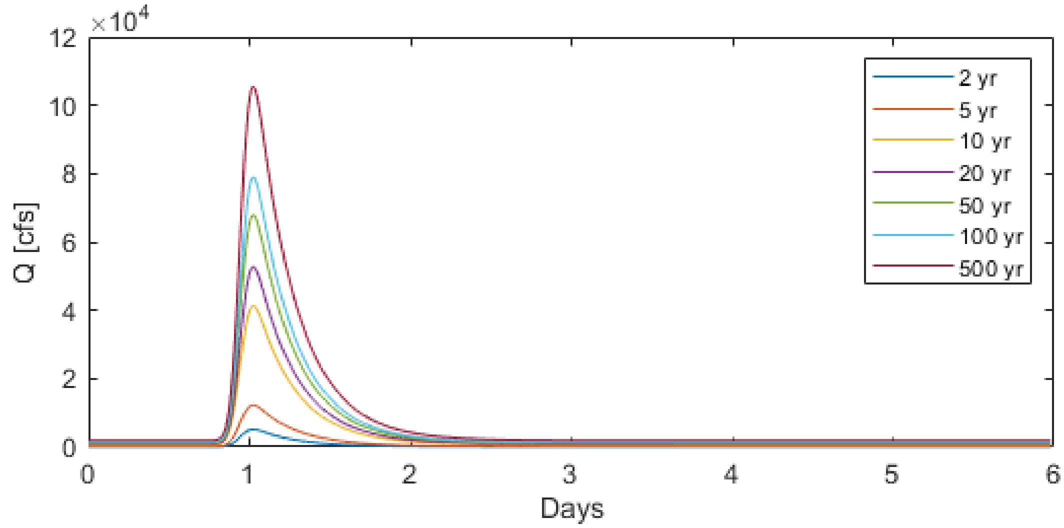

Figure 14. Modeled Return Period Event Discharge.

The offshore water level used in the analysis was specified using the same water level conditions for the dam release scenarios (Figure 8). An assumed king high tide immediately follows the peak in discharge and would lead to the worst-case conditions in terms of sediment deposition, flooding, and water quality impacts in the estuary.

The sediment loading at the upstream boundary of the estuary model was specified using the discharge curves and the rating curve coefficients for equilibrium sediment supply (no Matilija Dam) shown in Figure 5 for silt, sand, gravel, and cobble. The estuary model was developed to evaluate the potential impact of sediment deposits following dam removal within the estuary relative to current conditions. To that end, the model was developed to specifically predict the relative effect of dam removal on sedimentation and water quality in the estuary. Therefore, the model does not include a mobile estuary bed capable of scouring out during large flood events. For larger flood events (40-year return period and larger), the main channel in the estuary will be scoured and erode as was observed following the flood event in 2005. The estuary model presented here does not capture scouring of the river channel during these large flood events and is only intended to show relative effect of increased sediment loading following dam removal.

3.2.2 Results

The total sedimentation in the estuary following dam release and assuming select return period events is shown in Figure 15. The mapped regions indicate the areas that flood during each of the 2-, 10-, 50-, and 100-year return period events (the remaining sedimentation maps can be found in Appendix B).

As the return period events increase in magnitude, the sediment load and resulting sedimentation increase. The larger grain sizes become more mobile through the system as the flow rate increases. The smallest event anticipated that readily mobilizes the coarser grain material (gravel and cobble) is a 10-year return period event. The resulting grain size maps for a 10-year return period event is shown in Figure 16. This 10-year event transports substantial gravel and cobble (right panel) down to the estuary and out to the coastal ocean. The estuary model does not simulate the transport of sediment beyond the estuary mouth. Larger river flow events mobilize more large grain material, and lead to deposition of sand and silt farther into the floodplain region and adjacent habitat.

For context, the 1969 flood event that led to significant flooding, public and private property damage, and fatalities was approximately a once in 50-year flood event in Ventura. The flood event of 1992 was approximately a once in 20-year flood event that also led to significant damage and fatalities. These large flood events can cause significant damage in the Ventura area. Therefore, not surprisingly, the 50- and 100-year return period events lead to extensive flooding and sedimentation throughout the region.

An important component of this analysis was evaluating the impact of dam removal on subsequent return period events. Large return period flow events with restored sediment loading post-dam removal have been shown here (more results are included in Appendix B). While the impacts from these large events can be significant with extreme flooding and large sediment loads, these events are extreme events that will lead to significant effects to the estuary with or without dam removal.

The anticipated long-term impacts to the estuary due to restored sediment loading following dam removal (Stillwater 2019) are expected to be small. Based on analysis by Stillwater Sciences (AECOM and Stillwater 2016; Stillwater 2019), the silt, gravel, and cobble loading pre- and post-dam removal, for instance, is equivalent (see Section 2.2).[9] This is based on sediment loading estimates (for silt) and DREAM-2 model predicted gravel and cobble loading with and without the dam in place (AECOM and Stillwater 2016; Stillwater 2019). The relative increase in sand loading after dam removal relative to current conditions is a factor of 2.3 times larger, given by the coefficients specified in Table 4. Therefore, the most significant impact to the estuary associated with restored sediment loading is due to an increase in sand grain-sized particles. Deposition of sand appears to be along the main channel, in the river bridge-related scour hole and in the nearshore river delta.

[9] Due to uncertainty in the DREAM-2 model results at the estuary mouth, a 20 percent increase in gravel and cobble loading post-dam removal was simulated to evaluate model sensitivity (see Appendix B). The gravel and cobble load are still much less than the sand fraction, which generates the most significant sedimentation impacts on the estuary.

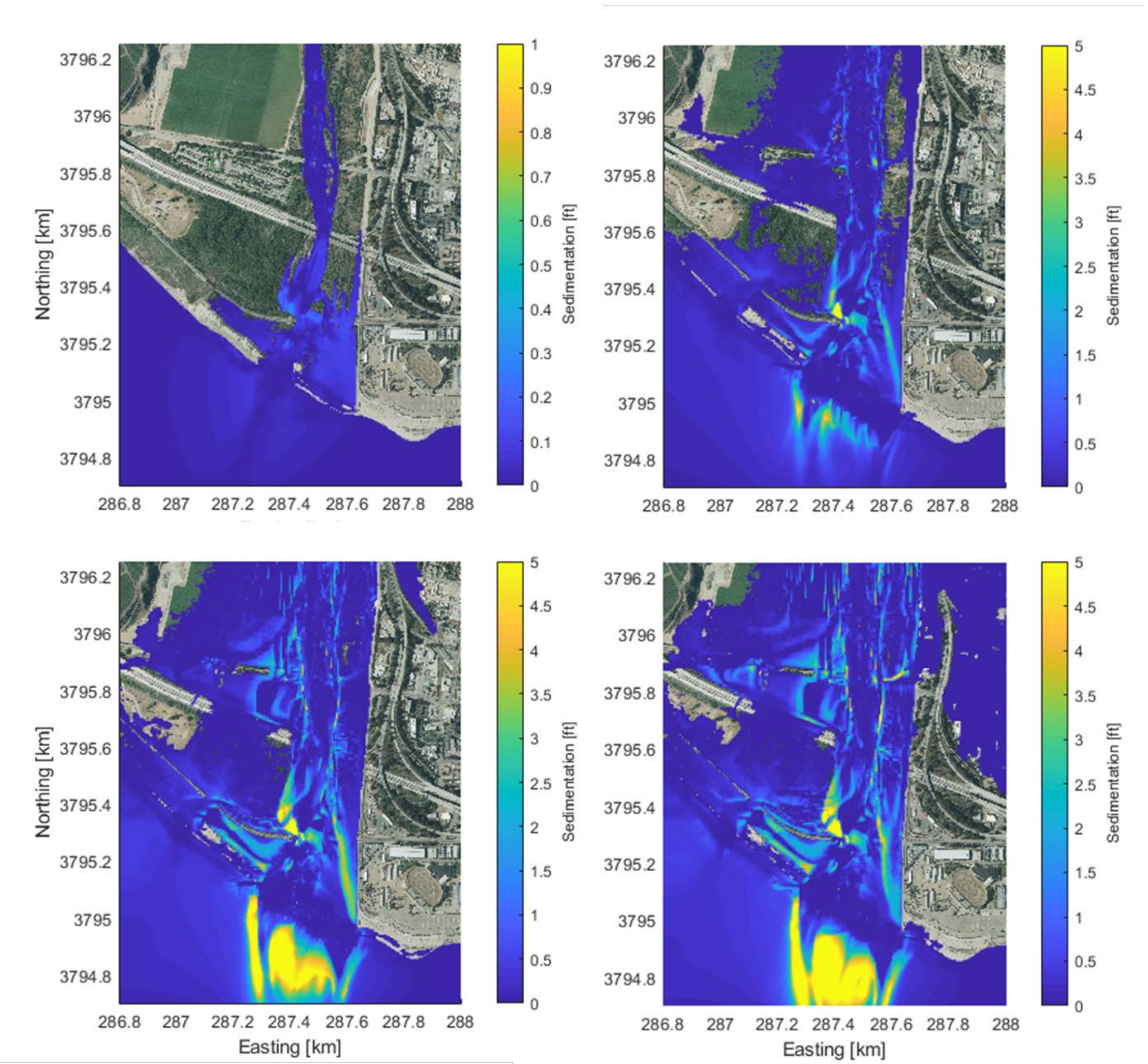

Figure 15. Sedimentation Maps of 2- (top left), 10- (top right), 50- (bottom left), and 100- (bottom right) Year Return Period Events with Restored Sediment Loading. Note the color scale in the top left panel plot differs from the remaining plots.

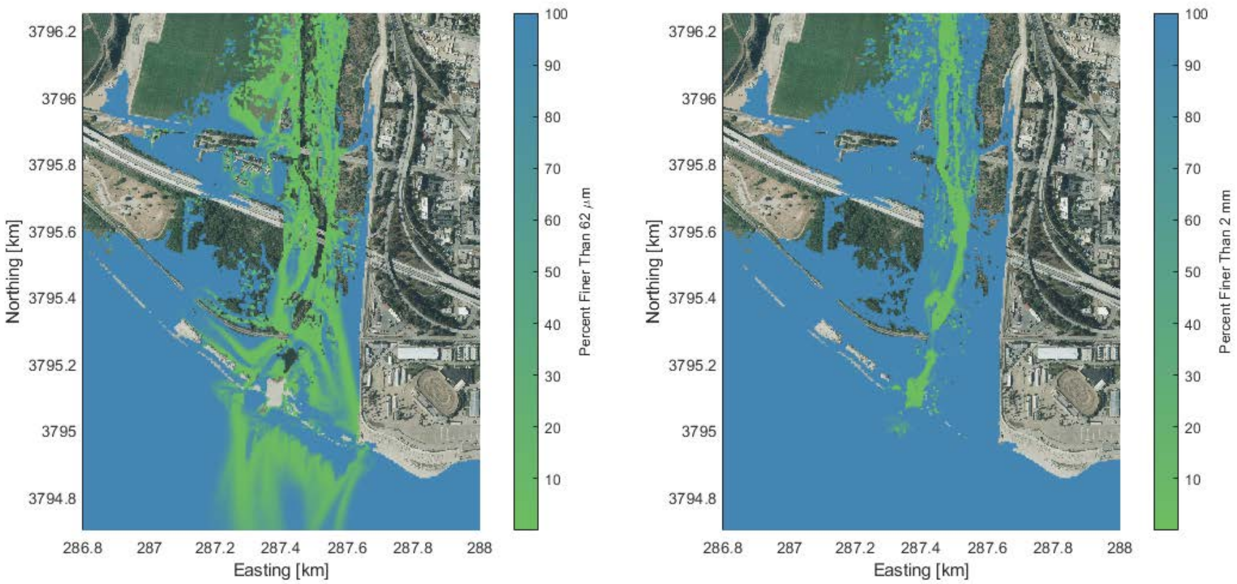

Figure 16. Percent Sedimentation Finer Than 62 µm (left panel) and Finer Than 2 mm (right panel) from the 10-Year Return Period Event.

3.3 LONG-TERM INLET CONDITIONS

While the 2-dimensional estuary model provides high-resolution results for specific flow events, the model does not resolve the inlet mouth conditions over long time scales well. Thus, an empirical inlet model, based on a mass water balance and calibrated with available data from Casitas Water District was used to project the long-term (50-year) impacts to the estuary (see Appendix A for more detail). Specifically, the model evaluated changes in the inlet breaching over time, including changes in timing, frequency, and duration of breaching, all of which may affect species and habitat within the estuary. The forcing data required for the inlet model included wave height and period, river discharge, and water level. Long-term forecast data were estimated from available data over the full simulation period. The empirical inlet model can be a useful tool to characterize dam removal and sea level rise effects on the estuary over long time scales.

The inlet model was developed following Rich and Keller (2013) and Behrens et al. (2015) using The MathWorks® MATLAB. The model is a mass balance that evaluates fluxes of water in to and out of the estuary as well as changes in the inlet elevation from fluvial erosion and wave swash, consistent with the model formulation described in Rich and Keller (2013) and Behrens et al. (2015). At each hourly time step, the volume fluxes of water in to and out of the estuary are computed, the estuary water surface elevation is updated based on the estuary hypsometry, and the inlet condition and elevation are then updated for the next time step. Volume fluxes in to and out of the estuary include river discharge, wave overtopping, groundwater, berm seepage, and inlet discharge such that the total volume change in the estuary at each time step is given by

$$\Delta V = \left(Q_{river} + Q_{overtop} + Q_{groundwater} - Q_{seep} - Q_{inlet}\right)\delta t$$

where δt is the model time step. More detailed description of the inlet model development and validation can be found in Appendix A.

3.3.1 Long-Term Model Setup

To evaluate long-term impacts, a set of inlet model scenarios was developed beginning in the 2019–2020 water year (October 1, 2019) through the 2069 water year (October 1, 2069). The scenarios were developed to evaluate the impacts of variable discharges over time, sea level rise, and changed estuary hypsometry from sediment deposition over the 50-year period.

The impact of dam release on the inlet and estuary dynamics was characterized by changes in the estuary hypsometry. The estuary hypsometry was calculated using the existing digital elevation model (DEM) (described in Appendix A) as well as using the modified elevation based on modeled sedimentation in the estuary following a dam release event. Of the three design flow events (approximately 4-year return period), Run 2d resulted in the most sediment deposition within the estuary and was used to specify the dam removal hypsometry curve. The current and dam removal estuary hypsometry curves show mild accretion in lower elevation habitats and higher accretion between 8- and 11-ft NAVD88, which corresponds to side bars and floodplain regions (Figure 17). The inlet model used the existing and modified hypsometry to evaluate the effect, if any, that dam release sedimentation may have on the estuary and inlet dynamics.

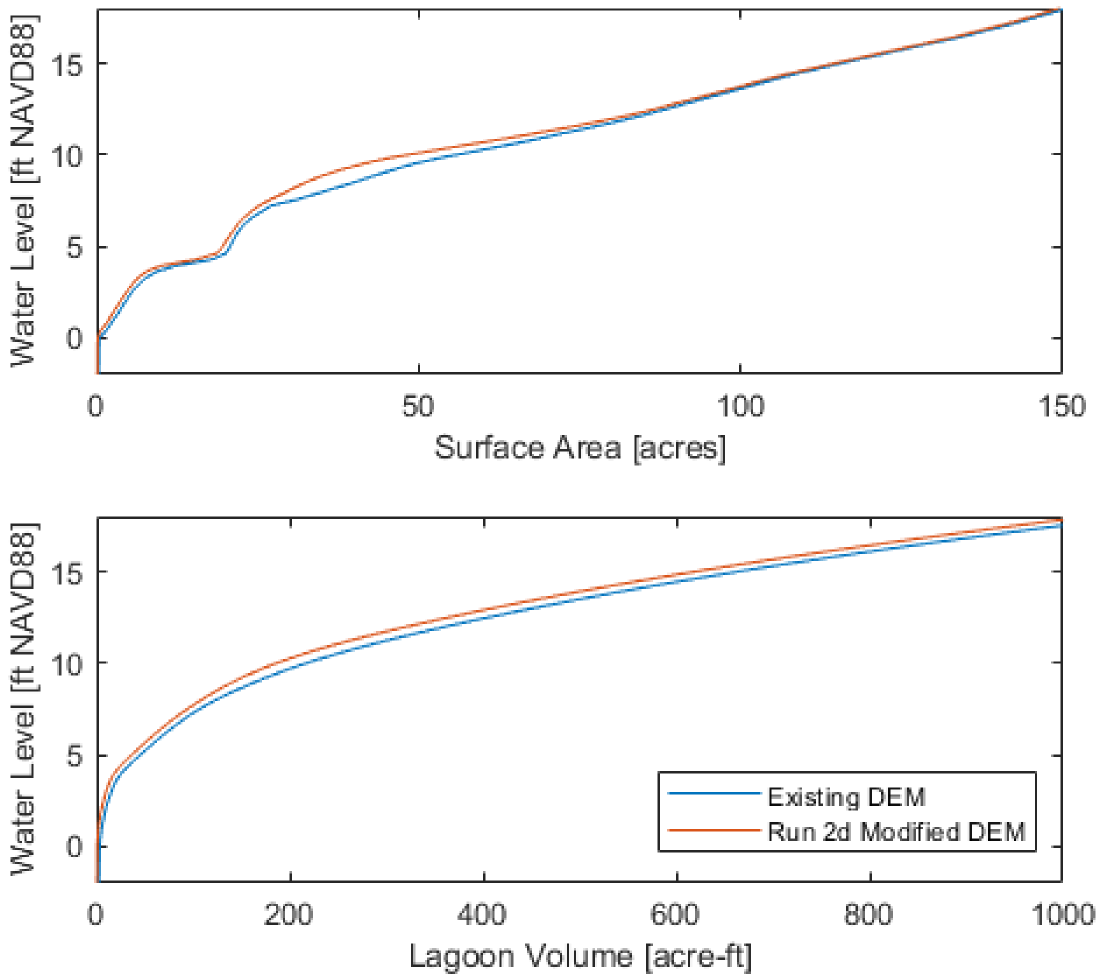

Figure 17. Estuary Hypsometry Using the Existing DEM and the Modified DEM Post-Dam Release Based on Sedimentation from Run 2d.

Four different river discharge scenarios were used to evaluate the sensitivity of the resulting breaching dynamics on the discharge time series. The 50-year forecast river discharge time series was generated using the available 30-year discharge data from the USGS gage station at Ventura (11118500).[10] The river discharge scenario A (Figure 18) was generated by concatenating the 30-year available data to generate a 50-year time series (1988–2018; 1988–1998). The largest river flow event during the 30-year record was in 1992 and represents

[10] Although daily discharge data dating back to 1929 are available, the inlet model requires higher resolution (hourly) discharge data. Therefore, the 15-minute discharge data recorded since 1988 were used in this analysis.

an approximately 20-year return period flow. A second discharge time series was developed by modifying the sequence of discharge events (Scenario B). Additional river discharge time series were developed to include a 50-year return period event (Scenarios C and D) by modifying the magnitude of the observed 20-year return period event.[11]

Table 9. Forecasted River Discharge Time Series for Inlet Model.

River Discharge Case	Dates	Largest Return Period Event
A	1988–2018; 1988–1998	20-year
B	2005–2018; 1988–2004	20-year
C	1988–2018; 1988–1998	50-year
D	2005–2018; 1988–2004	50-year

Nearshore projected wave data used in the long-term inlet model were from the USGS nearshore 21st century wave forecast. The nearshore forecast wave data from USGS are based on Representative Concentration Pathway (RCP) 4.5 climate change scenario and incorporate wave shoaling and refraction through use of a look-up table to generate nearshore wave conditions (Hegermiller et al. 2016). Forecast nearshore wave data were pulled from the closest nearshore location within 100 m of the river mouth (34.2744 ^{o}N and 119.3091 ^{o}W). The 3-hour forecast wave data were interpolated to generate hourly wave data near the estuary mouth. The nearshore forecast wave energy near the river mouth is shown over the entire inlet model period in the middle panel of Figure 18.

The forecast water level was specified using astronomic constituents for the tidal variability.[12] The tidal constituents at Santa Barbara were used to approximate projected water level. While a tsunami water level station exists in Ventura Harbor (Station 9411166), this gage station has never been surveyed to an elevation and thus was unable to be used to specify local water levels. However, the tidal range and tidal constituent amplitude between Ventura Harbor and Santa Barbara gage stations were compared and are nearly equivalent with a slight phase shift. Therefore, the Santa Barbara tidal constituents were used to specify forecast tidal forcing (bottom panel of Figure 18). The water level was then modified by a long-term average increase due to sea level rise (low, intermediate-high, and extreme scenarios from Sweet et al. (2017). These predictions of sea level rise (shown in Section 2.1.3) correspond to 1.28, 3.18, and 5.35 ft of

[11] River discharge conditions for the inlet model were developed using the record of observed discharge. However, additional analysis could be conducted to develop forecast discharge records based on regional precipitation estimates that incorporate climate change effects.
[12] Water level forecast estimates based on astronomical tides do not include meteorological effects or storm surge.

sea level rise by 2070 (Sweet et al. 2017).[13] The mean ocean water levels for the three sea level rise scenarios are shown in Figure 18. The full list of inlet scenarios is in Table 10.

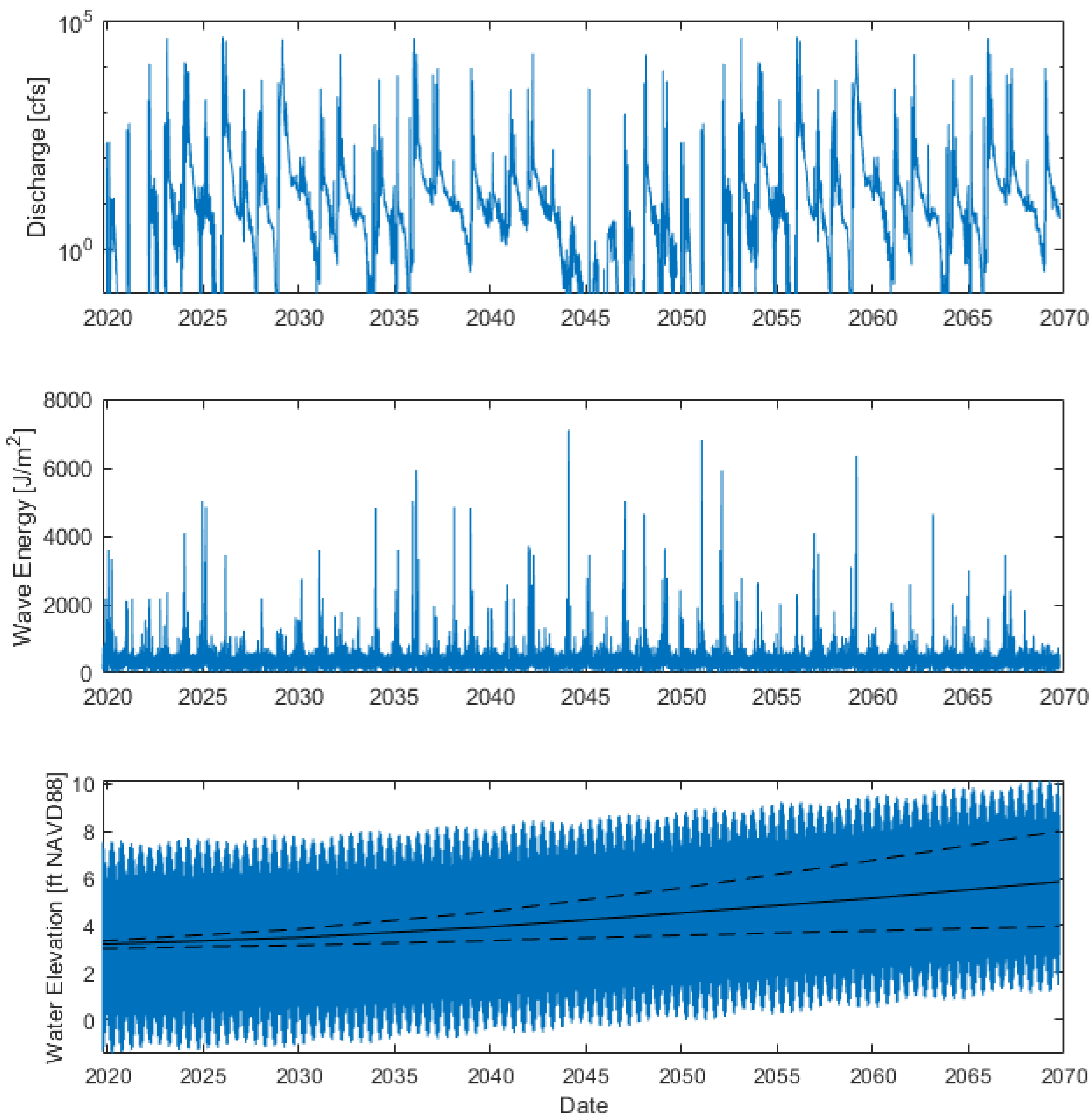

Figure 18. Forecast River Discharge Case A (top panel), Nearshore Wave Energy (middle panel), and Ocean Water Level Forcing (bottom panel) with Intermediate-High Sea Level Rise. The black lines in the bottom panel indicate the mean ocean water level over the three sea level rise scenarios used.

[13] https://coast.noaa.gov/slr/#/layer/slr

Table 10. Inlet Model Scenarios.

Run	Estuary Hypsometry	Sea Level Rise Projection	River Discharge Case
1	Existing	None	A
2	Run 2d Dam Removal	None	A
3	Existing	Low	A
4	Run 2d Dam Removal	Low	A
5	Existing	Intermediate-High	A
6	Run 2d Dam Removal	Intermediate-High	A
7	Existing	Extreme	A
8	Run 2d Dam Removal	Extreme	A
9	Run 2d Dam Removal	Intermediate-High	A
10	Run 2d Dam Removal	Intermediate-High	B
11	Run 2d Dam Removal	Intermediate-High	C
12	Run 2d Dam Removal	Intermediate-High	D

3.3.2 Inlet Model Results

The inlet model was used to evaluate the effect of the dam removal and sea level rise on inlet conditions and breaching dynamics (Figure 19). As described above, the small bar-built estuary is dynamic and a critical habitat to many species. Like the prior estuary modeling and characterization of sediment loading with and without the dam in place, the primary change to the estuary system following dam removal was characterized by changes in the estuary hypsometry. The estuary hypsometry remains constant throughout the inlet model simulation; however, in reality, the estuary hypsometry will continue to change with subsequent flow events. The relative difference between predicted inlet conditions with the existing and post-dam removal estuary hypsometry was used to characterize the dam removal effects on the conditions in the estuary. The model assumption of constant channel hypsometry likely overestimates the long-term effects of sedimentation on inlet dynamics because erosion during subsequent flood events will restore the hypsometry over time.

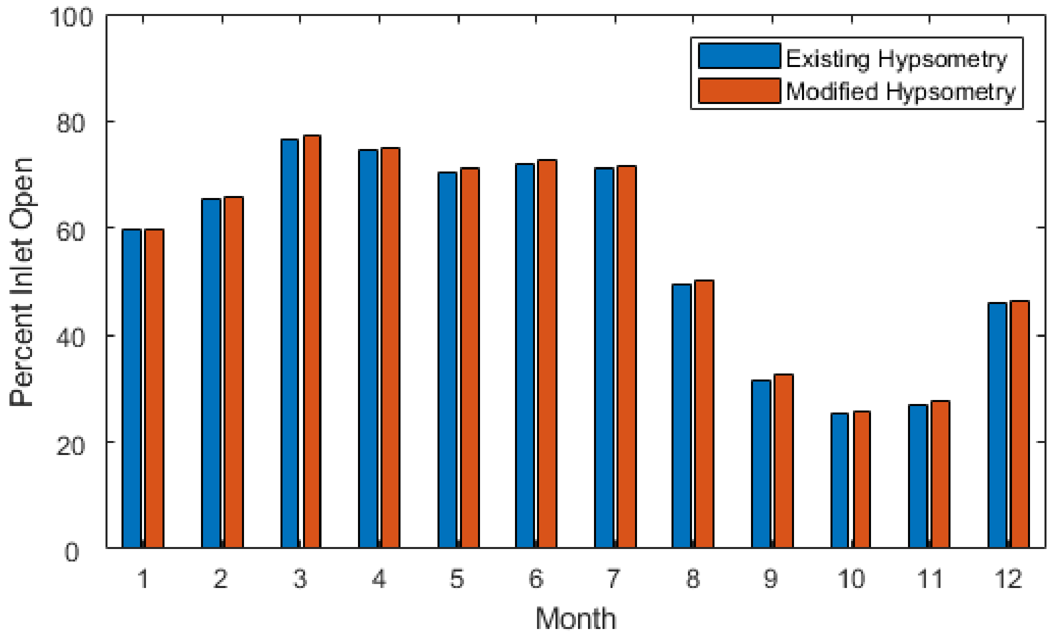

Figure 19. Percent Inlet Opening by Month of the Year with Existing and Modified Post-dam Removal Estuary Hypsometry with No Sea Level Rise.

A small bar-built estuary, such as the Ventura River estuary, is characterized by seasonal and tidal variability in the observed water level. The percent water level exceedance over the forecast 50-year period is shown in Figure 20 for the sea level rise scenarios (none, low, intermediate-high, and extreme) using both the existing estuary hypsometry (from existing DEM) as well as the modified estuary hypsometry (based on dam release sedimentation following Run 2d).

Consistent with the inlet conditions shown in Figure 19, the primary driver of change within the estuary system is due to rising sea level affecting the elevation of the berm crest. In contrast, the difference between existing and modified estuary hypsometry due to dam release (shown by the solid and dashed lines, respectively in Figure 20) is much less significant. The 2-dimensional estuary modeling further suggests that the changes in hypsometry due to dam release sedimentation are likely to be eroded over subsequent events following the dam release. Therefore, the changes to the inlet dynamics over the next 50 years due to dam removal are expected to be insignificant.

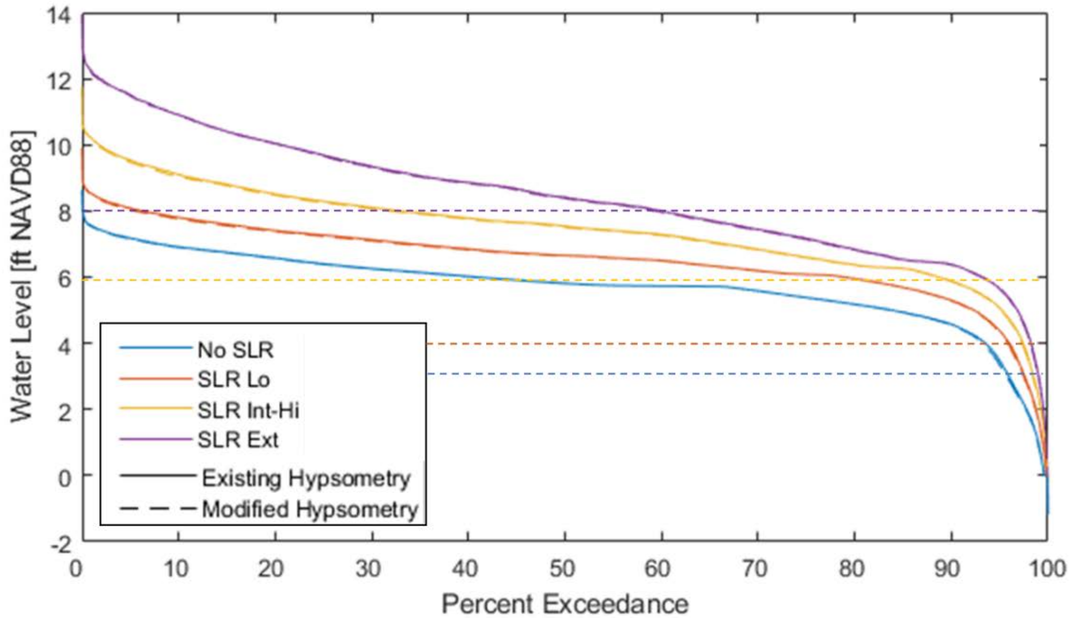

Figure 20. Forecast Percent Water Level Exceedance with Three Sea Level Rise Scenarios and with Existing (solid lines) and Modified Hypsometry (dashed lines). Mean ocean water level in 2070 for the four sea level rise (no, low, intermediate-high, and extreme) scenarios are indicated by the dashed lines.

The inlet model is an empirical model and able to highlight relative changes in breaching conditions. However, there are limitations of this model and uncertainty around predicted dynamics partially based on the temporal limitations of the calibrating data set from Casitas Water District. For example, the inlet model scenarios assume that wave swash and inlet buildup from ocean forcing will remain the same over time. In reality, the limited availability of sediment within the Santa Barbara littoral cell may mean that the inlet elevation and berm crest elevation is unable to keep pace with sea level rise. Therefore, it is possible that the inlet conditions over the sea level rise scenarios may underpredict the more predominantly open condition than predicted by the empirical inlet model.

3.4 HABITAT IMPLICATIONS

Results from the estuary and inlet modeling were used to evaluate sediment deposition from dam release and subsequent removal to provide information for potential stressors on species and habitat within the estuary using the worst-case dam release scenario Run 2d (the approximately 4-year event resulting in the most sediment deposition in the estuary). The contours showing the magnitudes of deposition are overlaid onto the highest resolution habitat data, a digitized 1990 habitat map (Ferren et al. 1990; Figure 21) as well as a current aerial photo

(Figure 22). Habitats mapped in 1990 show potential impacts from sedimentation to river channels, flats and bars, nonpersistent emergent wetland, riverbed and dune swale, exposed riverbed and bar, exposed riverbed forest, dune swale and saltbrush wetlands, southern coastal dunes, floodplain mixed shrub and grassland, *Scirpus californicus*, *Typha domingensis*, and *Arundo donax*.

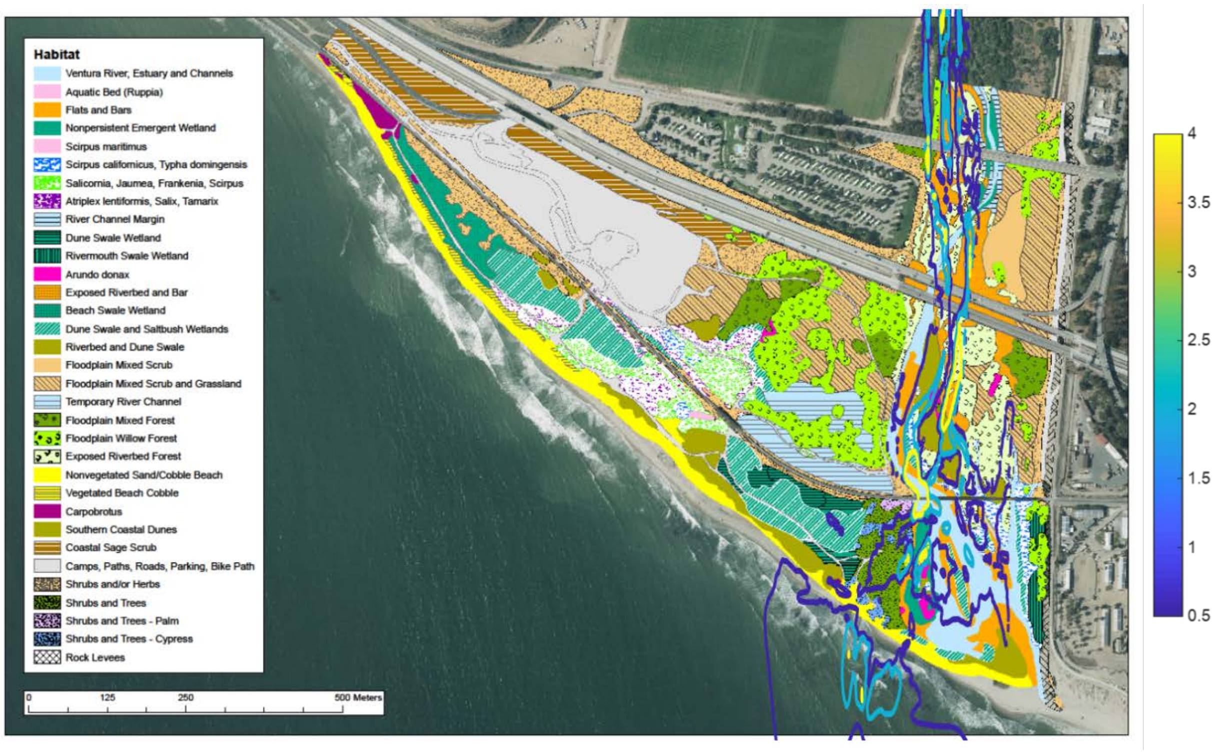

Figure 21. Contours of Sedimentation from Run 2d Overlaid onto Digitized Habitat Map from Ferren et al. (1990).

However, the main river channel and adjacent sand bars have changed since the habitat survey conducted by Ferren et al. (1990) and may be better represented in a more recent (2018) aerial photo (Figure 21). In the aerial photo, the sedimentation occurs largely within the river channels and adjacent to the exposed riverbed and sand bars. This may potentially affect juvenile steelhead that prefer deeper water habitats with overhanging cover.

Sedimentation is also observed in regions with mixed floodplain shrubs and grasses. While the sedimentation associated with a large dam release can be significant, sedimentation is largely constrained to the areas within and near the existing river channel. From subsequent flood event modeling, portions of the deposited sediment will be transported out of the estuary. However, some of these sediment deposits may persist within the system for a number of years depending on the subsequent frequency of larger river flushing events (e.g., 10-year event).

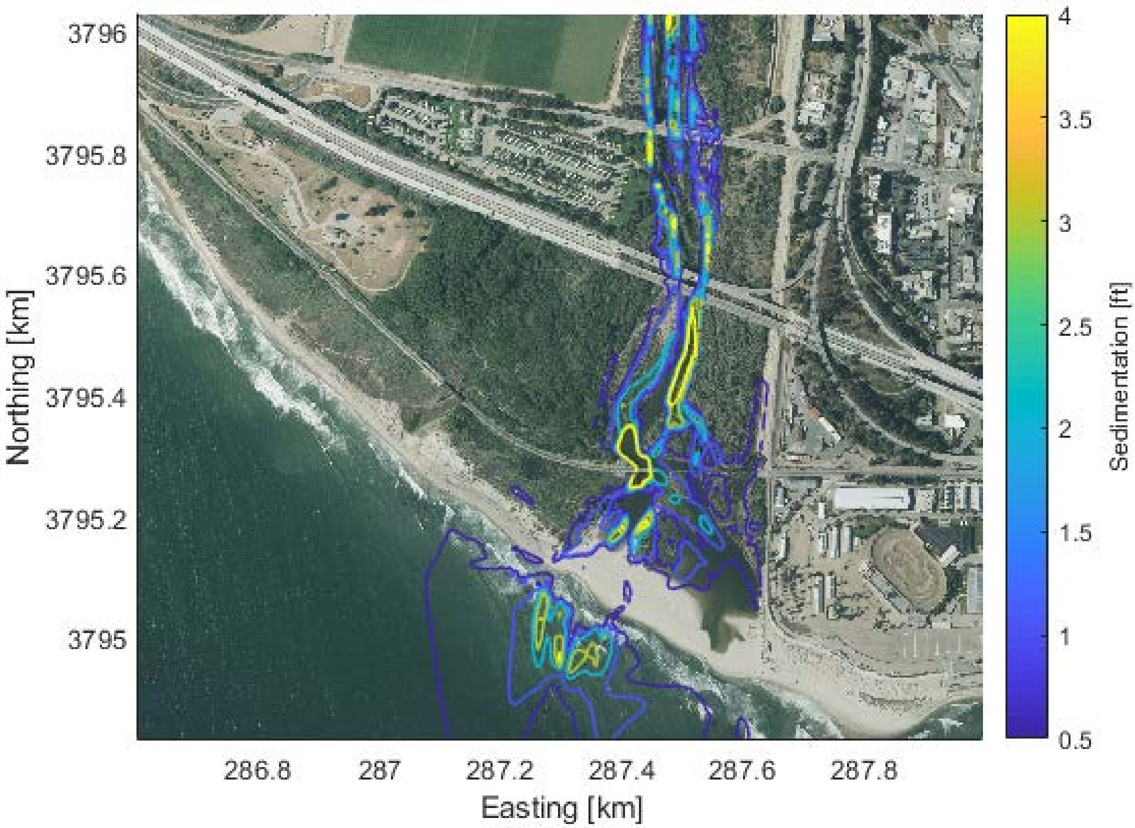

Figure 22. Contours of Sedimentation from Run 2d Overlaid onto Current Aerial Photo of the Estuary.

The sedimentation maps and the impact on habitat throughout this analysis are based on Run 2d, the design event scenario that resulted in the largest trapping efficiency of sediment in the estuary during a king high tide. It is important to acknowledge that larger flood events (greater than a 4-year return period) result in a larger magnitude of deposition in the floodplain regions outside of the main river channel. As the dam removal event increases in magnitude, larger areas of the floodplain will be engaged (including areas such as the RV park and agricultural field). Due to the increase in sediment load associated with dam release, any regions of the floodplain that are engaged will experience deposition of fine (predominantly silt) sediment during a dam removal event. Therefore, the impact to the estuary and nearby habitat (as well as the RV park and agricultural field) may increase as the magnitude of flood event increases.

The dynamics of the inlet over tidal, seasonal, and decadal time scales was evaluated using the inlet model. The frequency, duration, and timing of inlet breaching is an important indicator for species within the estuary system that rely on the episodic opening and closure of the estuary. As described above, the impact to inlet conditions due to the dam release are small in comparison to changes associated with sea level rise. Small increase in sea level rise lead to significant changes in estuary habitat. For instance, the percent exceedance curve shown in Figure 20 has been converted from water level elevation to estuary area that will be submerged (Figure 23). Under current conditions, 200 acres of estuary habitat are submerged only less than 5 percent of the time. For the three sea level rise scenarios, this same region of the estuary will be inundated between 30 and 75 percent of the time. This represents a significant change to the type of species and vegetation that are able to exist within that same region of the estuary as sea level rise increases.

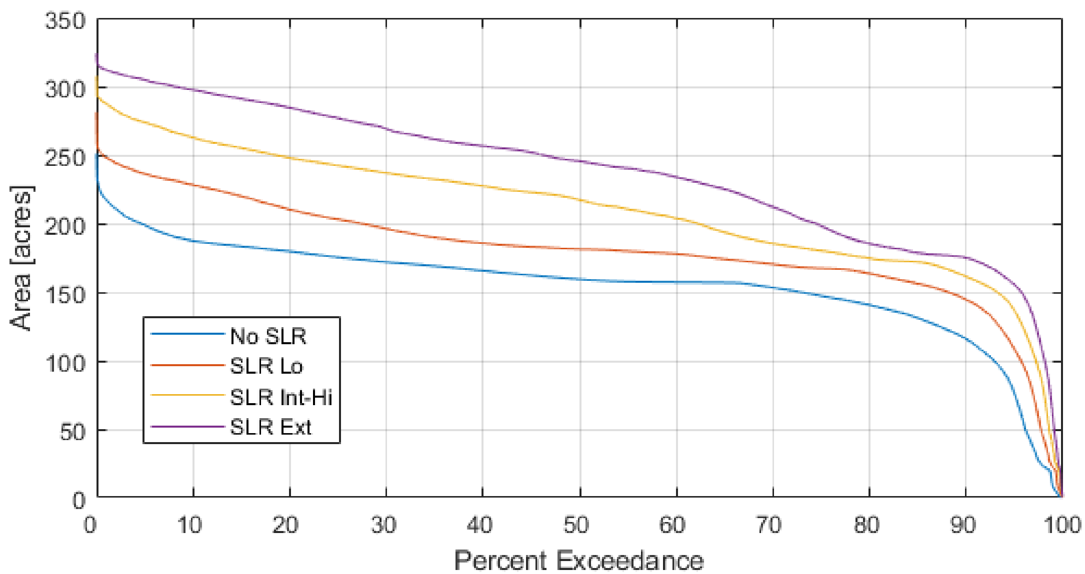

Figure 23. Percent of Time That Areas of Estuary Habitat Are Submerged under Various Sea Level Rise Scenarios.

Higher estuary levels may increase habitat for goby and steelhead compared to existing conditions (e.g., more inundated habitat), assuming the estuary geometry (i.e., bed elevations) remains static over time in response to sea level rise. However, there may be other adverse effects associated with rising sea level including an increase in estuary salinity and longer duration of open inlet conditions. The empirical inlet model is unable to predict estuary salinity or stratification; however, an increase in estuary stratification (low saline water over higher marine salinity) could have a negative effect on water quality for steelhead. Increased connectivity to regions upstream of the estuary due to higher water levels may reduce any potential negative effect of estuary stratification. This would allow steelhead to move upstream and out of the estuary when water quality conditions are poor. Temperature increases within the estuary can also have negative impacts on the steelhead that are not resolved by the inlet model. Finally, while wave driven sedimentation on the berm is incorporated into the inlet model, sea level rise may allow wave-driven sedimentation within lower elevation regions of the estuary, potentially modifying the estuary hypsometry. The effect of aggradation of lower estuary elevations in response to sea level rise may reduce storage within the estuary and further move the estuary to higher elevations.

4 COASTAL OCEAN

Once sediment reaches the coastal ocean, sediment transport is largely controlled by waves, coastal currents, and tides. The physical processes driving sediment transport in the coastal ocean were simulated using two distinct models: a high fidelity hydrodynamic and wave coupled coastal model (Delft3D/SWAN) as well as a long-term shoreline change model (USGS CoSMoS-COAST [Vitousek et al. 2017]). The Delft3D/SWAN coastal model was used to simulate short-term event transport of sorted grain sizes (silt, sand, gravel, and cobble)[14] associated with large river releases (Section 3). In contrast, the long-term shoreline change model approximates complex wave and hydrodynamics to project long-term (50-year) changes in shoreline position related to both changes in sediment loading and sea level rise. The long-term model is informed by the high-fidelity, short-term modeling and incorporates long-term sea level rise. Both the Delft3D/SWAN and COAST models were used to evaluate the relative impact of dam removal and increased sediment loads on the dynamics within the coastal ocean and along the Ventura shoreline. Therefore, these models were not intended to resolve all sediment transport processes within the coastal ocean, which would require more extensive data characterization and model validation. The qualitatively validated coastal ocean models were instead used to evaluate the relative effect of dam removal on shoreline position by comparing scenarios with and without dam removal.

4.1 SHORT-TERM DAM REMOVAL COASTAL MODELING SCENARIOS

The effect of dam removal and sediment release scenarios on the coastal ocean were evaluated with the coupled Delft3D/SWAN model. The coastal ocean model extends from Emma Wood State Beach in the north to beyond Ventura Harbor in the south, with an offshore extent of approximately 4 km (Figure 25). Bathymetry over the model domain ranges from approximately 0 to 32 m water depth. The curvilinear, 2-dimensional Delft3D/SWAN model grid has varied resolution to resolve small-scale processes near the Ventura River mouth and in the nearshore region (Figure 26).

[14] The sediment grain size used throughout this analysis for dam removal scenarios are 0.03, 0.2, 16, and 100 mm for silt, sand, gravel, and cobble, respectively.

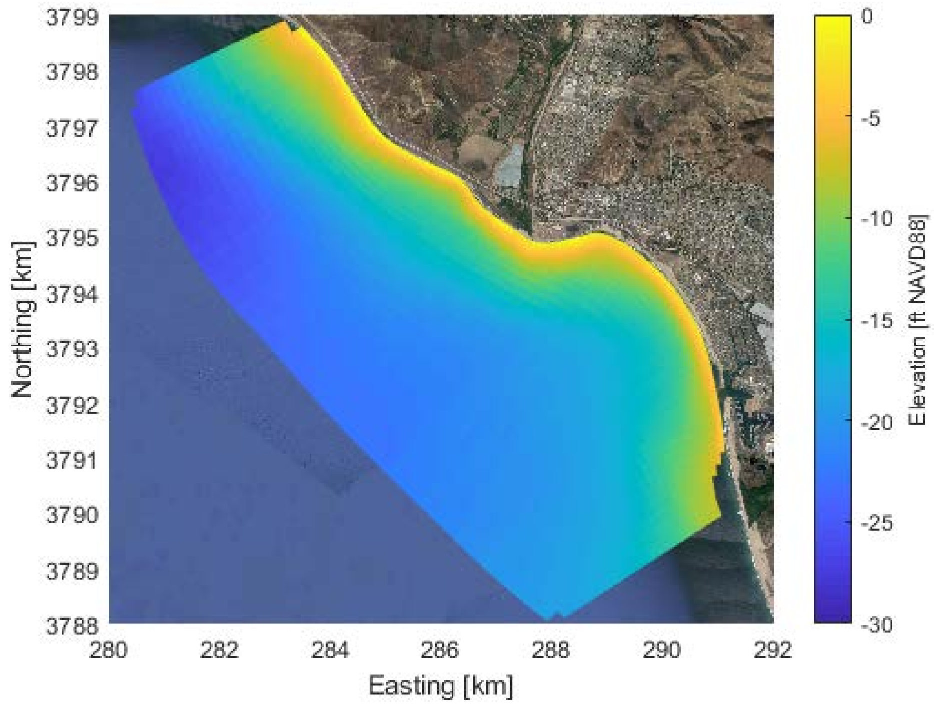

Figure 24. Overview of the Coastal Ocean Model Domain and Bathymetry.

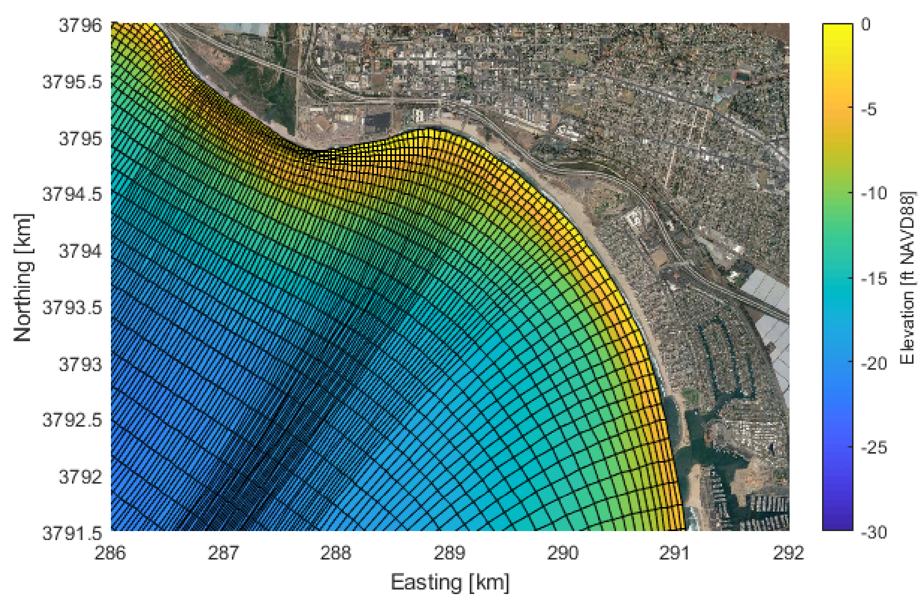

Figure 25. Zoomed in View of Coastal Model Bathymetry and Grid.

The coastal ocean model was validated using an observed wave event in January 2019. The Delft3D/SWAN model simulated the 48-hour January 2019 storm event. The period of peak river discharge coincided with small offshore wave heights (~ 1 m). As a result, the offshore currents were quite low, and provided a near worst-case scenario of large sediment deposition near the mouth. However, even with low wave conditions, there were longshore current velocities in excess of 1 m/s near the river mouth breach as seen in Figure 27. The nearshore transport runs alongshore to the east and south even during these conditions of low waves. Figure 28 shows suspended silt and sand concentrations in the water column during the peak discharge. The sand grain size for the validation case was set to 0.35 mm because the offshore sediment bed largely comprises medium to coarse sand.[15] Consistent with the modeling of alongshore currents and anecdotal observations from local expert reviewers, a high concentration plume of silts was transported to the south along the coast. The heavier sand particles (0.35 mm) are transported predominantly near the coast and are not transported as far as the silt particles. Overall the discharge plume transport is consistent with the observations in the area.

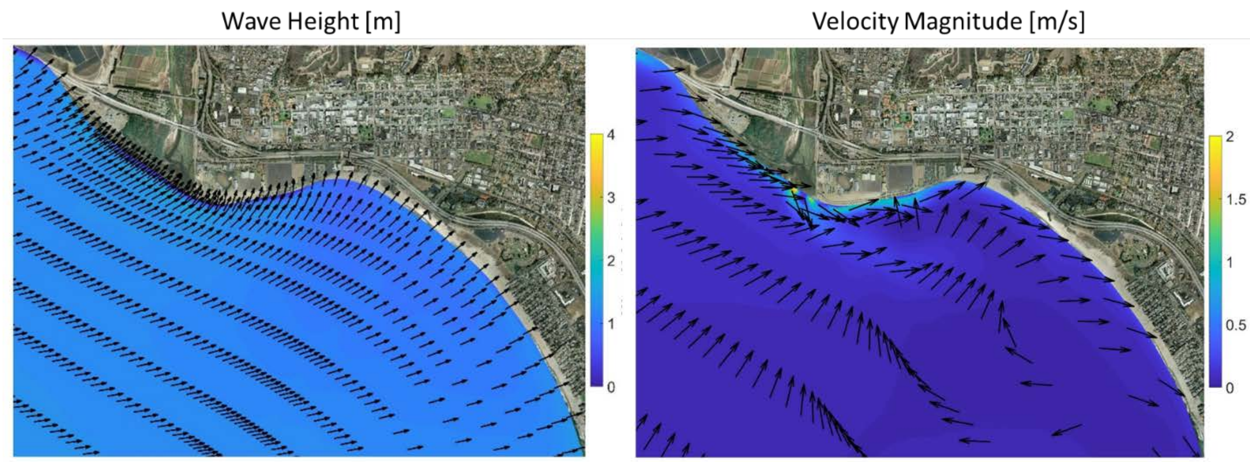

Figure 26. Wave Height and Direction (left) and Offshore Velocity and Direction (right) at 12:00 a.m. on January 17, 2019.

[15] The sand grain size used for the dam removal scenarios was 0.2 mm and was based on sediment observations in the reservoir and estuary. A value of 0.35 mm was used for model validation to qualitatively evaluate littoral transport due to wave events.

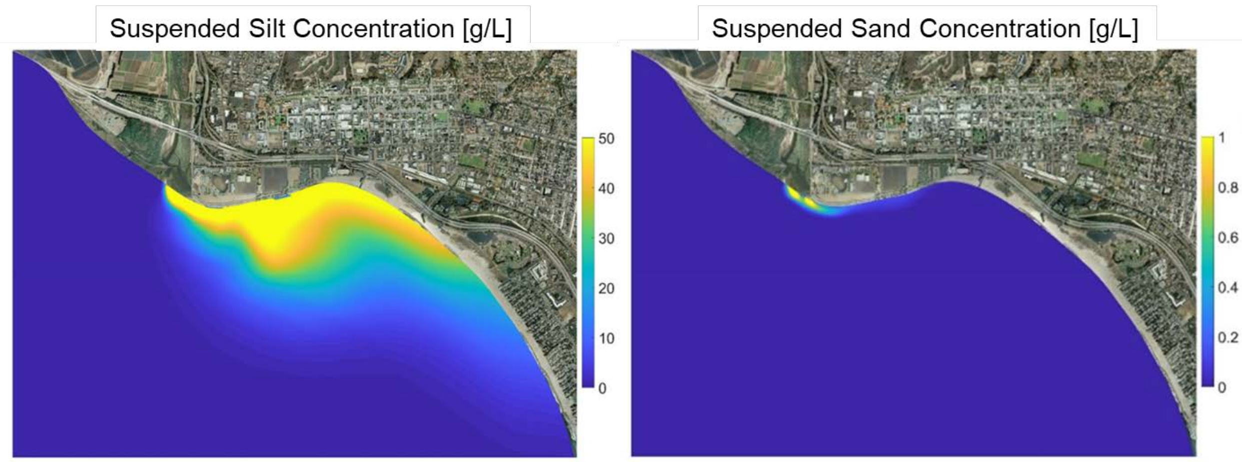

Figure 27. Suspended Silt (left) and Sand (right) Concentrations at 12:00 p.m. on January 17, 2019.

During the calibrating wave event, maximum offshore wave heights were approximately 4 m and occurred on January 18, after the peak discharge. Large waves during the simulation generated significant longshore transport in the nearshore (Figure 29). Velocities exceeding 1 m/s in the nearshore were consistent with anecdotal observations of local experts experienced during large wave events. The sediment plumes associated with peak discharge were transported alongshore and out of the region by the time the wave heights increase. Figure 30 shows the sediment mass deposited by the end of the event. The deposit was primarily sand from the river mouth and deposited around the point where the wave heights and velocities decreased during the event. Overall, the modeled waves, currents, and sediment transport reproduced observed trends in the region giving confidence that the Delft3D/SWAN modeling performed adequately for future projections in the study. Future improvements to the model based on additional observations and current velocity measurements can be made to increase model confidence and reduce uncertainty. Additional details on the Delft3D/SWAN coastal model development and validation can be found in Appendix A.

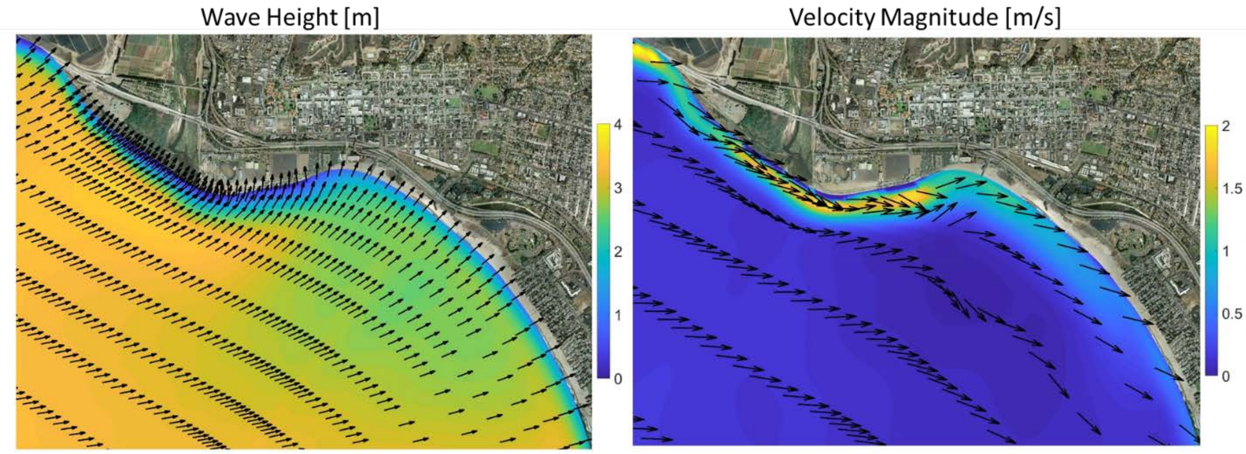

Figure 28. Wave Height and Direction (left) and Offshore Velocity and Direction (right) at 12:00 a.m. on January 19, 2019.

Figure 29. Sediment Mass Deposited from the River at 12:00 a.m. on January 19, 2019.

4.1.1 Coastal Model Scenarios

The transport of sediment from the Ventura River estuary within the coastal ocean is governed by multiple simultaneous processes including the river discharge relative to tidal and wave conditions offshore. A set of coastal scenarios was selected to bound the range of expected conditions and system response based on input from local experts who helped identify scenarios responsible for the majority of regional conditions. To that end, the maximum and minimum sediment loadings to the coastal ocean (from the estuary modeling) over the five dam release scenarios were selected. These corresponded to Run 2b (maximum coastal sediment loading) and Run 2e (minimum coastal sediment loading) from the Stillwater Sciences dam release scenarios described in Table 6. The sediment loading to the coastal ocean during a dam removal was based on results from the estuary modeling (see Section 2.2.1) and incorporated trapping of sediment within the estuary. The river discharge and sediment loading time series over the event were simulated in the Delft3D/SWAN model near the river mouth. Because 100 percent of the gravel and cobble loading to the estuary remained upstream of the river mouth during the course of the short-term dam removal scenarios and because the gravel and cobble loading were not expected to change pre- and post-dam removal, the coastal ocean simulations focused mainly on silt and sand transport.

Offshore water level was forced using tidal data from the Santa Barbara gage station. Wind speed and direction in each of the scenarios were taken from the East Santa Barbara Channel Coastal Data Information Program buoy over the same time period as the wave conditions. In general, wind forcing did not significantly alter transport conditions within the coastal model as determined through model development and testing (described in Appendix A).

Large discharge events most often occur during winter months and this typically coincides with larger offshore wave conditions relative to summer months. The Integral team evaluated discharge from the Ventura River to examine correlations between observed river discharge and offshore coastal ocean conditions. The USGS daily streamflow data were screened to extract annual maximum daily average discharge observations greater than or equal to a 2-year event (estimated to be approximately 1,278 cfs for daily average [AECOM and Stillwater 2016]). Coincident wave measurements occurring during a 36-hour window of each annual discharge event were also extracted to compare for potential correlation between discharge and various wave parameters (significant wave height, peak wave period, and peak wave direction). The subsections below describe the comparison findings for each of the offshore wave stations.

To select an appropriate range of wave conditions experienced throughout the year near the mouth of the Ventura River, a wave characterization evaluation was performed. Due to its closer proximity to the study site, NOAA buoy #46217 (Anacapa Passage) was selected for evaluation. The complete time series of wave measurements were binned by wave direction and period for each season to indicate the frequency of occurrence, average significant wave height, and maximum significant wave height within each bin. The results of the evaluation for each season are summarized below.

Winter (December–February): Waves consistently (85 percent frequency) approach out of the west at 9 to 15 seconds with an average significant wave height of approximately 4 ft (1.2 m). The largest winter storm waves also approach from the west at 9 to 15 seconds with an average peak significant wave height of approximately 14.5 ft (4.4 m). During the winter season, there is the largest difference between storm event waves and average wave conditions, indicating that during this time period storm waves can substantially increase transport relative to average wave conditions.

Spring (March–May): The spring wave climatology is similar to the winter with a shorter wave period. Waves consistently (71 percent frequency) approach out of the west at 9 to 13 seconds with an average significant wave height of 4 ft (1.2 m). The largest spring storm waves also approach from the west at 7 to 15 seconds with an average peak significant wave height of 13 ft (4 m).

Summer (June–August): There is more variability in the summer wave climatology, but waves tend to approach from the west (55 percent frequency) and south (24 percent frequency). Waves approaching from the west tend to have a peak period of 5 to 11 seconds (shorter period than winter) with approximately 3.3 ft (1 m) average significant wave height. Waves approaching from the south have longer periods of 13 to 17 seconds and slightly smaller average significant wave heights of 2.5 ft (0.75 m). Similarly, waves approaching from the west have larger peak significant wave heights of 9.5 ft (2.9 m) on average while waves approaching from the south tend to have peak significant wave heights of approximately 6 ft (1.8 m) on average.

Fall (September–November): Similar to summer, the fall wave climatology is associated with more variability than winter and spring. Waves tend to approach from the west (65 percent frequency) and south (10 percent frequency). The wave period from both dominant directions is 9 to 15 seconds, but average significant wave heights approaching from the west are 1.1 m while waves approaching from the south tend to be somewhat smaller with the average significant wave height being 0.7 m. The largest fall storm waves approach from the west with a 7 to 15 second wave period and peak significant wave height of approximately 3.6 m on average.

Based on the wave climatology findings, the following five wave conditions were identified to be used as representative wave conditions for the model input boundary:

- Large Winter Storm: 4.0–4.5 m wave height, 13–17 second period, west direction
- Average Winter/Spring: ~1.0–1.5 m wave height , 13–17 second period, west direction
- Average Summer/Fall (West Swell): 1.0 m wave height , 5–13 second period, west direction
- Average Summer/Fall (South Swell): 0.75 m wave height, 13–17 second period, south direction
- Strong Summer/Fall (South Swell): 1.0–2.0 m wave height, 13–17 second period, south direction (potential for long period swells of 19 seconds or longer).

For each condition listed above, the wave data from NOAA buoy #46217 (Anacapa Passage) were queried to find a period of time in the record that roughly matched each condition.

The "Large Winter Storm" event condition was selected based on the peak of the storm. The data window was expanded to include the 2 days prior to the event and 7 days after the event to extract a 10-day time series of wave data. The storm event was placed near the start of the time series to allow suspended sediment time to disperse and settle from the water column. All other wave conditions were selected based on an average of each wave parameter over the full 10-day time series. An example of the large winter storm and average winter/spring conditions is shown in (Figure 31). These scenarios are the mostly likely conditions to occur during a large dam release event because they characterize typical winter conditions when large flood events are expected. The large winter storm event is comparable to the observed offshore wave conditions during the large discharge event in January 2019. This event was used as the validation event for the coastal model and is described in more detail in Appendix A.

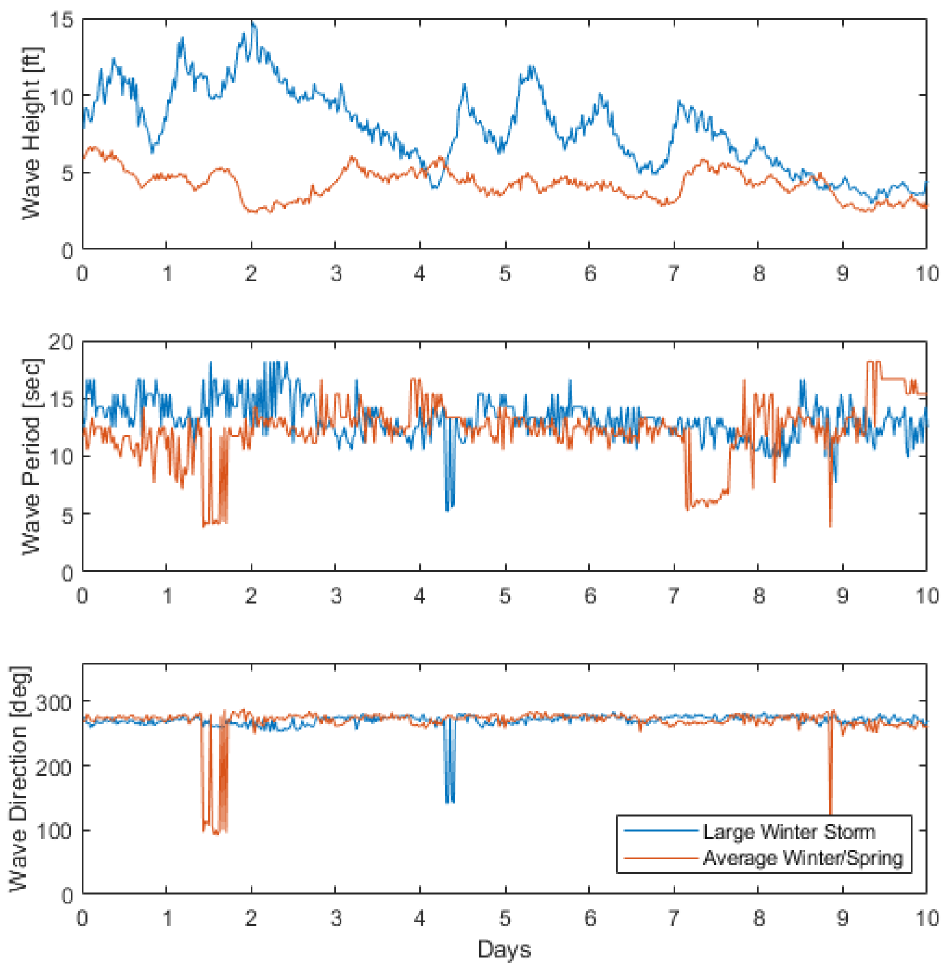

Figure 30. Wave Conditions from the Large Winter Storm (December 15–25, 2002) and Average Winter/Spring Conditions (February 1–11, 2011).

The dam removal coastal model scenarios are shown in Table 11. While the scenarios do not encompass every potential coastal ocean scenario, they do provide a wide range of the key wave conditions driving sediment transport in the nearshore coastal ocean during a dam removal sediment release.

Table 11. Matilija Dam Removal Coastal Sediment Release Scenarios.

Run	Discharge	Waves
1	Maximum Sediment Release Loading	Large Winter Storm
2	Maximum Sediment Release Loading	Average Winter/Spring
3	Maximum Sediment Release Loading	Summer/Fall Storm
4	Maximum Sediment Release Loading	Average Summer/Fall (south)
5	Maximum Sediment Release Loading	Average Summer/Fall (west)
6	Minimum Sediment Release Loading	Large Winter Storm
7	Minimum Sediment Release Loading	Average Winter/Spring
8	Minimum Sediment Release Loading	Summer/Fall Storm
9	Minimum Sediment Release Loading	Average Summer/Fall (south)
10	Minimum Sediment Release Loading	Average Summer/Fall (west)

4.1.2 Delft3D/SWAN Model Results

The coastal model results indicate that the majority of silt particles move offshore and do not deposit within the nearshore model domain over the 6-day simulation period. During the winter storm events and average winter and spring conditions (most likely conditions for a large discharge event), less than 3 percent of silt is deposited within the coastal model domain. The behavior is consistent with knowledge of coastal transport from local experts and the lack of silt observed in the nearshore. More silt deposition was observed during the average summer/fall wave conditions, but predominantly occurred in deeper regions further offshore. While silt particles make up the majority of the total sediment released during dam removal, these small-grained particles have negligible impact on the nearshore estuary and coastal region of interest and are readily transported offshore.

Most of the sediment particles deposited in the nearshore region across all scenarios were sand grain size particles. The amount of sand that remained in the nearshore area depended on the coastal wave conditions. Because the sand grain size was 0.2 mm, moderate wave conditions were able to move these fine sands offshore. Over the range of wave conditions and sediment release scenarios, approximately 55 to 89 percent of sand deposited in the nearshore region with the remaining sand moving offshore.

As expected, the patterns of sedimentation within the coastal ocean are heavily dependent on wave conditions. For instance, sediment is transported downcoast during the large winter storm events (Figure 32). In contrast, during milder wave conditions, the discharge pulse (18,000 cfs) dominates the flow patterns near the estuary mouth and forces sediment offshore. The deposition following the maximum dam release sediment scenario with both average winter and spring conditions results in more deposition near the river mouth (Figure 33).

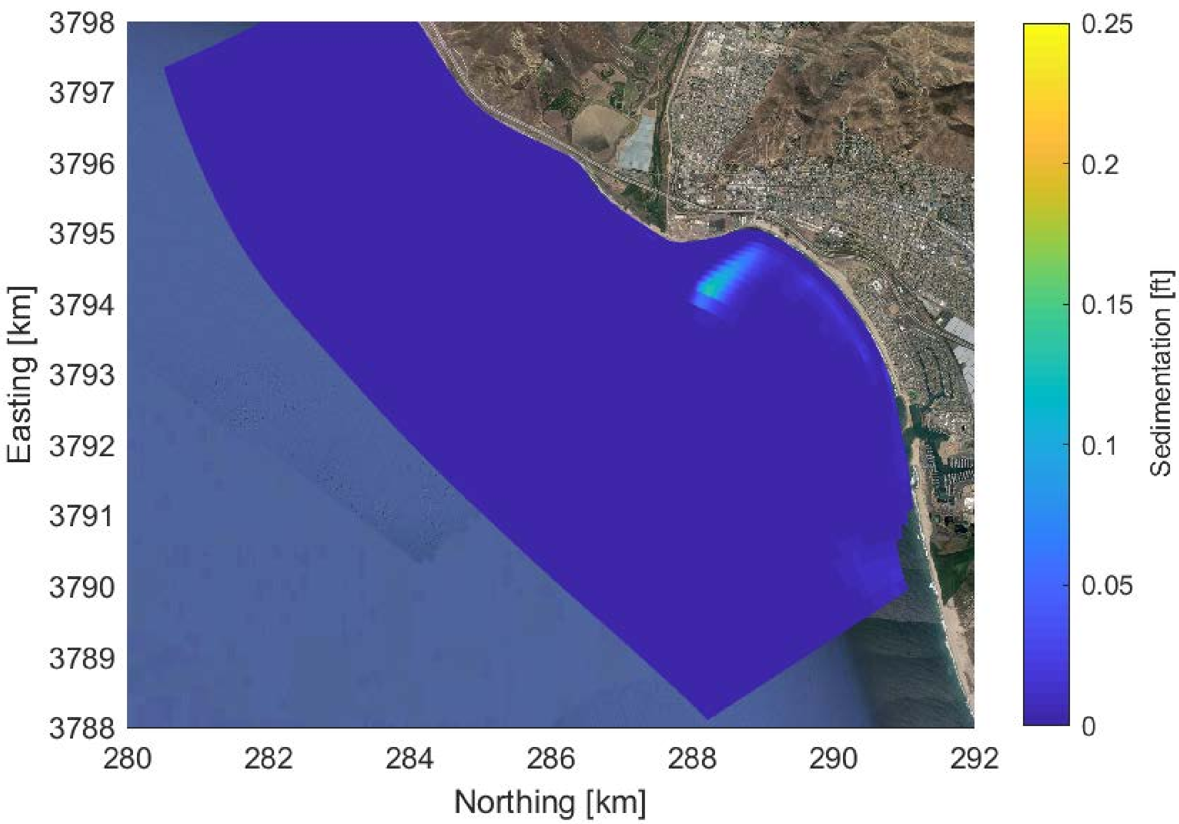

Figure 31. Sedimentation for Maximum Sediment Release During a Large Winter Storm.

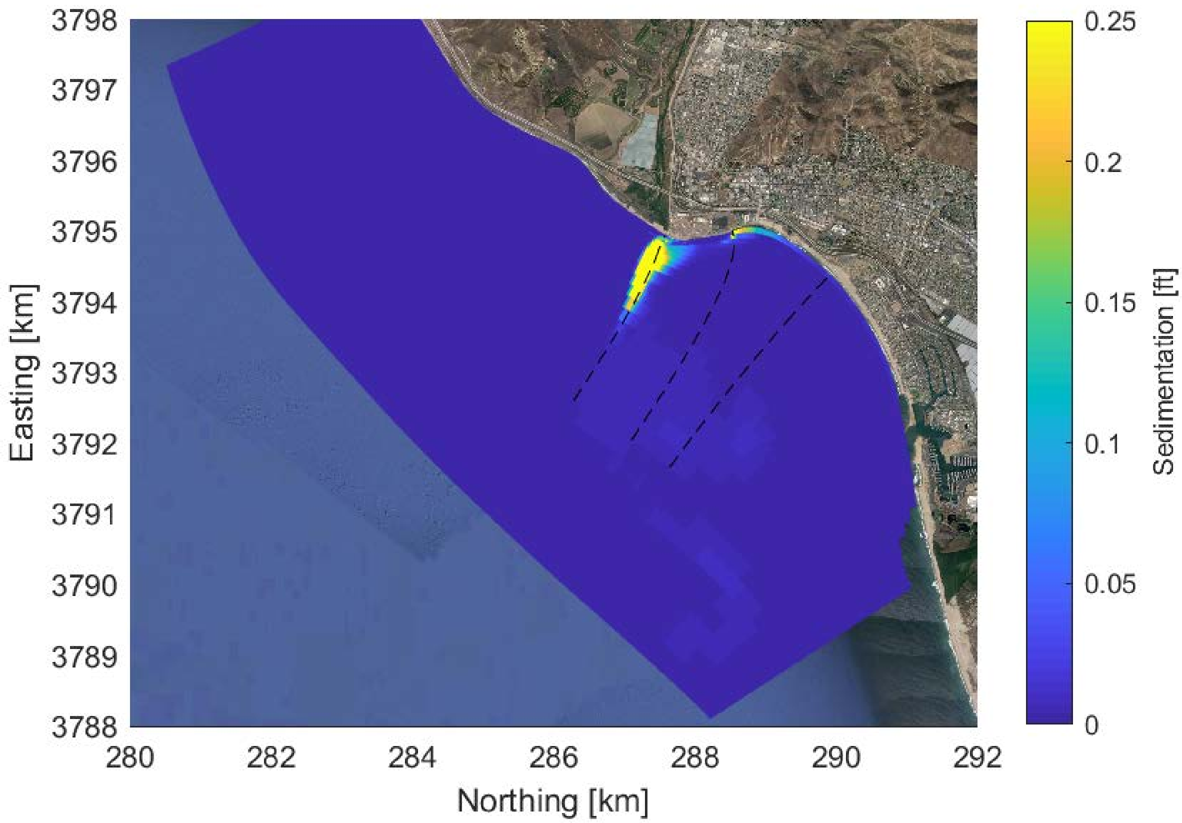

Figure 32. Sedimentation for Maximum Sediment Release with Average Winter/Spring Offshore Wave Conditions. Black dashed lines represent cross-section transects shown in the following figures.

The sediment deposition associated with the maximum sediment release following dam removal is compared across all wave conditions in Figure 34. The resulting bed elevation at the end of the simulation is shown plotted relative to the initial bed elevation at three transect locations (shown in Figure 33). The most significant sedimentation occurs just offshore of the estuary mouth (top panel of Figure 34). The downcoast transects (middle and bottom panels of Figure 34), however, indicate negligible sedimentation downcoast of both the silt and fine sand sediment following dam removal for the cases shown here.

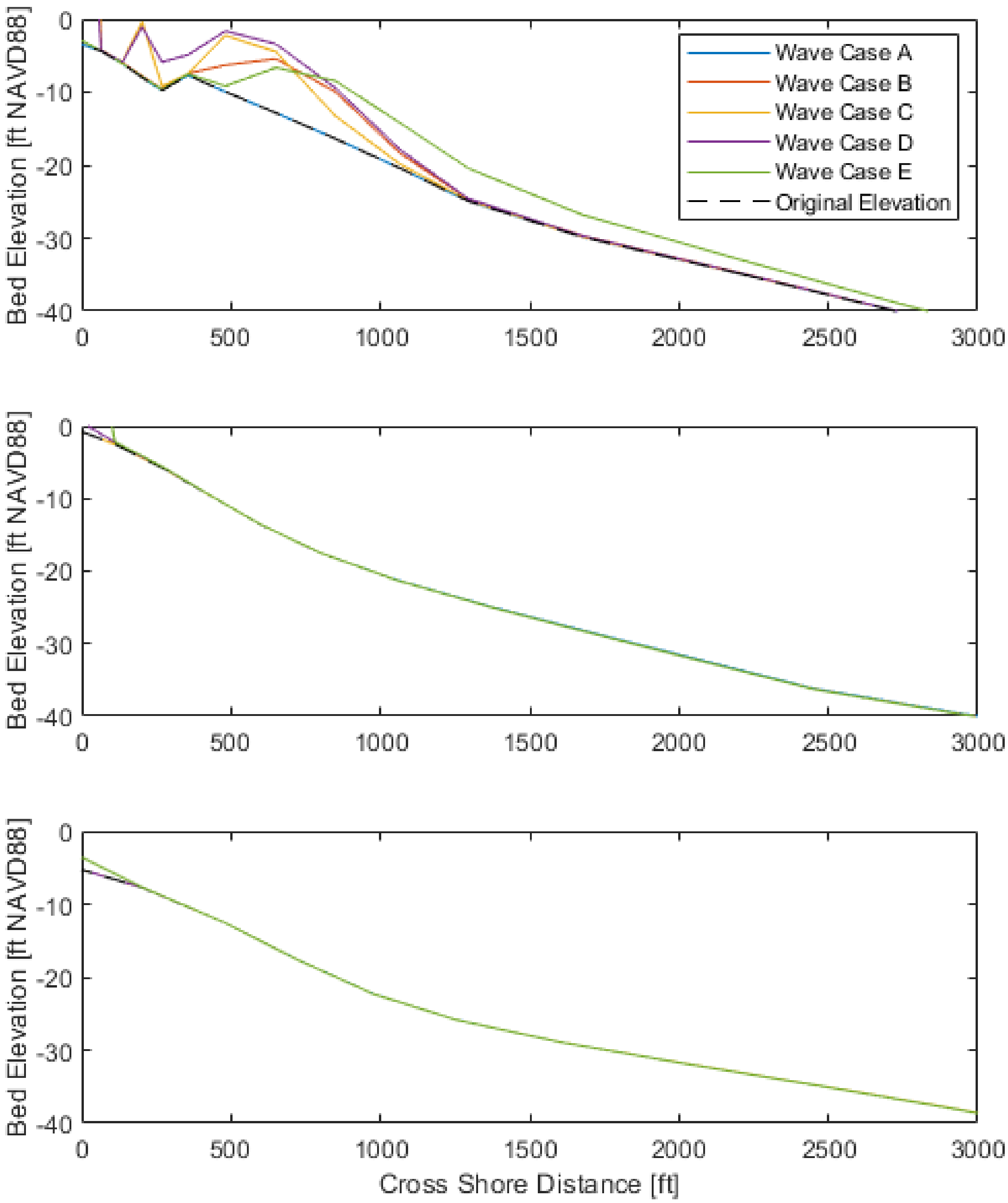

Figure 33. Sedimentation within the Coastal Ocean from Maximum Sediment Release Scenarios at Three Transect Locations Shown in Figure 32. Transects are located at the estuary mouth (top panel), near Ventura Pier (middle panel), and off San Buenaventura State Beach (bottom panel).

4.2 LONG-TERM SHORELINE CHANGE MODELING

The USGS – CoSMoS COAST long-term shoreline change model (Vitousek et al. 2017) has been developed and trained to the Ventura region and was used to evaluate the long-term coastal dynamics and morphology. The model is a modified one-line model for predicting shoreline change over longer time scales using a combination of physics-based transport and data assimilation from available digital shoreline positions. The model computes the cross-shore shoreline location at a series of transect locations along the coastline. The COAST model for the Ventura shoreline was developed with transects every 20 m along the coast. The transect locations form the model grid (Figure 35), where shoreline position is predicted at each model time step. Due to the presence of hardscape along the Ventura coastline, a non-erodible shoreline was also defined. The non-erodible shoreline limits the inland extent of erosion and shoreline position predicted by the model. The use of the shoreline change model in the present study was not intended to exactly predict shoreline position in 2070. Instead, the shoreline change model was used to evaluate the relative effect of dam removal and sediment loading to the system. Using the best available data and information, the estimated shoreline position was compared with and without dam removal influences and with and without sea level rise projections. The relative change in shoreline position provided a sound basis for evaluating the effect of dam removal on the coastal system.

Figure 34. COAST Model Grid with Transect Locations.

The shoreline change model was validated with remotely sensed shoreline positions (described in Appendix A). The model validation period for the shoreline change model started in October 2005 and ended in October 2017. The model-predicted mean shoreline positions over the model time period are shown along with observations of shoreline position in Figure 36. The 5th and 95th percentile model-predicted shoreline positions are also shown to bound the range of model predictions over the time period. The model captures the range of observed shorelines without relying on data assimilation methods.

Figure 35. Observed Shoreline Positions (white) Compared with Mean, 5th, and 95th Percentile Shoreline Predictions from COAST Model (black). Close-up maps are shown near the River Mouth and Ventura Harbor.

The impact of restored sediment loading to the coast over the next 50 years was evaluated using a set of shoreline change scenarios to evaluate the relative impact of dam removal with pre- and post-dam removal sediment loading. The restored sediment loading following dam release was anticipated to provide much needed sediment to the nearshore coastal region. However, based on sediment loading analysis (see Section 2.2 above) the Matilija reservoir is very near capacity such that currently the majority of upstream sediment is transported over the dam and downstream.

The shoreline change model uses projected tidal water level, nearshore wave conditions, river sediment loading to the coast, and sea level rise estimates over the 50-year horizon. The forecast conditions used for the shoreline change model were similar to conditions used for the inlet model described above in Section 3.3 and are described below.

The nearshore wave conditions (significant wave height, period, and direction) were interpolated from the available USGS nearshore wave data onto the transect locations (Figure 35). The nearshore forecasted wave data from USGS is based on RCP 4.5 climate change scenario and incorporates wave shoaling and refraction through use of a look-up table to generate nearshore wave conditions (Hegermiller et al. 2016). The nearshore wave data are provided at approximately 100 m intervals along the coast. The 3-hour forecast wave data were temporally interpolated to generate hourly wave data and spatially interpolated onto the COAST model transect locations. The spatially and temporally varying wave conditions (significant wave height, period, and direction) were used to force the shoreline change model over the next 50 years (from October 2019 through October 2069).

The tidal constituents at Santa Barbara were used to approximate projected water level. Although a tsunami water level station exists in Ventura Harbor (Station 9411166), this gage station has never been surveyed to an elevation and thus is unable to be used to specify local water levels. However, the tidal range and tidal constituent amplitude between Ventura Harbor and Santa Barbara gage stations were compared and are nearly equivalent with a slight phase shift. Therefore, the Santa Barbara tidal constituents are suitable for specifying tidal forcing. The water level was then modified by a long-term average increase due to sea level rise (low, intermediate-high, and extreme scenarios from Sweet et al. 2017). These predictions of sea level rise described in Section 2.1.3 above correspond to 1.28, 3.18, and 5.35 ft of sea level rise by 2070 (Sweet et al. 2017). The dam release scenarios were simulated with the four sea level rise projections (none, low, intermediate-high, and extreme).

Based on the coastal modeling described above, silt loading to the coastal ocean rapidly moves offshore and is not anticipated to deposit in the nearshore region. Therefore, the pre- and post-dam removal loading to the coast was based on the sand, gravel, and cobble rating curves for long-term river discharge. The immediate sediment release following dam removal was characterized as an initial mass of sand at the beginning of the shoreline simulation deposited in a delta offshore of the Ventura River (the volume of silt was not included because silt is not expected to deposit in the nearshore region). The initial mass of sand associated with the dam removal included in the shoreline change model was based on the fraction of available sand behind the dam (approximately 200,000 tons) and the trapping efficiency within the estuary. Based on estuary modeling results, approximately 60–90 percent of sand remains upstream of the estuary mouth during a dam removal event (Table 7). Subsequent events, can lead to additional delivery of sand from upstream regions to the coastal ocean. For the shoreline change scenarios, it was assumed approximately 50 percent of the impounded sand was delivered to the coastal ocean at the beginning of the model simulations. This estimate overpredicts the release of fine sand directly to the shoreline because during a high flow event the fine sand readily moves offshore. By increasing the total mass of sand delivered to the ocean for the shoreline change model, the impact of the initial sediment loading following dam removal is conservatively large.

Sensitivity of the shoreline change model was evaluated using three different discharge scenarios assuming post-dam removal sediment loading and intermediate-high sea level rise projections (Runs 9–11). Finally, the effect of the initial sediment pulse was projected (Runs 12–13).

Table 12. Shoreline Change Scenarios.

Run	Sediment Loading	River Discharge Case	Sea Level Rise Projection	Initial Dam Removal Loading
1	Pre-Dam Removal	A	None	None
2	Post-Dam Removal	A	None	Maximum Loading
3	Pre-Dam Removal	A	Low	None
4	Post-Dam Removal	A	Low	Maximum Loading
5	Pre-Dam Removal	A	Intermediate-High	None
6	Post-Dam Removal	A	Intermediate-High	Maximum Loading
7	Pre-Dam Removal	A	Extreme	None
8	Post-Dam Removal	A	Extreme	Maximum Loading
9	Post-Dam Removal	B	Intermediate-High	Maximum Loading
10	Post-Dam Removal	C	Intermediate-High	Maximum Loading
11	Post-Dam Removal	D	Intermediate-High	Maximum Loading
12	Pre-Dam Removal	A	Intermediate-High	None
13	Post-Dam Removal	A	Intermediate-High	None

The relative effect of dam removal and sea level rise on shoreline position was evaluated by comparing the predicted beach width (based on the non-erodible shoreline position) over time. Figure 37 below shows the beach width over the 50-year simulation period at four locations (near the Ventura River mouth, by Promenade Park, at San Buenaventura State Beach, and midway between the State Beach and Ventura Harbor at Seaward Avenue). The estimated beach width is without dam removal (blue) is compared to results with dam removal and initial sediment release (red) for the intermediate-high sea level rise scenario. Also shown is the resulting beach width assuming restored long-term sediment loading post-dam removal, but without the initial sediment release following dam removal (yellow). This scenario highlights the effect of long-term restored sediment loading post-dam removal relative to the initial release of sediment following dam removal.

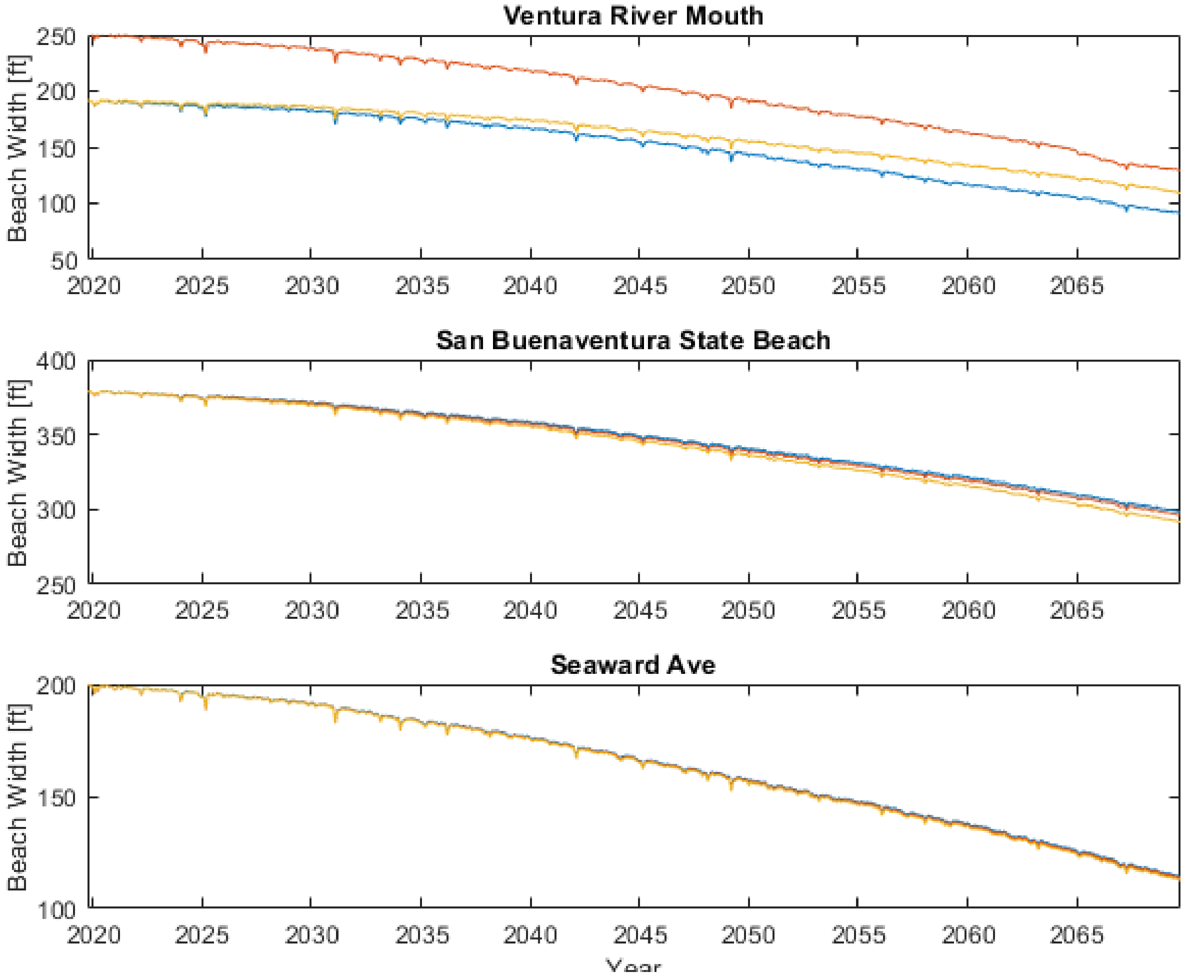

Figure 36. Beach Width With (Red) and Without (Blue) Dam Removal at Three Locations Assuming Intermediate-High Sea Level Rise Projections. The beach width is also shown based on results with restored post-dam removal sediment loading but without the initial dam release (Yellow).

The most pronounced effect of dam removal occurs near the estuary mouth. In particular, a large increase in beach width is observed at the beginning of the simulation due to the initial dam release. Over time, the restored sediment loading slightly increases the beach width relative to the no dam removal scenario. The effect of the initial release begins to decrease over time and approaches the long-term restored sediment loading scenario.

At San Buenaventura State Beach, the effect of the dam release is negligible. There is a slight increase in shoreline position at the end of the 50-year period relative to the no dam removal scenario. However, sea level rise has the largest impact on shoreline position at this location.

Midway between San Buenaventura State Beach and Ventura Harbor (at Seaward Avenue), the effect of dam removal is negligible with no measureable difference in shoreline position across the three scenarios shown.

The estimates of shoreline position due to sea level rise is uncertain because the COAST model does not incorporate cross-shore elevation profiles. Therefore, these model results are not intended to predict absolute shoreline position in 2070, but are used to evaluate the relative effect of various changes in the system. The relative change in shoreline position associated with restored sediment loading is small compared to current sediment loading because the total increase in annual sediment loading is only anticipated to increase by approximately 7 percent. The initial release of sediment following dam removal initially shifts the expected shoreline position and slightly delays the effects of sea level rise locally. In general, sea level rise is anticipated to have a much greater effect on shoreline position over the next 50 years compared with dam removal and the restored sediment loads from Ventura River are not anticipated to keep pace with sea level rise.

The Ventura Harbor dredging operations, predominately dredges sand sized sediments from the sand trap on the north side of the harbor and navigation channel and bypasses them to the southeast side of the harbor. Presently, approximately 600,000 cubic yards of sand are dredged annually from the sand trap located just upcoast of the Ventura Harbor. Historically, the total annual dredge volume varies substantially year to year largely based on available financial resources for dredging operations, the minimum dredge volume occurred in 1972 (17,000 cubic yards) and the maximum volume dredged occurred in 1983 (1,427,000 cubic yards).

Based on the COAST and Delft3D/SWAN modeling results, the impacts of restored sediment loading to the Ventura River will have minimal or negligible impact on the coastline around Ventura Harbor. The dredging of trapped sand historically is consistent with findings of natural transport patterns in this study, which indicate that silts and clays are readily transported offshore while coarser sand grain sized material is transported along the coast. Potential effects of dam removal and restored sediment load on the Ventura Harbor dredging operations could result due to added sand fractions to the system. Using both the BOR 2006 and Stillwater 2016 sediment loading estimates, the approximate increase in sand loading over the long-term is 16,000 to 21,000 m^3/yr (or approximately 21,000 to 27,000 cubic yards per year). Even if 100 percent of the increase in Ventura River sand deposited in the sand trap, which is not possible, it would represent less than 5 percent of the average 600,000 cubic yards of sediment dredged. Therefore, based on the potential changes in Ventura River sediment loading and magnitude of the local sediment budget, the increased sand loading from the Ventura River following dam removal is anticipated to have a negligible impact on the Ventura Harbor sand trap and dredging operations.

5 SUMMARY OF KEY FINDINGS

To evaluate potential impacts of dam removal and subsequent sedimentation on the Ventura River estuary and nearshore coast, a set of estuary and coastal models was developed to evaluate the impacts on the morphology, habitat and inlet dynamics within the estuary and coastal ocean across a range of time scales. The modeling effort utilized high-resolution short-term modeling (Delft3D and Delft3D/SWAN) to accurately characterize transport during flood events post dam removal. Long-term impacts to the estuary and coast were modeled using an empirical inlet and shoreline change model, which included the effect of sea level rise to evaluate changes to estuary opening and closure dynamics and shoreline position. The multi-model approach allowed for characterization of dam release impacts over a plausible range of temporal and spatial scales that were reviewed and informed by local knowledge and expertise.

The sediment transport modeling of the estuary and coastal ocean relied on prior analysis (BOR 2006; AECOM and Stillwater 2016; Stillwater 2019) to characterize sediment delivery to the estuary pre-dam removal, during dam release, and post-dam removal. Based on this analysis, coarse sediment (> 2 mm) delivery to the estuary is not anticipated to change substantially pre- and post-dam removal. While dam removal will allow coarse grain material to move past the dam, the effects of dam removal on coarse grain material in the estuary will not be felt for many decades because gravel and cobble move slowly through the system and only during large flow events (> 10 year return period). Gravel and cobble loading at the estuary provided by Stillwater Sciences (DREAM-2 model results) indicate no anticipated difference in loading pre- and post-dam removal. Therefore, while gravel and cobble are important components of the estuary and coastal sediment budget, the dam removal is not anticipated to modify current gravel and cobble transport in the system.

The silt and sand material, in contrast, is much more mobile and could have immediate impacts on the downstream system. Silt is the largest component of total sediment behind the dam. Sediment loading to the estuary predominantly consists of silt and clay constituting approximately 88 percent of the annual post-dam removal sediment budget. However, silt and clay particles readily move through the estuary and offshore. Relying on prior analysis of sediment loading (BOR 2006; AECOM and Stillwater 2016), the silt loading to the estuary pre- and post-dam removal is not anticipated to change because the Matilija Dam is not currently trapping silt and clay material. The post-dam removal estimates of restored sand delivery to the estuary indicate that the annual sand budget will increase relative to pre-dam removal delivery by approximately a factor of 2.3. Therefore, across the range of sediment grain sizes considered (silt, sand, gravel, and cobble), sand is the primary grain size that is anticipated to change pre- and post-dam removal.

That said, the most direct effect of dam removal is the anticipated erosion of approximately 880,000 to 1,170,000 metric tons of fine sediment from the reservoir immediately following dam removal concept 2A/2B, which is approximately 83 percent silt and 17 percent sand. (Assuming the maximum anticipated erosion, this corresponds to 970,000 and 200,000 tons of silt and sand, respectively.) Estuary modeling of dam release scenarios shows that the majority of silt is readily transported through the estuary and out to the coastal ocean. Only approximately 7 to 15 percent of the silt deposits upstream of the estuary mouth during an initial dam release. Approximately 60 to 90 percent of the total sand load deposits upstream of the estuary mouth. Once in the coastal ocean, silt particles are readily transported offshore and negligibly contribute to the coastal sediment budget.

Therefore, while silt constitutes the largest component of sediment loading to the system, the long-term impacts of deposited silt on habitat in the estuary and coastal ocean are minimal. The water quality effects of high suspended sediment concentrations during high flow events are note directly evaluated as part of this effort; however, the magnitudes of the transient levels are presented for further evaluation. However, because silt is readily transported through the system, any floodplain regions that are engaged during a dam release event will experience sedimentation from silt. This may include regions of the agricultural field and RV park as well as upland riparian habitat. As the magnitude of the dam release event increases, more of the floodplain is engaged and more sedimentation may be observed. Sediment is nature's adaptation resource and so additional deposition may not be an entirely negative impact. However, to minimize potential sedimentation changes, there is a benefit to choosing a dam release event as near to the 4-year design event as possible.

The modeling further suggests that the changes in estuary hypsometry due to dam release sedimentation are likely to be eroded over subsequent events following the dam release and not substantially change potential estuary habitats. Using the modeled deposition and resulting hypsometric changes in the inlet model shows negligible change in the inlet opening and closing behavior, however better data on water levels and more recent habitat mapping could improve this analysis. However, given the small modeled changes to the dynamics within the estuary over the next 50 years due to dam removal, habitat impacts are projected to be small to insignificant. In contrast, the effect of sea level rise may lead to significant changes in estuary dynamics and habitat.

The coastal model results indicate that most of the silt particles associated with the dam removal move offshore and do not deposit within the nearshore model domain (less than 30 m water depth) over the simulation period. During a range of wave scenarios including a winter storm wave event and average winter and spring wave conditions (most likely conditions for a large discharge event), less than 3 percent of silt deposited within the coastal model domain. The largest deposition of the sand particles deposited in the modeled region over the simulation period (greater than 98 percent) across all average coastal wave scenarios, with the exception of the large winter storm event, which rapidly transported sand downcoast. The large wave conditions resulted in between 55 and 89 percent deposition for the maximum and minimum sediment release scenarios, respectively.

The patterns of sand deposition within the coastal ocean are heavily dependent on wave conditions. For instance, sediment is rapidly transported downcoast during large winter storm wave events. In contrast, during milder wave conditions, the discharge pulse (18,000 cfs) dominates the flow patterns near the estuary mouth and forces sediment to deposit offshore. The sand-sized sedimentation following the maximum sediment release in the river combined with average winter and spring conditions results in more deposition near the river mouth. Downcoast areas during average to small wave conditions, however, indicate negligible sedimentation of the silt and fine sand material following dam removal.

The long-term effect of dam removal on restored sediment loading (pre- and post-dam removal) is small to negligible because annual estimated total sediment loading following dam removal is anticipated to increase by only 7 percent (Stillwater 2016). Therefore, the primary effect of dam removal on the coastal ocean is associated with the initial pulse of sand associated with dam removal (silt moves offshore and does not deposit nearshore following dam release). The initial release of sediment was conservatively incorporated into the shoreline change model (assuming 50 percent estuary trapping). The dam removal and initial sediment release had local effects on shoreline position and increased beach width within a few hundred meters of the river mouth, but little effect on shoreline position downcoast. The restored sediment loading minimal effect on shoreline position and negligible effect on shoreline position relative to the initial dam removal sediment release. The most significant impact to shoreline position over the long-term is due to sea level rise.

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Appendix A

Model Development and Validation

MATILIJA DAM REMOVAL ECOSYSTEM RESTORATION PROJECT

Appendix A: Model Development and Validation

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ACRONYMS AND ABBREVIATIONS

CDIP	Coastal Data Information Program
cfs	cubic feet per second
CMWD	Casitas Municipal Water District
COAST	Coastal One-line Assimilated Simulation Tool
CoSMoS	Coastal Storm Modeling System
CSM	conceptual site model
DEM	digital elevation model
DREAM-2	Dam Removal Express Assessment Model 2
LiDAR	light detection and ranging
NBDC	National Buoy Data Center
NOAA	National Oceanic and Atmospheric Administration
RV park	Ventura Beach RV Resort
SWAN	Simulating WAves Nearshore
USGS	U.S. Geological Survey

1 INTRODUCTION

The processes driving sediment transport in the Ventura River ecosystem vary widely over a range of spatial and temporal scales. The range of processes, system responses, and time scales at work in the Ventura River ecosystem requires a multi-pronged modeling approach to effectively model the system as a whole. The primary processes to be considered include the time-varying flow and sediment load from the Ventura River to the lagoon, the variability in the sediment grain size distribution (silt, sand, gravel, and cobble), sediment deposition and morphodynamic changes within the lagoon, the periodic breaching of the bar-built lagoon, and the wave-driven littoral transport in the nearshore littoral cell. There is a complex interplay between all of these processes, with multiple feedback loops within the system.

To address habitat changes over time scales ranging from days to decades, both short- and long-term modeling were conducted. The modeling approach relied on forcing conditions (river loading, wave and tidal conditions, and sea level rise predictions), site-specific parameters (lagoon and shoreline geomorphology and sediment grain size distribution), data for model validation (shoreline and lagoon observations), and a well-developed conceptual site model (CSM) to accurately set up the coupled sediment transport model. Key aspects of the modeling approach include the following:

- An estuary model driven by upstream river discharge and sediment loading with episodic seasonal coastal exchanges through the estuary and inlet
- An inlet model that predicts the conditions under which there is connectivity between the estuary and the littoral zone
- A coastal sediment transport model that replicates littoral sediment transport processes associated with storm events
- A shoreline change model to evaluate long-term sediment transport patterns and shoreline position along the Ventura coast
- Evaluation of physical process modeling for key habitat metrics which include water quality, connectivity, and habitat quantity and interpretation of potential impacts on sensitive and endangered species.

The multi-model approach provides predictions of sediment transport processes across multiple spatial and temporal scales. The estuary and coastal ocean models are used to evaluate sediment transport over short-term, event-based time scales (days to weeks) using high-resolution and high-fidelity modeling to ensure that the transport processes are accurately simulated. These event-based models allow for high-fidelity modeling of all components of the Ventura River system including the estuary, inlet, and coastal ocean. In contrast to the event-based estuary and coastal ocean modeling, the long-term dynamics (decadal) are predicted using an inlet model and shoreline change model, which incorporate simplified transport processes. The combination of short- and long-term modeling allows for high fidelity simulations of complex processes with event-based modeling to inform long-term simulations (years to decades).

A key component of model development is validation of model predictions with observed data. For the Ventura River system, limited quantitative information (e.g., water levels, currents, sediment loads) exists for typical model calibration and validation in either the estuary or coastal regions. Therefore, qualitative model validation provides the best method for evaluating and validating model behavior. This includes sensitivity analysis and "what-if" simulations, designed not for projecting future conditions (prognosis), but for understanding model behavior (diagnosis) in relation to observed site conditions. For example, the interaction of river runoff, routine tides, and storm waves is an important part of the model. Validating that the models can reproduce combinations of scenarios consistent with the CSM, historical information, and anecdotal information provides confidence in the ability of each of the modeling components to evaluate such dynamics. Using this approach, the models have been qualitatively validated to ensure that model predictions are consistent with the CSM and that the models are able to evaluate relative impacts to the estuary and coast associated with dam removal.

The following sections describe data sources relied on as well as model development, setup, boundary conditions, and validation for the estuary, coastal ocean, inlet, and shoreline change models. Throughout the model application, the primary modeling goal of investigating the short- and long-term effects of sediment from the Ventura River on the estuary and coastal morphology and habitat will guide all modeling decisions. All model source code and executables have been provided along with this report and all modeling tools are open source allowing for transparency during review processes and for future application of the modeling tools by any interested parties.

2 DATA SOURCES

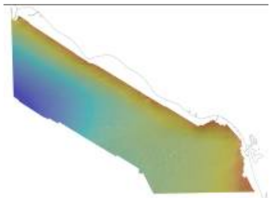
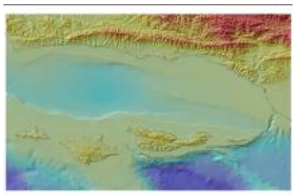
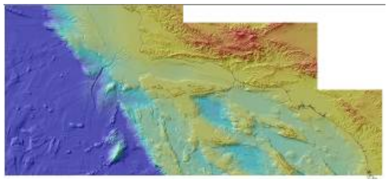
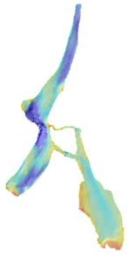
The modeling work requires a combination of bathymetric, topographic, sediment bed composition, water, sediment loading, and other environmental spatial and temporal data as model initial and boundary conditions. This section describes the data sources relied upon for each modeling component (estuary, inlet, coastal ocean, and shoreline change).

2.1 BATHYMETRY AND TOPOGRAPHY

Model configuration (i.e., grid) development relies on an accurate digital elevation model (DEM) constructed from multiple topographic and bathymetric data sources (Table 1). To develop a site DEM, Integral has compiled all available topographic and bathymetric data sets of the coastal ocean, inlet, estuary, and upland areas. Upon project initiation, the lack of available estuary bathymetry was identified as a key data gap. Because estuary bathymetry is critical to an estuary model, bathymetry data were collected by Ventura County in November 2018. Figure 1 shows topographic and bathymetric data that have been compiled in the current iteration of the DEM. All elevation data are relative to NAVD88.

Figure 1. Compiled Elevation Map with LiDAR and Bathymetry Contours.

Table 1. Spatial Topographic and Bathymetric Data Sources.

Thumbnail	Source	Resolution
	Ventura County LiDAR 2018	0.5 m
	USGS bathymetry from 10 to 40 m water depth	2 m
	NOAA elevation data—regional topography of Santa Barbara channel, channel islands and mainland	10 m
	NOAA elevation data—regional southern California mainland, borderland, and basin	90 m
	Ventura County single beam bathymetry of estuary (2018)	1 m

2.2 VENTURA RIVER DISCHARGE

The discharge and sorted sediment loading from the Ventura River serve as critical components to the estuary and coastal modeling efforts. Daily discharge data from U.S. Geological Survey (USGS) gage station (11118500) have been recorded since 1929, with higher resolution data (15-minute sampling interval) recorded beginning in 1988.

Flood frequency analysis presented in BOR (2006) was used to define flood event magnitude throughout the river reach including at the Matilija Creek gage station (11115500) and the Ventura River gage station (11118500). The standard method recommended in Bulletin 17b was rejected for this location as described in BOR (2006) because of poor fit with available data. The results of the flood frequency analysis are shown in Table 2 for peak 15-minute discharge at Matilija Creek gage station (11115500), at Ventura River gage station (11118500), and at Shell Road, which is approximately 3 miles upstream of the Ventura River mouth. The 15-minute peak flow frequency analysis (distinct from the daily average flow frequency analysis) was used to develop return period discharge events to the estuary and coastal ocean. The design dam removal flow event was defined by AECOM and Stillwater (2016) based on the daily average discharge on Matilija Creek (11115500) to be greater than 1,700 cfs daily average discharge (or 3,000 cfs peak discharge).

Table 2. Peak 15-Minute Flood Frequency Analysis from BOR (2006).

Return Period (yr)	Upstream Confluence with N. Fork Matilija Creek (Station 11115500) (cfs)	Casitas Road Bridge (Station 11118500) (cfs)	Shell Road (cfs)
2	3,060	4,520	5,080
5	7,090	11,060	12,250
10	12,500	36,040	41,300
20	15,200	46,400	52,700
50	18,800	59,700	67,900
100	21,600	69,700	78,900
500	27,900	93,100	105,500

Source: BOR (2006).

2.3 SEDIMENT LOADING

Sediment loading to the estuary will govern the potential impacts associated with dam removal and restored sediment loading; therefore, the transport of silt, sand, gravel, and cobble is a critical modeling input to the estuary and coastal modeling. For each sediment grain size (silt, sand, gravel, and cobble), a sediment rating curve was developed for pre- and post-dam removal conditions to characterize the sediment loading associated with discharge magnitudes. In addition, the pulse of sediment following dam removal was estimated so that the short-term effects of the dam removal on the estuary could be evaluated.

The sediment rating curve and dam removal loading analysis, described in more detail below, relied heavily on prior analysis and modeling studies. In particular, prior studies conducted by the U.S. Bureau of Reclamation (BOR), AECOM, and Stillwater Sciences (BOR 2006; AECOM and Stillwater 2016; Stillwater 2019) were leveraged to develop a robust understanding of sorted sediment loading to the estuary. The BOR (2006) sediment analysis included characterization of impounded sediment, sediment yield both with and without the dam in place, and sorted sediment rating curve analysis.

The range of sediment loading analysis (BOR 2006; AECOM and Stillwater 2016; Stillwater 2019; Cui et al. 2017) within the system are used in concert for estimates of sediment delivery and loading to the estuary and the coastal ocean. Each of the four sediment grain sizes (silt, sand, gravel, and cobble) are treated individually in the estuary and coastal models. The following summarizes available sediment loading associated with dam removal as well as the development of sediment supply curves for the Ventura River with and without the dam in place.

2.3.1 Sediment Supply Rating Curves

Sediment rating curves can be used to estimate sediment loading for a particular grain size based on river discharge at a given location within a watershed. To estimate the sediment loading to the estuary from the watershed (i.e., not associated with the erosion of impounded sediment following dam removal), sediment rating curves were developed pre- and post-Matilija Dam removal from prior studies (BOR 2006; AECOM and Stillwater 2016; Stillwater 2019).

The sediment loading for each grain size class (silt, sand, gravel, and cobble), Q_s, can be estimated using the equation:

$$Q_s = a\, Q_w^b$$

where a and b are coefficients, Q_w is the river discharge, and both sediment loading and discharge are in m^3/s. The b coefficients depend on dynamics of the watershed, the sediment grain size, and general transport characteristics, and the a coefficients modify the magnitude of the sediment load and can be scaled to appropriately account for sorted sediment loading pre- and post-dam removal based on annual sediment supply estimates.

Sediment rating curves were developed under current conditions (i.e., dam in place) for silt, sand, and gravel based on sediment concentration data and long-term sediment supply estimates at multiple gage stations (BOR 2006). While it is acknowledged that the concentration data do not capture bedload and gravel material not in suspension, a key assumption is that the concentration data can be reasonably used to determine the shape of the sediment rating curves (b coefficients). The magnitude of the total load is then based on watershed estimates of annual loading using the a coefficients. The b coefficients were derived at the Ventura River gage station for silt, sand, and gravel loading as 1.6, 2.4, and 3.0, respectively (BOR 2006). For silt and sand sediment loading, annual estimates of loading were used to develop the rating curves. For gravel and cobble, however, the DREAM-2 model outputs were available at the upstream end of the estuary to develop the rating curves.

Estimated pre- and post-removal equilibrium (i.e., no sediment trapping behind Matilija Dam) sediment loading to the Ventura River from Stillwater (2019) is shown in Table 2. For transparency, the pre- and post-dam removal estimates developed by BOR (2006) are also shown (Table 3) and indicate similar total magnitude estimates of sediment loading. However, the Stillwater (2019) estimates assume zero trapping of silt sediment by Matilija Dam and suggest much smaller annual sand loading to the system. Differences between the two estimates may be due to differences in the assumptions regarding trapping of sediment grain sizes in the system. It is also worth noting that the BOR (2006) post-dam removal estimates applied a constant trapping efficiency across all sediment grain sizes. In reality, coarser grain material is more likely to be trapped behind the dam compared to fine-grained material as indicated in the Stillwater estimates. Because the primary focus of this study is to evaluate the effect of dam removal relative to current conditions, the difference between pre- and post-removal sediment loading is of primary importance. Fortunately, since the goal of this study is to evaluate the change in sediment load, the pre-removal total sediment load still allows for the evaluation of changes in total load relative to current conditions. Therefore, while there are differences in the magnitude of estimated sand loading to the estuary from Stillwater (2019) and BOR (2006) reports, the increase in sand loading ranges from approximately 16,000 to 21,000 m^3/yr for both cases.

Table 3. Estimated Annual Sediment Delivery at the Estuary from Stillwater (2019).

	Sediment Loading (m^3/yr)			
	Silt	Sand	Gravel	Total
Total Pre-removal	344,210	12,190	7,600	364,000
Total Post-removal Equilibrium	344,210	28,190	17,600	390,000
Percent Increase Post-removal	0%	131%	131%	7%

Table 4. Estimated Annual Sediment Delivery to the Ocean from BOR (2006).

	Sediment Loading (m^3/yr)				
	Silt	Sand	Gravel	Cobble	Total
Total Pre-removal	237,000	104,000	7,200	400	349,000
Total Post-removal Equilibrium	285,000	125,000	8,600	480	419,000
Percent Increase Post-removal	20%	20%	20%	20%	20%

For silt and sand, sediment rating curves were developed from the estimated annual load of sediment in Table 2 based on the Stillwater (2019) work as the most up to date system description. The *b* coefficients, as described above, are based on measured sediment concentration in the Ventura River at Station 11118500 (BOR 2006) to best approximate the loading curve given the available data. The coefficients for silt and sand at the gage station are 1.6 and 2.4, respectively. Using the total estimated annual sediment load, the *a* coefficients were computed for both the current loading as well as the long-term post-removal equilibrium sediment loading based on the 15-minute discharge data measured at Station 11118500 over the 30-year period of available data.

The DREAM-2 modeling study evaluated coarse sediment (diameter > 2 mm; gravel and cobble) transport through the watershed under current conditions (Runs 1a, 1b, 1c, 1d, and 1e) and following dam removal (Runs 2a, 2b, 2c, 2d, and 2e) using five discharge scenarios (a–e). Stillwater Sciences provided the Integral team with daily discharge and sorted coarse sediment loading across all 10 scenarios at the West Main St. Bridge (just upstream of the estuary) over the entire 68-year simulation period. The loadings across all 10 scenarios were used to estimate the sediment rating curve coefficients for coarse grain material (> 2 mm) for pre- and post-dam removal conditions. The best fit between total gravel and cobble loading and discharge across the 10 scenarios was computed to estimate the rating curve coefficients. Coefficients were computed for each of the 10 scenarios and all but two of the cases (Runs 1c and 2c) generated identical *a* and *b* coefficients (Table 5).

Table 5. Rating Curve Coefficients for Silt, Sand, Gravel, and Cobble.

Rating Curve Coefficients	Silt (0.03 mm)	Sand (0.2 mm)	Gravel (16 mm)	Cobble (100 mm)
b	1.6	2.4	3.0	3.0
a (pre-removal)	4.07E-04	1.21E-07	6.80E-10	5.40E-11
a (post-removal equilibrium)	4.07E-04	2.80E-07	6.80E-10	5.40E-11

Importantly, there was no difference in the gravel and cobble loading for the cases with and without dam removal based on the DREAM-2 modeling. This is because the coarse grain material will likely take decades to travel from the dam to the coastal ocean. Therefore, while gravel and cobble are important features of the watershed, the dam release and removal are not expected to appreciably modify coarse grain transport in the system appreciably. There are also significant gravel and cobble contributions from other tributaries, primarily, San Antonio Creek. In addition, there are other significant gravel and cobble sources to the Ventura River that are not impacted by the Matilija Dam (North Fork Matilija Creek and San Antonio Creek) such that the total change in gravel and cobble loading post-dam removal is small. Another likely reason that the predicted gravel and cobble loading at the estuary are equivalent pre- and post-dam removal is due to uncertainty in DREAM-2 model predictions, particularly in regions where the river channel slope flattens out. Near the estuary, the river channel slope decreases and the DREAM-2 model correspondingly predicts large sediment deposits.

To ensure that the dam removal impact on estuary habitat was conservatively predicted in the present study, sensitivity of the model results on the estimated gravel and cobble loading was evaluated. Additional modeling studies were conducted that incorporated a 20 percent increase in the post-dam removal gravel and cobble sediment loading. This increase is consistent with the BOR (2006) predicted increase in gravel and cobble loading from pre- to post-dam removal conditions.

Based on the derived sediment rating curve coefficients shown in Table 4, the rating curves for silt, sand, gravel, and cobble in the Ventura River post-dam removal are shown in Figure 5. The sediment grain sizes used throughout this analysis for silt, sand, gravel, and cobble are 0.03, 0.2, 16, and 100 mm, respectively. These rating curves are used throughout the analysis.

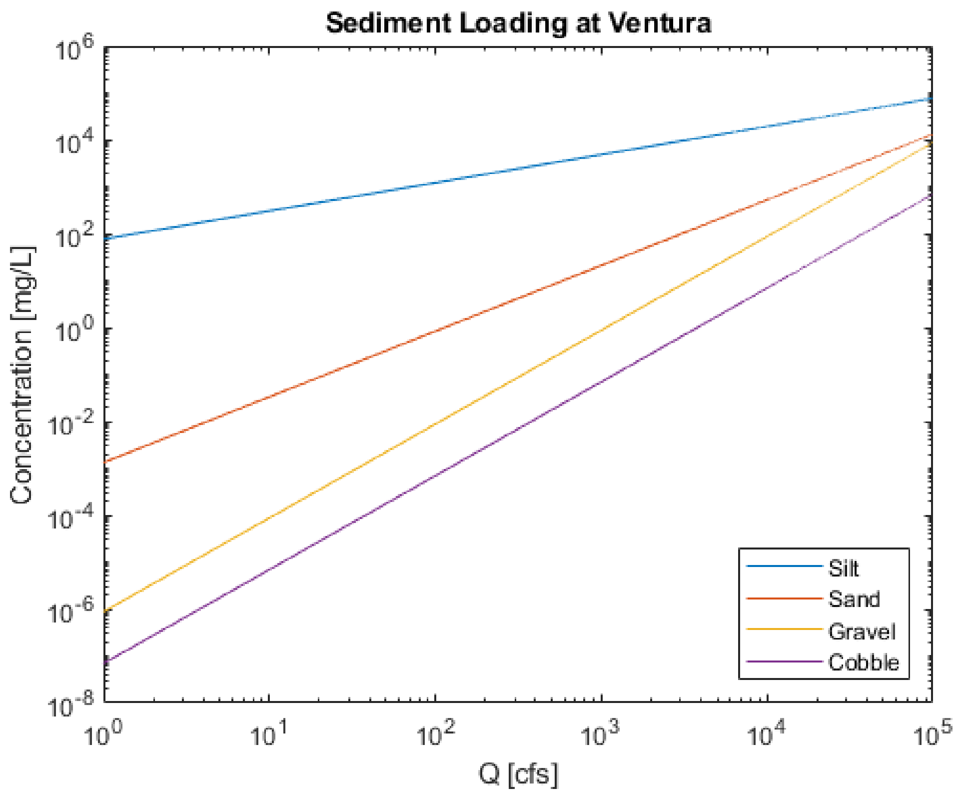


Figure 2. Post-removal Sediment Rating Curves at Ventura Gage Station (11118500) Developed for the Four Sediment Size Classes.

2.3.2 Dam Removal Sediment Loading

The dam removal concept 2A/2B (uncontrolled orifices with optional gates) would involve blasting open boring tunnels when a high-flow event occurs to erode significant portions of fine sediment deposits in the reservoir. Based on analysis from AECOM and Stillwater (2016), the design high-flow event on Matilija Creek would need to exceed 1,700 cfs[1] to sufficiently erode accumulated silt and sand from behind the dam (AECOM and Stillwater 2016). If the observed flood event is not adequate to remove accumulated fine sediment from the reservoir, gates might be installed that allow the reservoir to refill until the next high-flow event occurs. The dam would then be removed when a sufficient amount of fine impounded sediment has been eroded from the reservoir (AECOM and Stillwater 2016).

The character of the sediment behind the Matilija Dam has been used to estimate grain size distributions and sediment loading to the system during dam removal (AECOM and Stillwater 2016; Stillwater 2019). The DREAM-2 model output from the first design flow-event (in the 68-

[1] The design high-flow event on Matilija Creek of 1,700 cfs is approximately a 4-year return period event (AECOM and Stillwater 2016).

year simulations) was used to specify the gravel and cobble loading to the estuary for the five dam removal modeling scenarios. While the DREAM-2 scenarios are used to specify coarse sediment (>2 mm) loading to the estuary, a separate approach had to be used for fine (silt and sand) sediment transport. Silt and sand sediment transport following dam removal has been estimated in Cui et al. (2017) using an empirical approach. The total mass of sediment to be eroded following a design event was estimated between 850,000 and 1,170,000 metric tons. The range of sediment is based on estimates of channel formation and is supply limited based on the available sediment in the reservoir. The total mass of fine sediment eroded from Matilija reservoir during dam removal release was used to specify the sediment load to the estuary over a dam removal event. The erosion of impounded silt and sand following dam removal was added to the post-dam removal sediment supply rating curves to account for silt and sand originating from other regions of the watershed.

A summary of the dam removal sediment loading is shown in Table 5. The total sorted sediment load anticipated during the initial release following dam removal as well as the restored annual sediment loading in Table 5 are used throughout the analysis to evaluate the effect of dam removal on the estuary and coast.

Table 6. Sorted Sediment Loading to the Estuary Associated with Initial Dam Removal and Restored Loading Post-Dam Removal.

	Silt (0.03 mm)	Sand (0.2 mm)	Gravel (16 mm)	Cobble (100 mm)
Initial Dam Removal (m^3)	607,000	124,000	-	-
Post Dam Removal Annual Loading (m^3/yr)	344,000	28,200	3,200	260

2.4 WAVE AND WATER LEVEL CONDITIONS

Wave and tidal conditions are an important boundary condition in the modeling analysis. Wave and water level measurements near and within the Santa Barbara Channel are available through the Coastal Data Information Program (CDIP),[2] the National Oceanic and Atmospheric Administration's National Data Buoy Center (NOAA NDBC),[3] and the National Ocean Service Center for Operational Oceanographic Products and Services.[4] The nearest water level stations include Santa Barbara (9411340), Rincon Island (9411270), and Santa Monica (9410840). In addition, a tsunami warning water level sensor was deployed in Ventura Harbor beginning in 2014. The East Santa Barbara Channel CDIP buoy (46053) measures spectral wave parameters and bulk wave statistics, as well as meteorological conditions. Additional CDIP buoys measuring bulk wave parameters are available throughout the region with the nearest buoy located at Anacapa Passage (46217).

In addition to these raw data observations of waves and water levels, studies in the region have used available data to develop hindcast and forecast time series data. USGS, for instance, has developed 30-year hindcast wave data (1980–2010) through reanalysis of offshore wave data. USGS has also produced historical and forecast (through 2100) wave data in the nearshore region using CoSMoS modeling (Hegermiller et al. 2016). The forecast wave data were generated using global climate model offshore wave conditions and projected into the nearshore using a lookup table. The global climate model used was the Geophysical Fluid Dynamics Laboratory's Earth System Model (GFDL-ESM2M) under the Representative Concentration Pathway (RCP) 4.5 climate scenario (Hegermiller et al. 2016)

Future total water levels were estimated for forecast model scenarios using available wave and constituent tidal data with the inclusion of sea level rise estimates. Regional projections of sea level rise from a variety of sources (Sweet et al. 2017; OPC 2018) were considered. All of these estimates take into account global mean sea level rise as well as regional effects of ocean circulation, ice melt redistribution, and local vertical land motion. The final sea level rise assumptions selected for modeling came from the Sweet et al., 2017 projections due to proximity of the Rincon Island station to the Ventura River mouth. Decadal sea level rise estimates at nearby gage stations are available for five relative sea level rise scenarios (low, intermediate, intermediate-high, high, and extreme; Sweet et al 2017; Figure 1). The projected sea level rise estimates are from 2000, and, are consistent with projections adopted in the State of California Sea Level Rise Guidance (OPC 2018) for Santa Barbara (Table 1). The Rincon Island extreme sea level rise estimates bound the potential range of sea level rise projections at the Ventura River mouth. Throughout this report, the low, intermediate-high, and extreme sea

[2] https://cdip.ucsd.edu/?units=metric&tz=UTC&pub=public&map_stati=1,2,3
[3] https://www.ndbc.noaa.gov/
[4] https://co-ops.nos.noaa.gov/

level rise projections at Rincon Island (Figure 3 and Table 7) were used for all long-term modeling of the inlet and shoreline position.

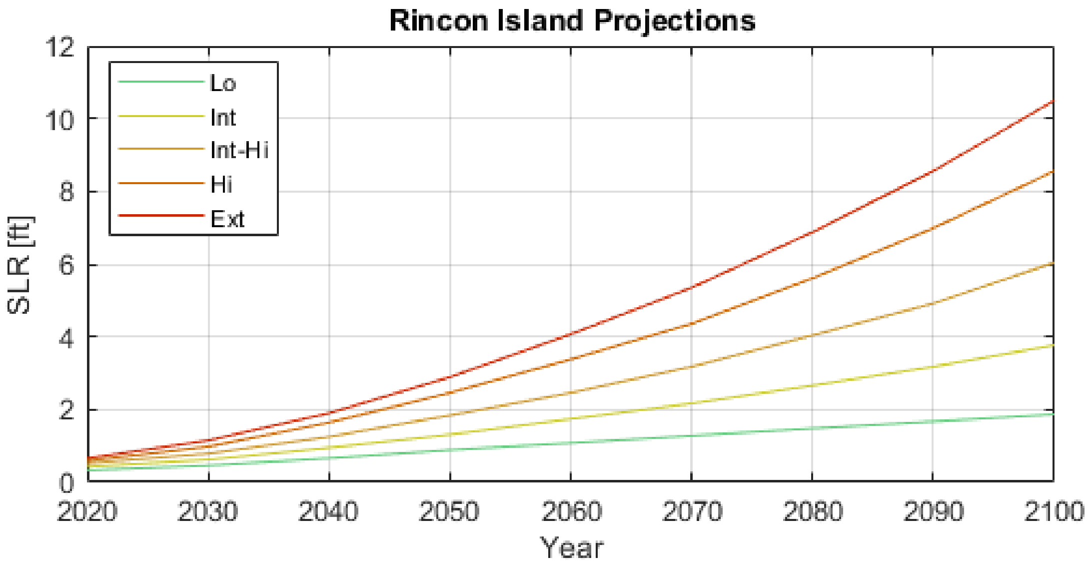


Figure 3. Sea Level Rise Projections for Five Scenarios (low, intermediate, intermediate-high, high, and extreme) from Sweet et al. (2017) at Rincon Island Water Level Station.

Table 7. Decadal Sea Level Rise Projections at Rincon Island from Sweet et al. (2017) with Projections from OPC 2018 at Santa Barbara Indicated in Parentheses[1].

Sea Level Rise Projections	Lo [ft]	Int-hi [ft]	Ext [ft]
2020	0.33	0.52	0.66
2030	0.46 *(0.4)*	0.79 *(0.7)*	1.15 *(1.0)*
2040	0.66 *(0.7)*	1.25 *(1.1)*	1.9 *(1.6)*
2050	0.89 *(1.0)*	1.84 *(1.8)*	2.89 *(2.5)*
2060	1.08 *(1.0 – 1.3)*	2.46 *(2.2 – 2.5)*	4.07 *(3.6)*
2070	1.28 *(1.3 – 1.7)*	3.18 *(2.8 – 3.3)*	5.35 *(4.9)*
2100	1.87 *(2.0 – 3.1)*	6.04 *(5.3 – 6.6)*	10.5 *(9.8)*

[1] OPC 2018 sea level rise projections are included for low-risk aversion, medium-high risk aversion, and extreme risk aversion estimates at Santa Barbara. A range is shown where both low and high emission scenarios were reported (OPC 2018).

2.5 INLET OBSERVATIONS

Data collected by Casitas Municipal Water District (CMWD) since 2005 was used to verify and validate the inlet opening and closure model. The inlet conditions (open, closed, and intermittent overtopping) have been visually inspected by CMWD approximately every 2 weeks since 2005. Additional data have been collected by CMWD including discharge at Foster Park and estuary water level measured from the railroad bridge shown in Figure 4. As can be seen in the figure, the inlet is more frequently closed during dry periods and during wet periods, the inlet appears to be open or intermittently open over long time periods (years). These data have been acquired by Integral from CMWD and are detailed in the Robles Fish Passage Facility Progress Reports from 2006–2017.

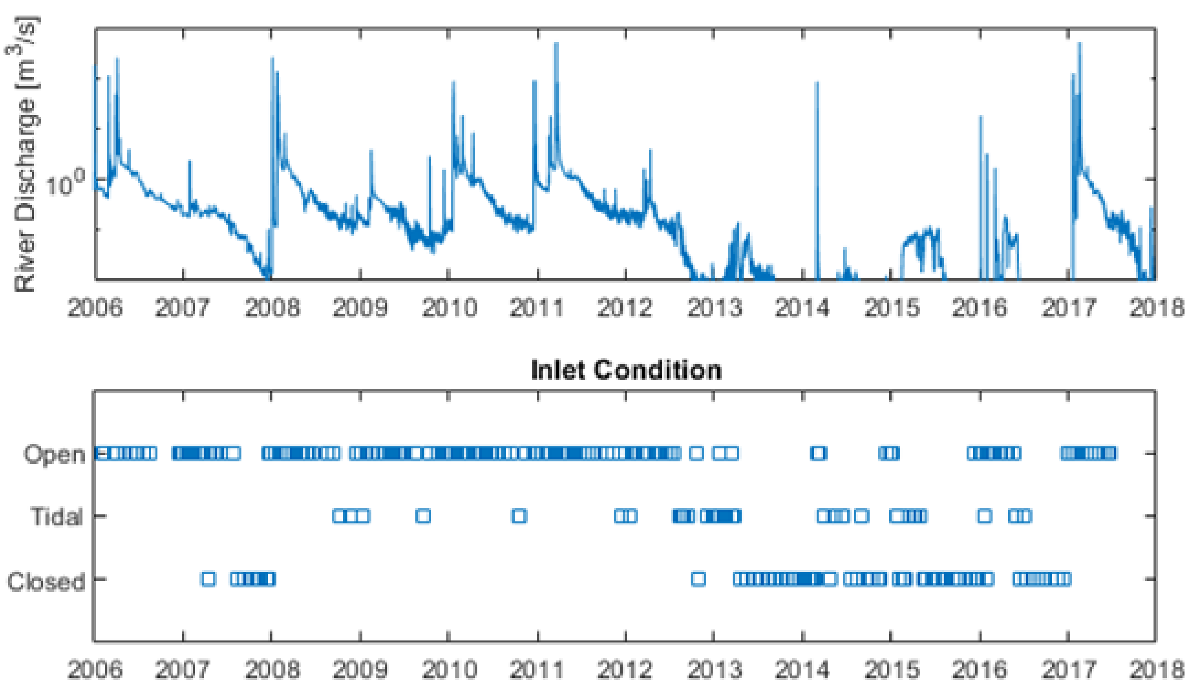


Figure 4. Ventura River Discharge (USGS gauge station; top panel) and Inlet Observation Data Collected by CMWD (Robles Fish Passage Facility Progress Report from 2006–2017; bottom panel)

2.6 SHORELINE POSITION OBSERVATIONS

Long-term shoreline change modeling using the USGS CoSMoS-COAST (Vitousek et al. 2017) will rely on historical shoreline data for data assimilation. The shoreline and beach change data will also be used to develop a large scale sediment budget (Patsch and Griggs 2006). Shoreline data have been compiled from the following sources:

- USGS National Assessment of Shoreline Change (SoCal—1852, 1920, and 1971)
- USGS BEACON regional survey lines (1987–present) and Focus Areas (2005–present)
- Revell (2007) historical shoreline data (1870s–2005)
- Digitized historical air photos.

The USGS BEACON regional survey data have been collected every other year and twice yearly in the focus areas. The shoreline profiles are collected from onshore to offshore and generally, the shoreline profiles have changed little from survey to survey over the past decade indicating there may be significant rocky regions. USGS has additionally conducted beach topography surveys every spring and fall including the position of mean high water, which can be used to evaluate the long-term shoreline change model. Variation in shoreline position can be observed seasonally with shoreline erosion during the winter and accretion during low wave periods in the summer.

Historical aerial photos in the region have been made available by the University of California, Santa Barbara and the National Mapping Database, and historical topographic maps are available from USGS. The mapping of estuary delineation indicates that historical breaching more typically occurred near the eastern edge and that breaching on the western side of the beach has developed more recently. To address the transient and variable breaching location, an analysis of sensitivity to breaching location will be conducted. Additional shoreline position and beach width data are available from Revell (2007), the USGS National Assessment of Shoreline Change for SoCal, and from historical digitized aerial photographs. A sample of the available shoreline data is shown in Figure 5.

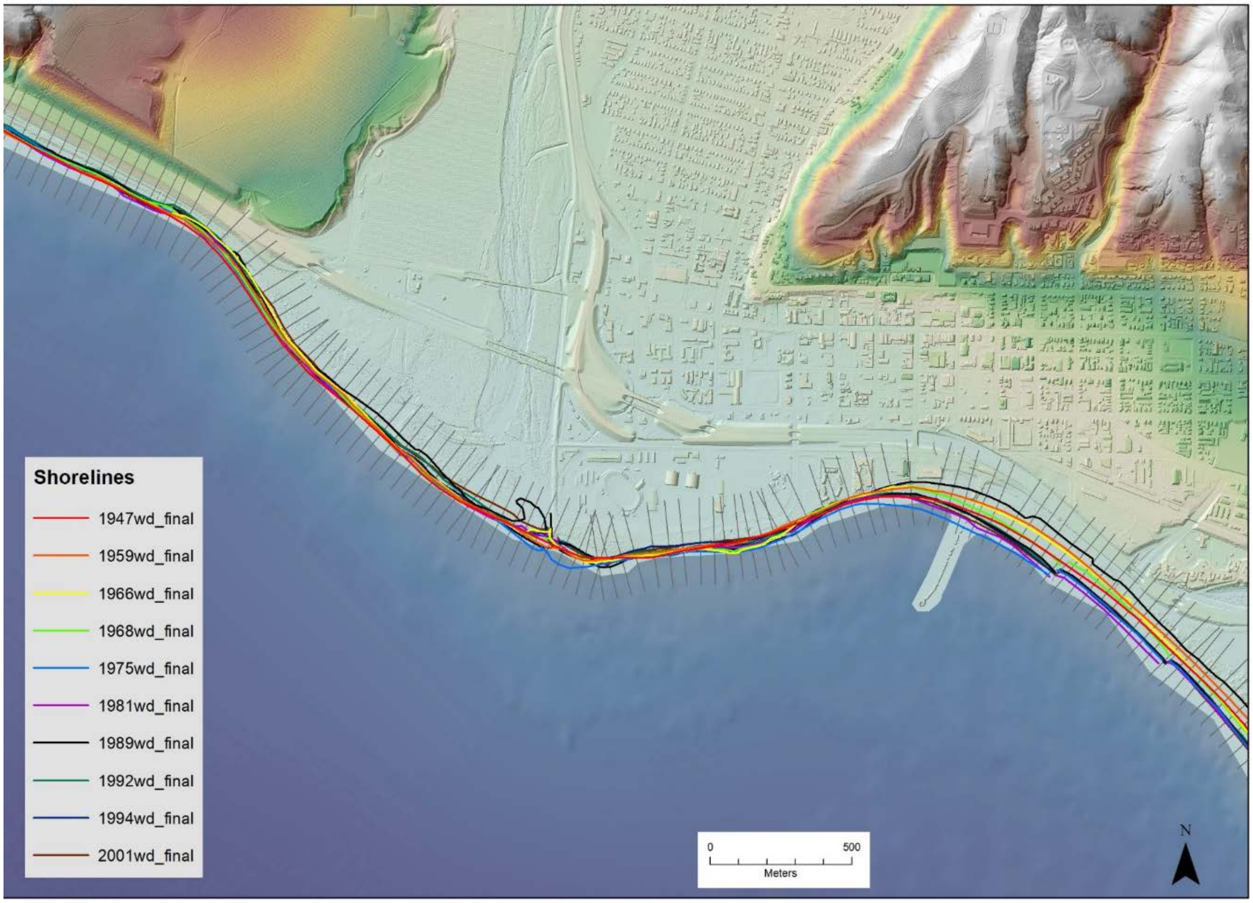


Figure 5. Subset of Shoreline Profiles (Revell 2007) Mapped onto the DEM.

2.7 HABITAT DATA AND METRICS

The primary goal of the estuary and coastal modeling effort was the characterization of physical stressors caused by sediment from the dam to habitat and species within the estuary and coastal ocean. Current habitat mapping within the estuary is limited so the team relied on a detailed mapping effort from 1990 to begin to evaluate sedimentation impacts on estuary habitats habitat (Ferren et al. 1990). A digitized map of the habitat survey (Figure 4) was used to evaluate potential habitat stressors due to sedimentation within the estuary following dam removal. More current habitat mapping that coincided with recent elevation data would improve this analysis and may be warranted in future work.

Coastal habitats ranging from sand to cobble beaches provide diverse flora and faunal resources in the area such as giant kelp and lobsters that could also be potentially impacted by the Matilija Dam removal (Hunt et al. 1992). Anthropogenic disturbances in intertidal marine habitats have been investigated in Sousa (1979) and documented by others in southern California (for example Klose et al. 2015).

Figure 6. Digitized Map of Habitat from Ferren et al. (1990).

The removal of the Matilija Dam provides an opportunity to increase steelhead spawning and rearing habitat in the Ventura River watershed over existing conditions by reconnecting habitat upstream of the dam (Capelli 2004; Allen 2016). The Southern California steelhead Distinct Population Segment is federally endangered and important to California coastal ecosystems. Southern Steelhead are an anadromous *Oncorhynchus mykiss*, which like other salmonids transitions from freshwater to the ocean during its life cycle, and then returns to their natal rivers to spawn. Estuaries form an important link in this life cycle by providing juveniles habitat to grow and physiologically adapt to saltwater prior to their oceangoing life stage. Steelhead upstream migration can be impeded by barriers particularly during low-river flow periods. Significant changes to the estuary depth from sedimentation may cause additional challenges to their survival. Estuary opening and closure duration as well as wave overtopping and freshwater inflows may impact steelhead and estuary water quality conditions. Timing of inlet open versus closed conditions also has impacts on fish passage and water quality (CMWD 2017). Although steelhead rely on the estuary for a critical period of their life history, steelhead also spend most of their life cycle outside of the estuary. However, further north in central California, juvenile steelhead that rear in bar-built estuaries (versus upstream freshwater habitats) have faster growth rates, attain a larger size for their age, and have a higher ocean survival rates (Hayes et al. 2008); whether this life history strategy occurs in southern California estuaries is not known. In addition, bar-built estuaries that remain connected to their freshwater tributaries allow juvenile steelhead to move upstream if estuary water quality conditions become less suitable (Hayes et al. 2011).

The tidewater goby is another federally threatened species that is completely reliant on the estuary for all aspects of its life history/life cycle. A concenptual model of positive drivers and potential negative stressors for tidewater goby across its life cycle is shon in Table 8 and based on analysis at the Santa Clara River estuary. This sensitive species prefers low velocity conditions with sandy substrate for spawning. Tidewater goby habitat may be tempoarily or permanently modified when the Matilija dam is removed due to changes in the system, including sediment erosion, deposition, and sediment properties; water depth and duration of inundation; water velocities; and water quality.

Table 8. Tidewater Goby Life Stage Conceptual Model for the Santa Clara River Estuary Showing Positive Drivers and Negative Stressors (USFWS 2005; Hellmair and Kinziger 2014).

Life Stage	Negative Stressor	Positive/Beneficial Driver
Egg (the peak of spawning activity occurs during the spring and then again in late-summer; duration 9–11 days; spawns in burrows in soft sediments [e.g., sand, silt and mud])	1) Unseasonal breaching 2) Low dissolved oxygen 3) Toxics	1) Stable estuary water surface elevation 2) Substrate suitable for burrows 3) Low salinities (0–15 ppt) 4) Low velocity
Larvae (planktonic duration 1–3 days)	1) Unseasonal breaching 2) Rapid salinity change 3) High velocity 4) Low dissolved oxygen 5) Toxics	1) Stable estuary water surface elevation 2) Low salinities (0–15 ppt) 3) Low velocity
Juvenile (benthic)	1) Unseasonal breaching 2) Rapid salinity change 3) High velocity 4) Low dissolved oxygen 5) Toxics 6) Predation/competition by nonnative species	1) Stable estuary water surface elevation 2) Low salinities (0–15 ppt) 3) Low velocity 4) Submerged and emergent vegetation
Adult (benthic, 1-year lifespan typical)	1) Unseasonal breaching 2) High velocity 3) Low dissolved oxygen 4) Toxics 5) Predation/competition by nonnative species	1) Stable estuary water surface elevation 2) Low velocity 3) Submerged and emergent vegetation 4) Tolerant of high salinity

In addition to steelhead and tidewater goby, a wide range of other species utilize the Ventura River estuary seasonally or peridodically, including Pacific lamprey (Reid and Goodman 2016), forage fish such as topsmelt, and flatfishes. A wide array of species has been documented within the estuary (Yoklavich and Cailliet 2006); however, many of these species do not entirely rely on the estuary for completion of their life cycles. In contrast, the tidewater goby is almost completely reliant on the estuary for all aspects of its life history/life cycle (Table 8). Based on analysis of species within the estuary, the tidewater goby was selected as a key species for analysis because it is the most sensitive indicator for the ecology of the Ventura River estuary. Although steelhead relies on the estuary for critical periods of its life history, steelhead also spends most of its life cycle outside of the estuary.

The most fundamental life history requirements for tidewater goby are low velocity, stable water surface elevations, and low salinities (less than 15 ppt) during egg, spawning and early larval and juvenile life stages (e.g., spring, early summer). Early tidewater goby life stages require low salinity water quality for early growth and survival that typically occurs in the spring, when the hydrograph drops and the beach and outlet channel thalweg elevation build reducing salinity inputs. Similarly, juvenile steelhead rear in the estuary during the spring and summer season, and depend on cool water temperatures (less than 25°C; Boughton et al. 2017), low salinities, and rearing habitat with low velocity flows and abundant food sources. Unseasonal breaching can result in stranding, transport out of the estuary and exposure to high salinities in the estuary when they are not physiologically prepared. Out-of-season artificial breaching is a primary negative impact on survival of these life stages for both species and has resulted in mortality of tidewater goby and steelhead in the past (Swift et al. 2018).

Recent literature has improved scientific understanding of habitat factors affecting tidewater goby and steelhead survival. For example, earlier goby life stages lack tolerance of abrupt salinity changes, such as those that occur during breaches, particularly artificial breaches (Hellmair and Kinziger 2014). Not only are these life stages susceptible to transport out of the estuary during artificial breaches, but those that remain in the estuary are exposed to rapid increases in salinity and are also negatively affected. This early life history typically occurs during low wave conditions with reduced likelihood of wave overtopping. Artificial breaches also affect the adult life stage by stranding adults or transporting them out of the estuary to the coast during summer and fall, as observed by Swift et al. (2018). The adult life stage is the dispersive life stage for tidewater goby, and under natural conditions, natural breaching would occur when storm events increase river flows in the winter and early spring in the estuary and in adjacent rivers and streams, such that all of the nearby estuaries breach simultaneously and freshwater plumes along the coast can guide dispersing adults to adjacent watersheds and provide recolonization or genetic exchange (Lafferty et al. 1999). The percent of time that the mouth is open and the acreage of habitat are not good indicators for quality habitat conditions; however, percent time closed during critical life stages can be a reasonable indicator.

In addition, the adult tidewater goby can withstand high salinity conditions (i.e., in excess of 41 ppt [USFWS 2005]). Higher salinity conditions could help decrease competition and predation from nonnative invasive fish, but the estuary is unlikely become hypersaline, although it could become more saline under future sea level rise scenarios. Most nonnative fish predators and competitors in the estuary are less tolerant of saline conditions. Hence, periods of increased or variable salinity—especially in the fall during the more salinity-tolerant adult tidewater goby life stage and during the steelhead smolting stage—could improve habitat quality by making habitat less tolerable to many of the introduced fish predators and competitors.

The physical and biological features essential to the conservation of tidewater goby consist of persistent, shallow (approximately 0.3 to 6.6 ft [0.1 to 2 m]), still-to-slow-moving lagoons, estuaries, and coastal streams with salinity up to 12 parts per thousand (ppt), which provides adequate space for normal behavior and individual and population growth that contains (i) substrates (e.g., sand, silt, mud) suitable for the construction of burrows for reproduction; (ii) submerged and emergent aquatic vegetation, such as *Potamogeton pectinatus*, *Ruppia maritima*, *Typha latifolia*, and *Scirpus* spp., which provides protection from predators and high flow events; or (iii) presence of a sandbar(s) across the mouth of a lagoon or estuary during the late spring, summer, and fall that closes or partially closes the lagoon or estuary, thereby providing relatively stable water levels and salinity.

3 ESTUARY MODEL DEVELOPMENT

The estuary dynamics were modeled using a high-fidelity 2-dimensional hydrodynamic and sediment transport model (Delft3D) as well as an empirical mass balance inlet model. The two models were used to characterize dynamics within the estuary over both short-term events (i.e., dam removal and large flow events) and long-term (decadal) changes to the system (i.e., sea level rise). Each model was separately developed and validated, and the following describes development, setup, and validation of the Delft3D estuary model and the empirical inlet model.

3.1 ESTUARY MODEL (DELFT3D)

The Ventura River estuary model simulates discharge and sediment loading from the Ventura River through the estuary and to the coastal ocean over short-term events (i.e., days). The estuary morphology and habitat are dependent on the interplay of a number of dynamic processes. For instance, factors such as the shape of the estuary, beach berm conditions, and river flow dictate how sediment and water navigate to the ocean or become trapped and distributed within the estuary. To model the interplay of these processes over the time scales required to evaluate the Matilija Dam removal and future trajectory of the system, a hydrodynamic and sediment transport model of the estuary has been developed using the open source model Delft3D maintained by Deltares Inc.

The model is a state-of-the-art hydrodynamic modeling tool that has been validated in a wide variety of estuarine and coastal environments. The open-source Delft3D hydrodynamic and sediment transport model readily couples with other Deltares models including the wave model Simulating Waves Nearshore (SWAN), and a morphological model (Delft3D-MOR), allowing for transfer of model input and output parameters with the other modeling tools (e.g., river model, coastal model). In addition, the Delft3D hydrodynamic and sediment transport model allows wetting and drying of grid cells, which is important for accurately simulating river flooding and associated sedimentation.

Critical components for accurate modeling of the estuary include accurate engagement of the floodplains during high flow conditions and mobilization and transport of sediment through the system. For the purposes of model validation, a flood event in early February 2019 was selected because aerial photos of flooding and floodplain engagement were widely available[5] that allowed for qualitative validation of the model behavior. The event was a 5-year flood event (peaking at approximately 16,000 cubic feet per second [cfs]) and coincided with extensive qualitative information related to discharge/breach locations and flooding extents collected via

[5] Aerial imagery includes drone survey imagery from Friends of Ventura and drone-collected LiDAR imagery (Dr. Kiki Patsch) of the inlet and berm before and after the event.

photographs and video. Imagery of sediment delivery from the estuary to the coastal ocean indicate significant transport of silt and sand during the event. The following description of the estuary model development focuses on setup, results, and validation for the event observed in February 2019.

3.1.1 Model Development and Setup

The Delft3D Ventura River estuary model domain extends from the ocean to approximately 1 mile upstream of the coastal inlet and from the southern extent of Emma Wood Beach to the east and beyond the levee to the west (Figure 7). This area captures the extents of the estuary, the beach along the coast adjacent to the estuary, as well the floodplain regions (the agriculture field, the Ventura Beach RV Resort [RV park], and the trails and vegetation to the northwest of the estuary) that are known to flood during large events (Keller and Capelli 1992). Thus, these floodplain regions must be included to ensure that the model accurately captures the distribution of water and associated sediment load during high-flow events.

The 2-dimensional estuary model grid is rectilinear (square) with 5 m horizontal resolution. This relatively fine grid resolution captures key bathymetric features such as small channels and breach locations, which allow for accurate engagement of the floodplains (Figure 8). The model elevations at each grid cell were derived from the DEM. The LiDAR elevation data in the DEM were corrected to allow for flow under bridges. In particular, flow paths between the agricultural field and the RV park have been corrected to eliminate the West Main Street Bridge.

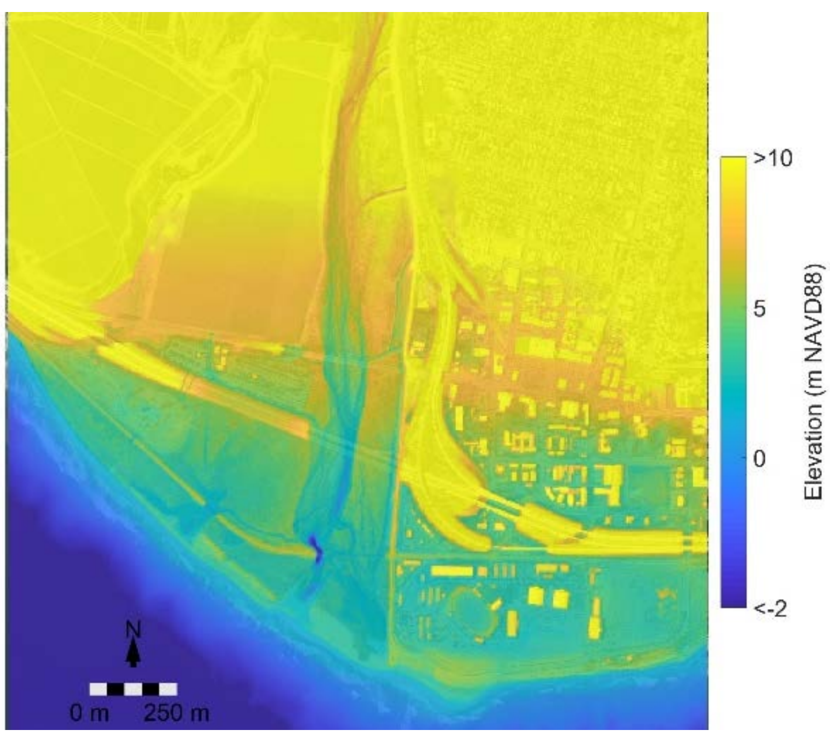


Figure 7. Estuary Model Domain with Elevation Data.

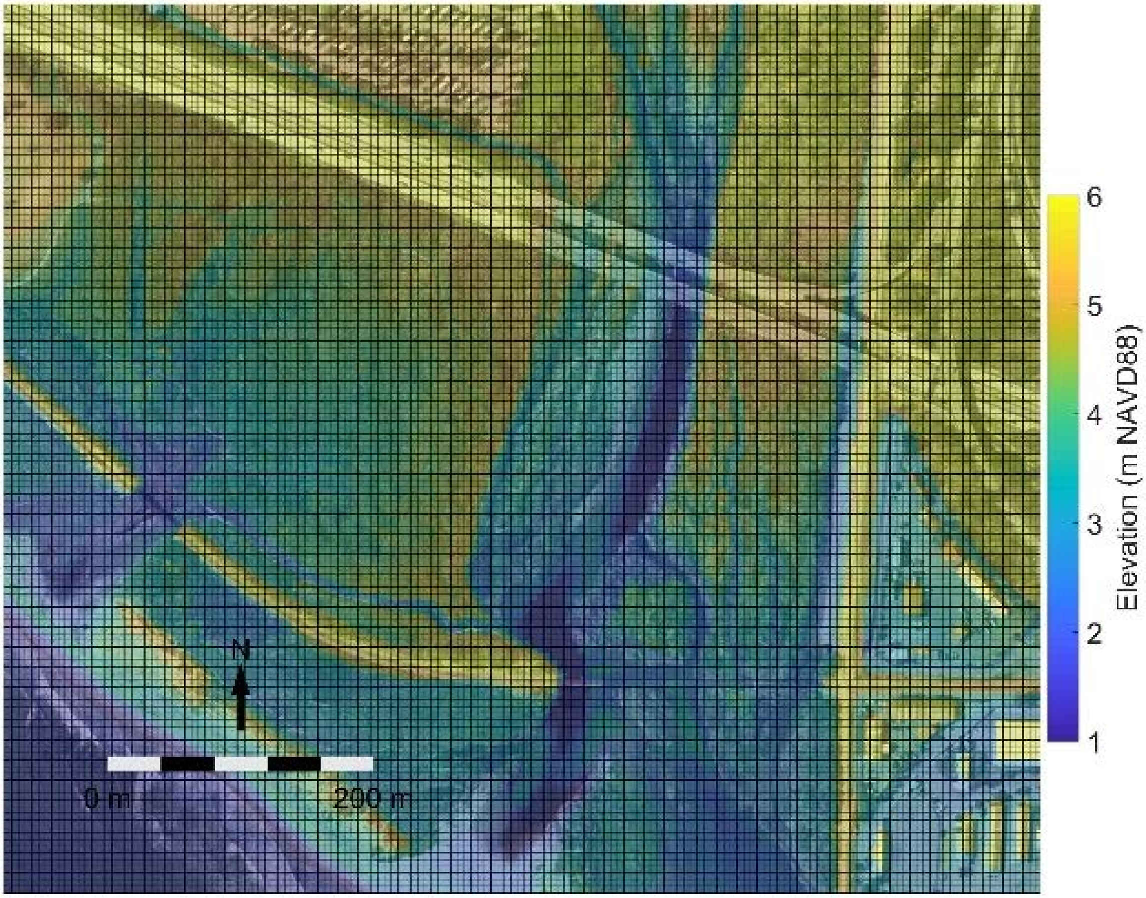


Figure 8. Estuary Model Grid (5x5m) and Elevation of Zoomed-In Region.

The estuary model boundary conditions include river discharge, sediment loading, and ocean water level over the duration of the February 2, 2019, flood event (Figure 9). As described above, the recent flood event was selected because of the extensive imagery and aerial photography available for qualitative validation of the estuary model.

The USGS gauge station (11118500) on the Ventura River provided river flowrates at the upstream boundary of the model. The sediment loading associated with river discharge was estimated using rating curves developed by AECOM and Stillwater (2016). The sediment loading for the validation event relied on sediment rating curves for the four sediment grain size classes (silt, sand, gravel, and cobble) developed under current (dam in place) conditions, described in Section 2.3. The current loading coefficients from Table 5 were used for the February 2019 flow event to generate sorted sediment concentration over the event. The grain sizes specified for included silt, sand, gravel, and cobble are 0.03, 0.2, 16, and 100 mm, respectively.

The NOAA water level station at Santa Barbara (9411340) provided water level measurements of the ocean. The water level elevation was applied to the southern boundary of the estuary model to incorporate the effect of tides on estuary dynamics and inlet transport. The model does not take into consideration local rainfall, evaporation, effects of wind, or ocean waves.

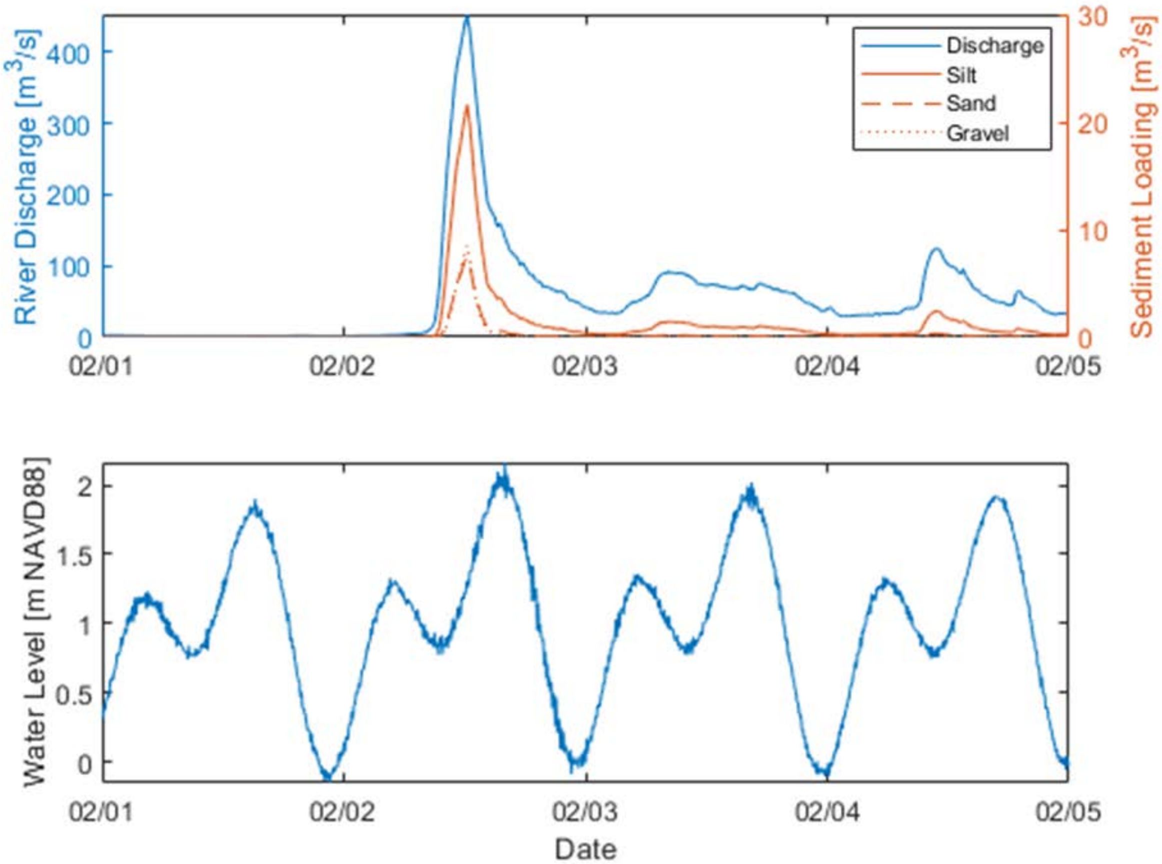


Figure 9. Ventura River Discharge and Sediment Loading (top panel) and Ocean Water Level at Santa Barbara (bottom panel) from the February 2, 2019, Discharge Event.

3.1.2 Model Results and Validation

Hydrodynamic and sediment transport results show good agreement with the qualitative data from 5-year discharge event on February 2, 2019 (Figure 9). Aerial footage captured after the peak discharge (approximately 16,000 cfs, or 450 m^3/s) displays the extents of the flooding in the agriculture field and the drainage both into the RV park and subsequently back into main river channel. In addition, flooding in the low-lying areas along the coast occurred around the train tracks and pooled near the western breach area. Figure 10 shows aerial imagery from the Friends of Ventura video footage on February 4, 2019, with key locations annotated.

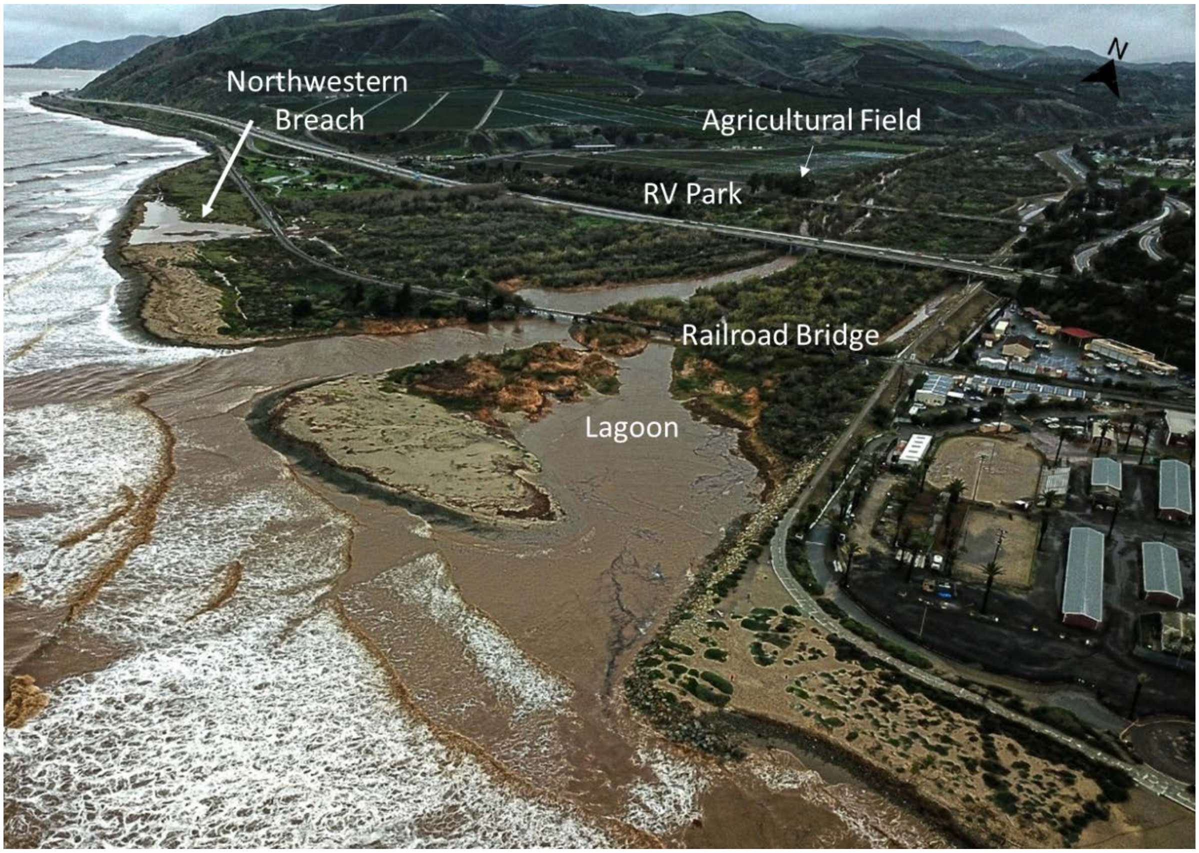


Figure 10. Aerial Imagery of Estuary and Flooding after Flood Event on February 4, 2019 (footage courtesy of Jimmy Young and Watchdog Ventura).

Prior to the flood event, modeled river flows are confined to the main river channels and bifurcate around the island in the estuary, connecting to the ocean in the main inlet as shown in Figure 11. Key indicators that the model is accurately simulating flooding include flooding of the southern portion of the agriculture field and subsequent flow into the RV park. As river flow increases, the river flow breaches the bank and flows into the agriculture field and the RV park (Figure 12). An additional key feature observed during the February 2 event is flooding into the third breaching location northwest of the estuary (northwestern breach). Floodwaters within the model are shown to extend west into the low-lying areas along the train trestles where they pool near the northwestern breach, consistent with aerial observations in the area (Figure 13).

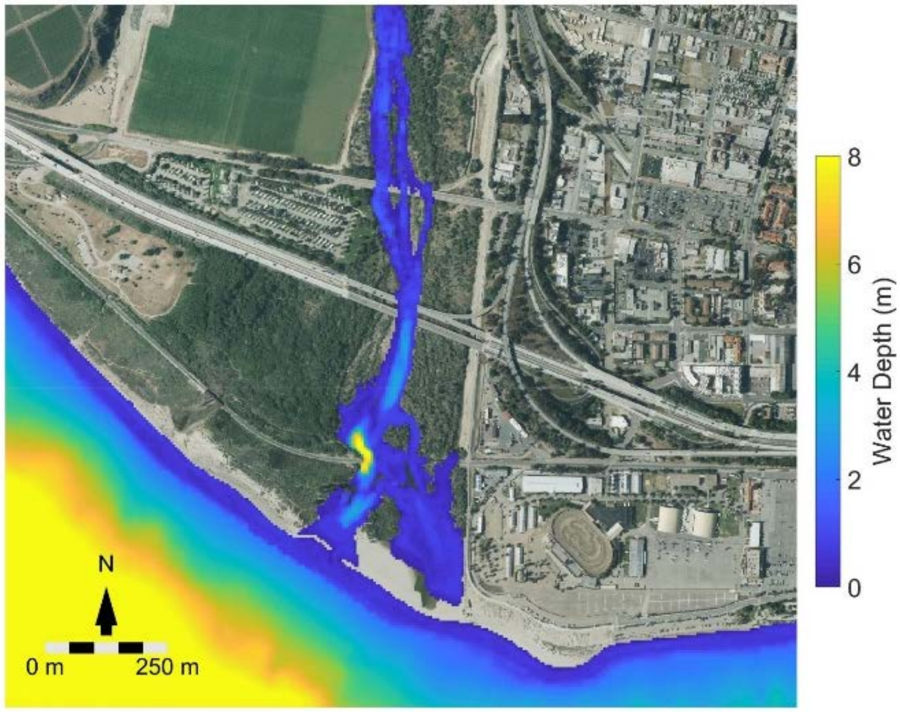


Figure 11. Modeled Water Elevations on February 1, 2019, prior to the Flood Event.

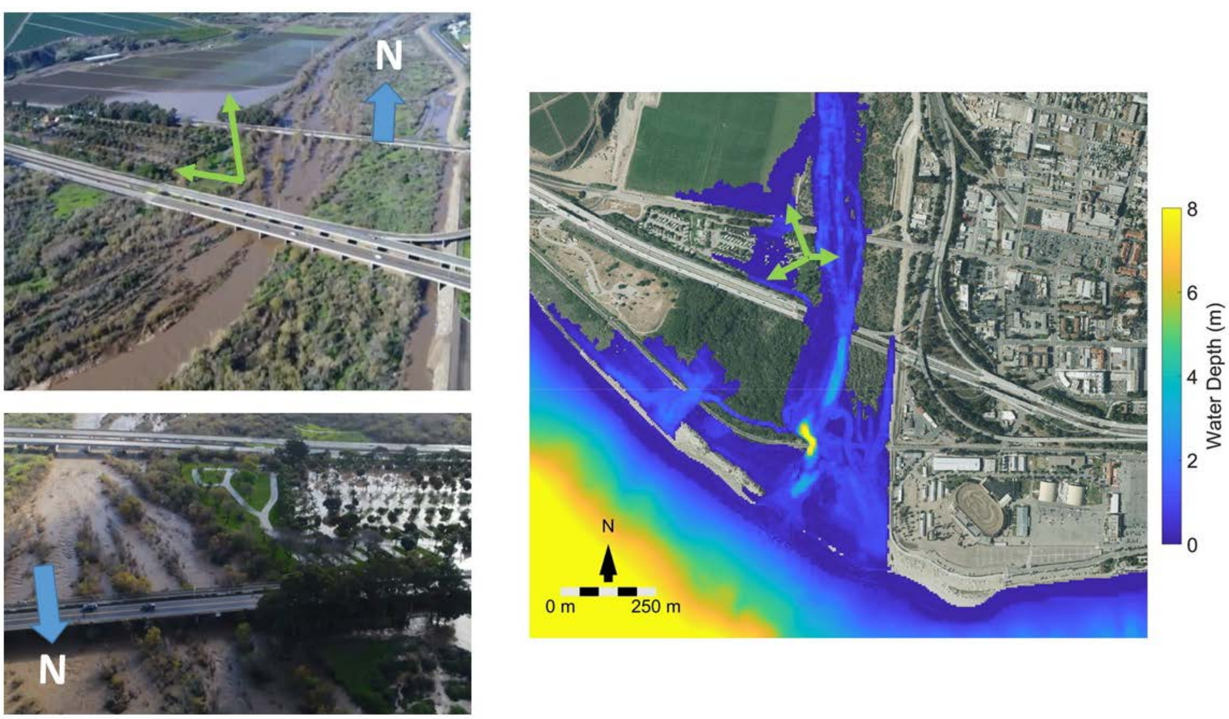


Figure 12. Photographs of Flooding Extents Taken February 4, 2019, in the Agriculture Field and RV Park (left) and Model Predicted Water Levels (right) with Green Arrows Indicating Regions with Similar Flood Patterns.

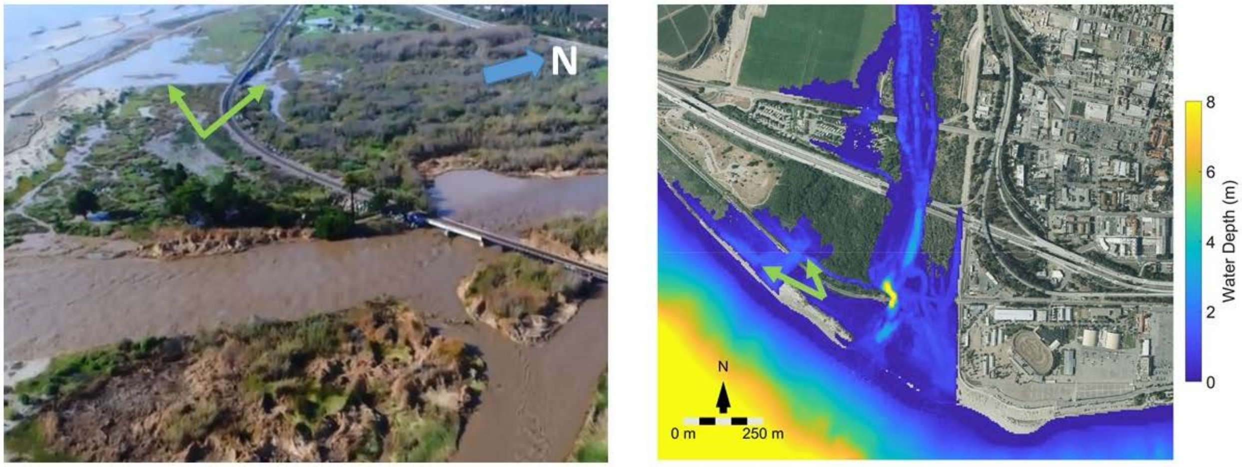


Figure 13. Photographs taken February 4, 2019, of Flooding in the Northwestern Breach Location and Along Railroad Bridge (left) and Model Predicted Water Levels (right) with Green Arrows Indicating Regions with Similar Flood Patterns.

The inclusion of sediment parameters during the flood event allowed for the analysis of distribution patterns across multiple sediment types. The silt and sand classes have different physical characteristics and therefore, the resulting transport dynamics vary. Silt particles readily move through the system and distribute to the coastal ocean. The silt loading was 3 times as large as sand loading at the peak of discharge during the event (Figure 9) and resulted in higher suspended sediment concentrations. The fine sediment grain size is readily transported into the floodplains and settles as shown in Figure 14. The sand loading is less mobile and results in a smaller deposition footprint in the regions immediately adjacent to the main river channels (Figure 14). The gravel and cobble loading is much smaller, and the larger particles are less mobile. While some of the coarse grain material propagates to the coastal ocean, the small coarse grain load predominantly deposits within the main river channel (Figure 14).

In summary, the estuary model was developed and validated using a flood event observed in February 2019. The event was a 5-year flood event (peaking at approximately 16,000 cfs) and coincided with extensive qualitative information related to discharge/breach locations and flooding extents collected via photographs and video. Overall, the estuary model was able to accurately reproduce flooding of the agricultural field and RV park, as well as flooding along the railroad track and at the northwestern breach location and transported silt and sand through the system consistent with the CSM.

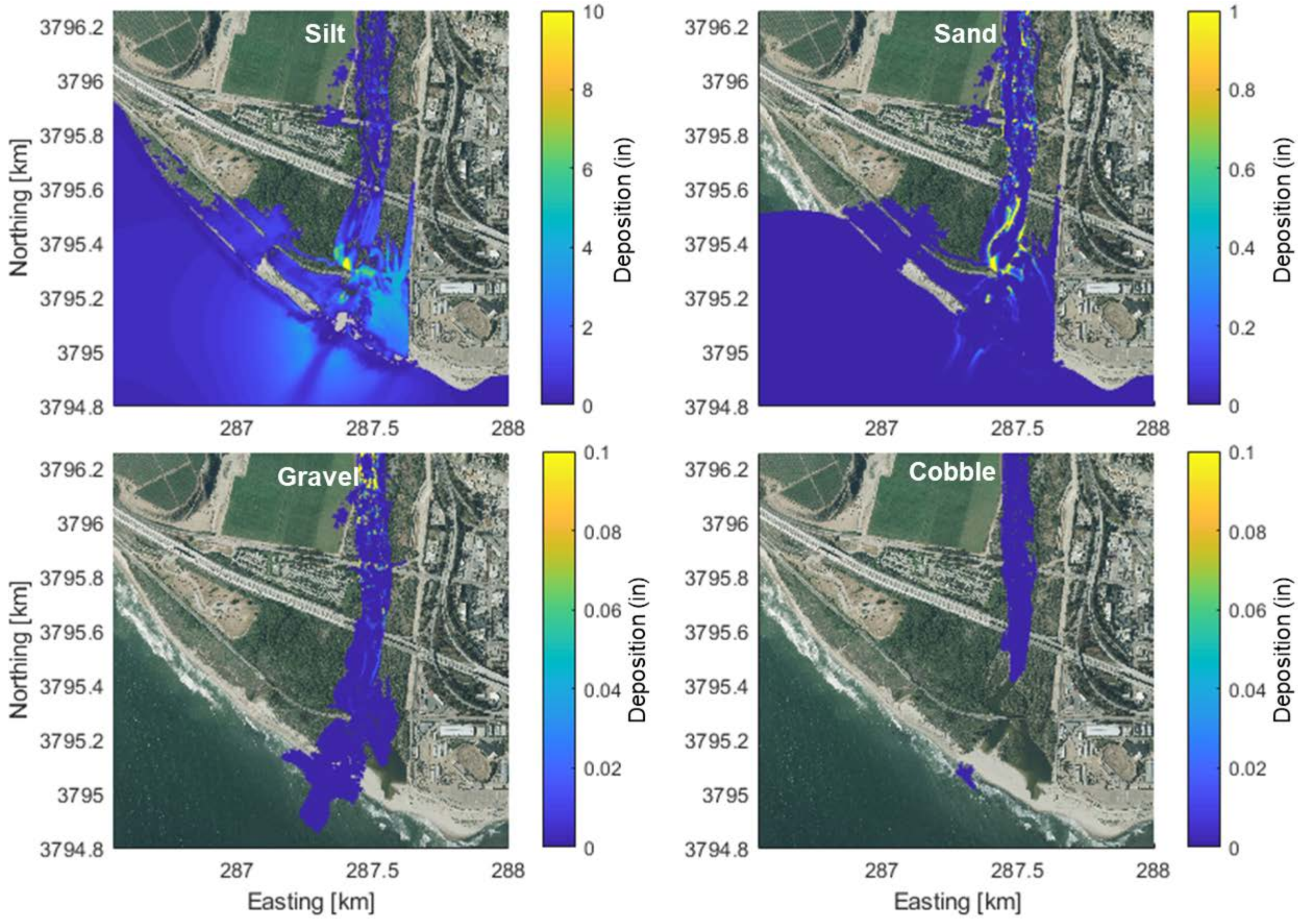


Figure 14. Model-Predicted Deposition in Inches for Silt (top left), Sand (top right), Gravel (lower left), and Cobble (lower right) after February 2, 2019, Flood Event.

3.2 INLET MODEL

The Ventura River estuary is typically closed to exchange of surface waters with the nearshore zone, but subject to occasional breaches of the bar due during high-flow events. Numerical modeling of the inlet dynamics is extremely challenging and remains a subject of open research. However, several empirical models have been demonstrated in recent years to be sufficiently accurate in modeling inlet dynamics (Rich and Keller 2013; Behrens et al. 2015). The inlet breaching and closure model developed by Rich and Keller (2013) relies upon a water mass-balance, control volume approach with various process-based fluxes into and out of the estuary.

The empirical models have been found to be useful in similar bar-built estuaries elsewhere in California, such as the Carmel River in Monterey and Scotts Creek in Santa Cruz. The inlet model is capable of reproducing seasonal inlet closure, breaching following high-streamflow events, and berm erosion and accretion by wave overwash. When conditions are met and the inlet is open, a tidally driven exchange of waterborne sediment occurs between the estuary and the coastal zone. Results of this model will provide estimates of the duration of lagoon opening and closures, as well as potential water level exceedances and the effect of modified estuary hypsometry (relationship between water level and lagoon volume). While transport of sediment and water to the coastal zone will be explicitly simulated by the estuarine and coastal models, the estuary inlet model will inform the frequency and duration of inlet breach conditions over both seasonal and interannual variability. The inlet model is critical to long-term simulation of inlet conditions and discharges that affect habitat and access for steelhead and tidewater goby.

The empirical inlet breaching model (Rich and Keller 2013; Behrens et al. 2015) relies heavily on available data sources to ensure that the model is accurately predicting inlet conditions. From available data and the CSM of the inlet, the seasonal variability of the inlet conditions is strongly driven by river and ocean conditions. For example, the inlet is typically open during the winter and spring when river discharge and wave energy are high (Figure 15). River discharge and wave forcing decrease into the summer and fall during which the inlet is more commonly closed. The inlet model development depends strongly on a firm understanding of the inlet dynamics driven by observations and forcing conditions at the site.

Data required for model development include berm, inlet, and estuary geometry, estuary water level, upstream discharge, wave and tidal conditions, and observations of inlet conditions. Data sources relied on for the inlet model include river discharge (USGS gage station), wave forcing (CDIP East Santa Barbara Channel), tidal forcing (Santa Barbara water level), meteorological data (CDIP East Santa Barbara and Oxnard Airport), estuary hypsometry, and observations of inlet conditions (Casitas Water District).

The berm geometry (berm height, beach width, channel width) was evaluated using available LiDAR data (Ventura County 2018 LiDAR) and LiDAR of the berm during different breaching conditions collected by Dr. Kiki Patsch. The available LiDAR data will be used to estimate typical berm conditions and any sensitivity of these parameters under different conditions. The hypsometric curve was developed from the DEM using the recent estuary bathymetric survey and topographic data. At each estuary elevation, the surface area and total volume of the estuary were computed using the polygon volume method in ArcGIS[6] (Figure 16).

[6] https://pro.arcgis.com/en/pro-app/tool-reference/3d-analyst/polygon-volume.htm

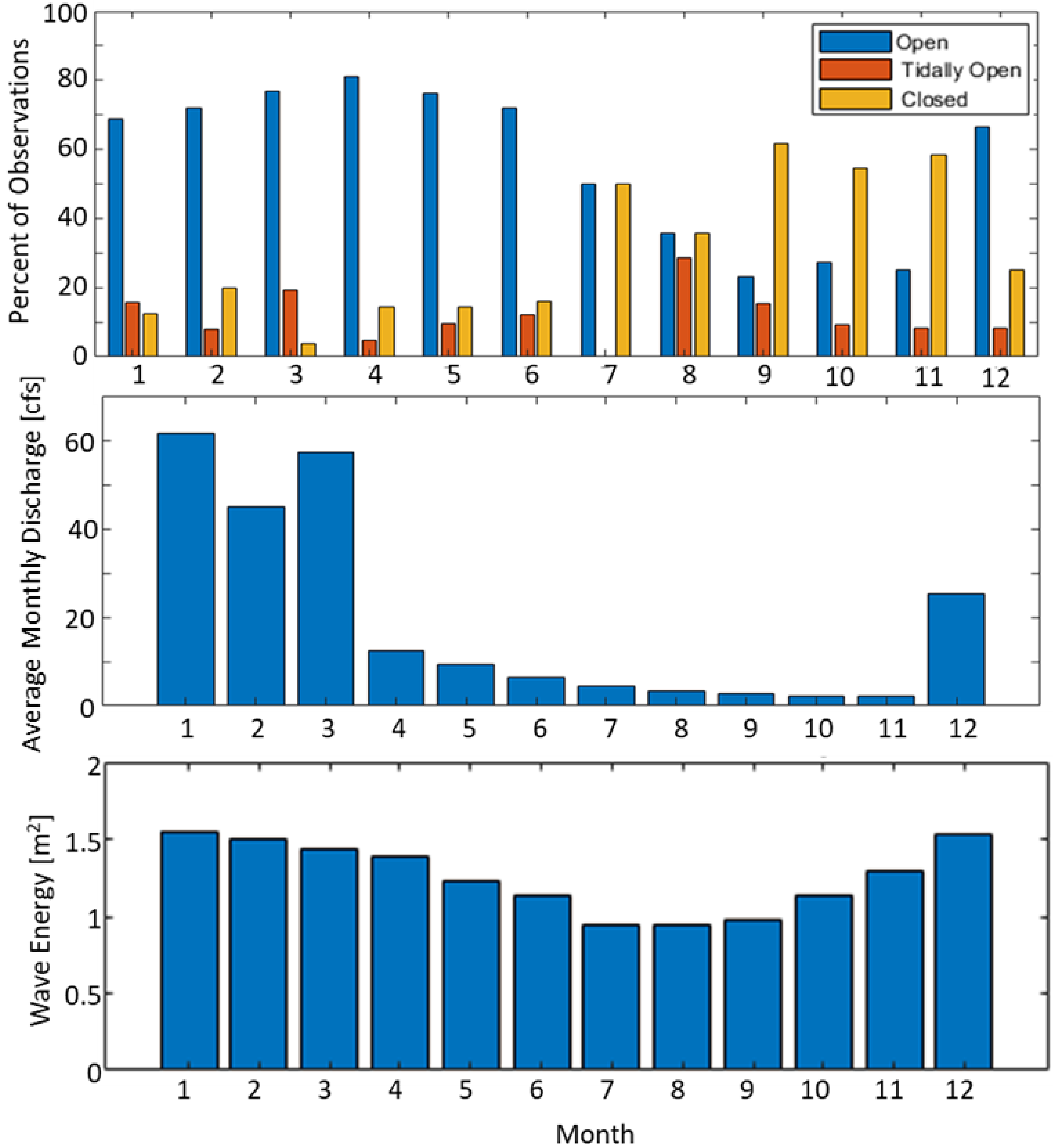


Figure 15. Percent of Observed Inlet Conditions (top panel), Average River Discharge (middle panel), and Average Wave Forcing (bottom panel) for Each Month of the Year.

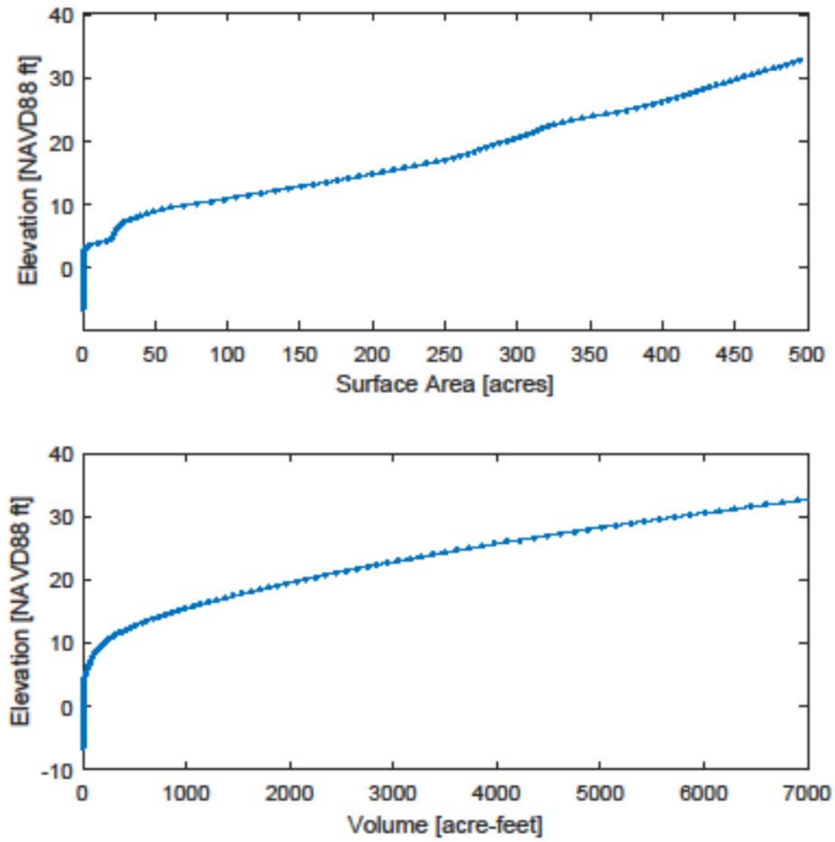


Figure 16. Estuary Hypsometry from DEM.

3.2.1 Model Development

The inlet model was developed following Rich and Keller (2013) and Behrens et al. (2015) using MathWorks® MATLAB. The model is a mass balance approach that evaluates fluxes of water into and out of the estuary as well as changes in the inlet elevation from fluvial erosion and wave swash, consistent with the model formulation described in Rich and Keller (2013) and Behrens et al. (2015). At each hourly time step, the volume fluxes of water into and out of the estuary are computed, the estuary elevation is updated based on the estuary hypsometry, and the inlet condition and elevation are then updated for the next time step. Volume fluxes into and out of the estuary include river discharge, wave overtopping, groundwater, berm seepage, and inlet discharge such that the total volume change in the estuary at each time step is given by

$$\Delta V = \left(Q_{river} + Q_{overtop} + Q_{groundwater} - Q_{seep} - Q_{inlet}\right)\delta t$$

where δt is the model time step. A schematic of the model formulation is shown in Figure 17.

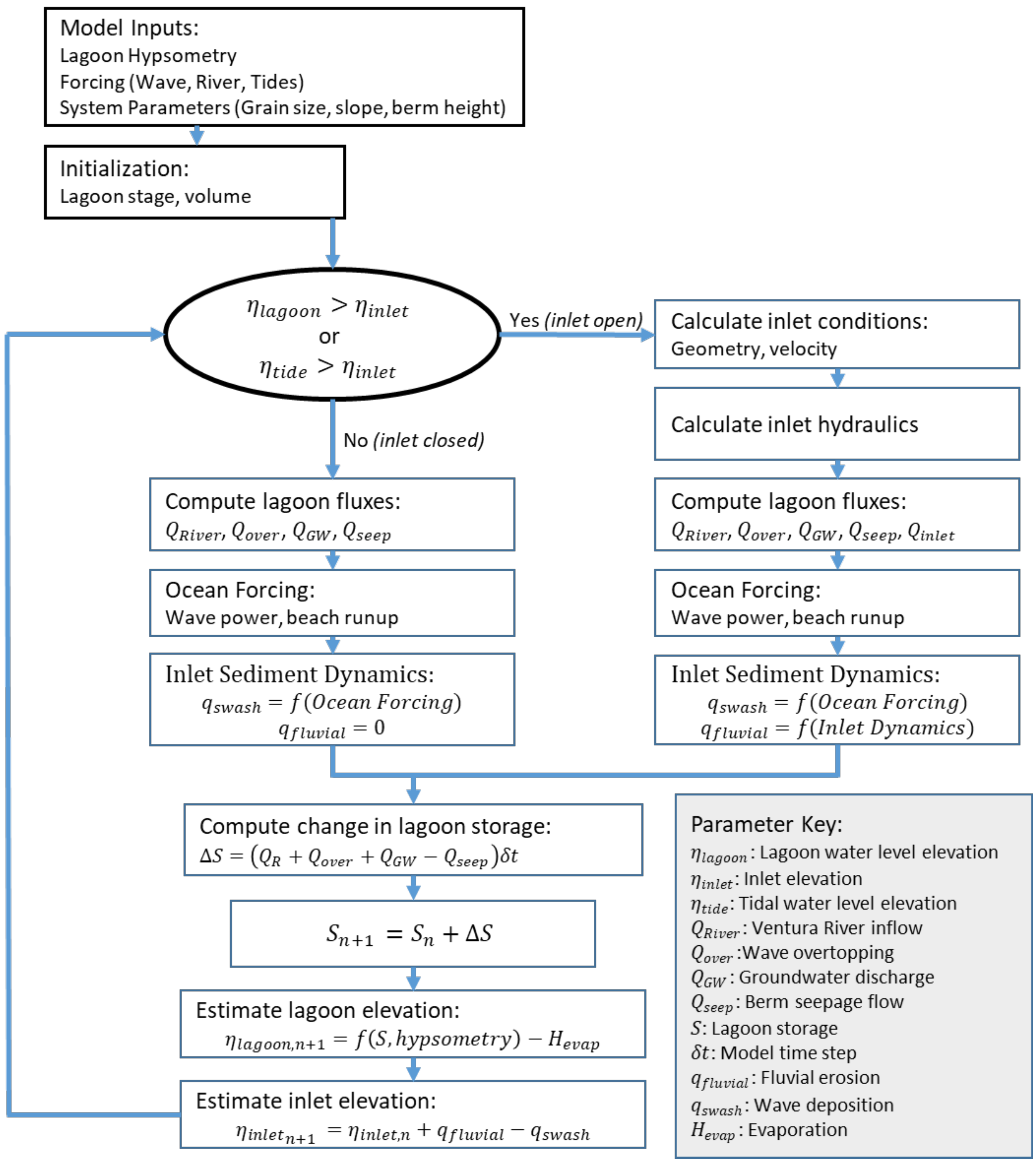


Figure 17. Inlet Model Formulation.

While the river discharge (Q_{river}) can be explicitly pulled from available data, the remaining fluxes into the estuary must be estimated with available data. The overtopping flux ($Q_{overtop}$) is computed following equations in Rich and Keller (2013) as a function of offshore wave conditions (from Anacapa Passage[7]), beach slope, water level, and berm length. The groundwater flux ($Q_{groundwater}$) is incorporated to contribute to estuary storage when river discharge is low. Due to limited availability of data on groundwater discharge, the flow rate was set following Rich and Keller (2013). The berm seepage rate (Q_{seep}) depends on the berm geometry and grain size characteristics as well as the water level of the estuary relative to the coastal ocean. When the inlet is closed, berm seepage serves as a primary mechanism by which water leaves the estuary.

When the inlet is open, the inlet discharge (Q_{inlet}) is governed by open-channel flow where the velocity through the channel is a function of the inlet slope and roughness. The inlet geometry is able to vary throughout the simulation depending on river discharge conditions (Rich and Keller 2013; Behrens et al. 2015). Due to the dynamic nature of the inlet, capturing the variability of inlet width and depth is critical to accurately estimating the inlet discharge. The inlet discharge is estimated using Manning's equation for open-channel flow based on the channel geometry, roughness, and beach slope.

Once all volume fluxes and sediment dynamics are computed, the volume fluxes modify the total storage in the estuary and the estuary elevation is then derived from the estuary storage based on the estuary hypsometry (Figure 16). The rate of evaporation (H_{evap}) is incorporated by modifying the elevation of the estuary. The evaporation rate is estimated as a function of wind speed, air temperature, and dew point temperature following the equation in Wanielista et al. (1997) and Martin and McCutcheon (1998).

In addition to volume fluxes, which modify the estuary storage, the inlet elevation is dynamically modified by fluvial erosion and wave-drive accretion. Fluvial erosion is computed from the inlet discharge and is based on the estimated velocity and shear stress in the inlet. When the inlet shear stress exceeds a critical shear stress value (based on sediment grain size), the inlet elevation erodes, given by $q_{fluvial}$. The inlet elevation can also be modified by wave-driven accretion of sediment (q_{swash}). When the wave power is low, the accretion of sediment on the inlet and berm are computed based on the wave runup and an estimate of sand deposition on a wave-by-wave basis. The wave swash parameter is computed at each time step regardless of inlet conditions. The inlet elevation is then updated based on the computed fluvial erosion and wave accretion. At the next time step, the inlet condition is then evaluated based on the computed estuary and inlet elevations and the observed ocean elevation (Figure 17).

[7] Anacapa Passage data were used instead of data from East Santa Barbara Channel because the East Santa Barbara Channel wave data have an approximately 1-year data gap in 2015 due to buoy servicing.

3.2.2 Model Results and Validation

The inlet model was used to simulate inlet observations from 2006 through 2017 with a time step of 1 hour. The model parameters were initially based on those described in Rich and Keller (2013). Figure 18 shows the river and ocean forcing conditions over the simulation period along with the observed inlet condition. The inlet condition was more frequently open from 2006 to 2012 during which the average observed Ventura River discharge was approximately 40 cfs. This was followed by a period of drought from 2013 to 2016, where the average river discharge was approximately 1 cfs. The interannual variability in the river discharge during this record is evident in the inlet breaching observations, with more frequent inlet closure observed during the drought. Over the period of observations, the wave forcing is consistently seasonal with larger wave heights observed during the winter months compared to summer months.

A critical component of the inlet model is dynamic erosion and accretion of inlet over time. The inlet is anticipated to rapidly erode and breach during high-flow events due to fluvial erosion associated with high shear stresses. During quiescent periods, the inlet is then expected to slowly close as sediment is accumulated due to wave driven processes. The model-predicted inlet elevation is shown in Figure 19 along with river discharge. As anticipated, the model is reasonably able to predict erosion during discharge events and accretion of sediment during quiescent periods.

Results of inlet model validation using observed inlet conditions indicate that the model was able to correctly predict observed inlet conditions 75 percent of the time (Figure 20). Differences between modeled and actual inlet conditions, when observed, were primarily due to phase lags in opening and closure rather than the actual inlet condition itself (i.e., 25 percent of the time the precise timing of intermittent events did not always perfectly align with observations). Overall, the model is able to accurately predict intermittent inlet opening associated with high-flow events and the subsequent inlet accretion and closure as well as the long-term inlet condition associated with high flow and drought. The ability of the model to capture the short- and long-term trends in observed inlet conditions provides confidence that the model can be used to evaluate inlet conditions under varying river, ocean, and meteorological forcing.

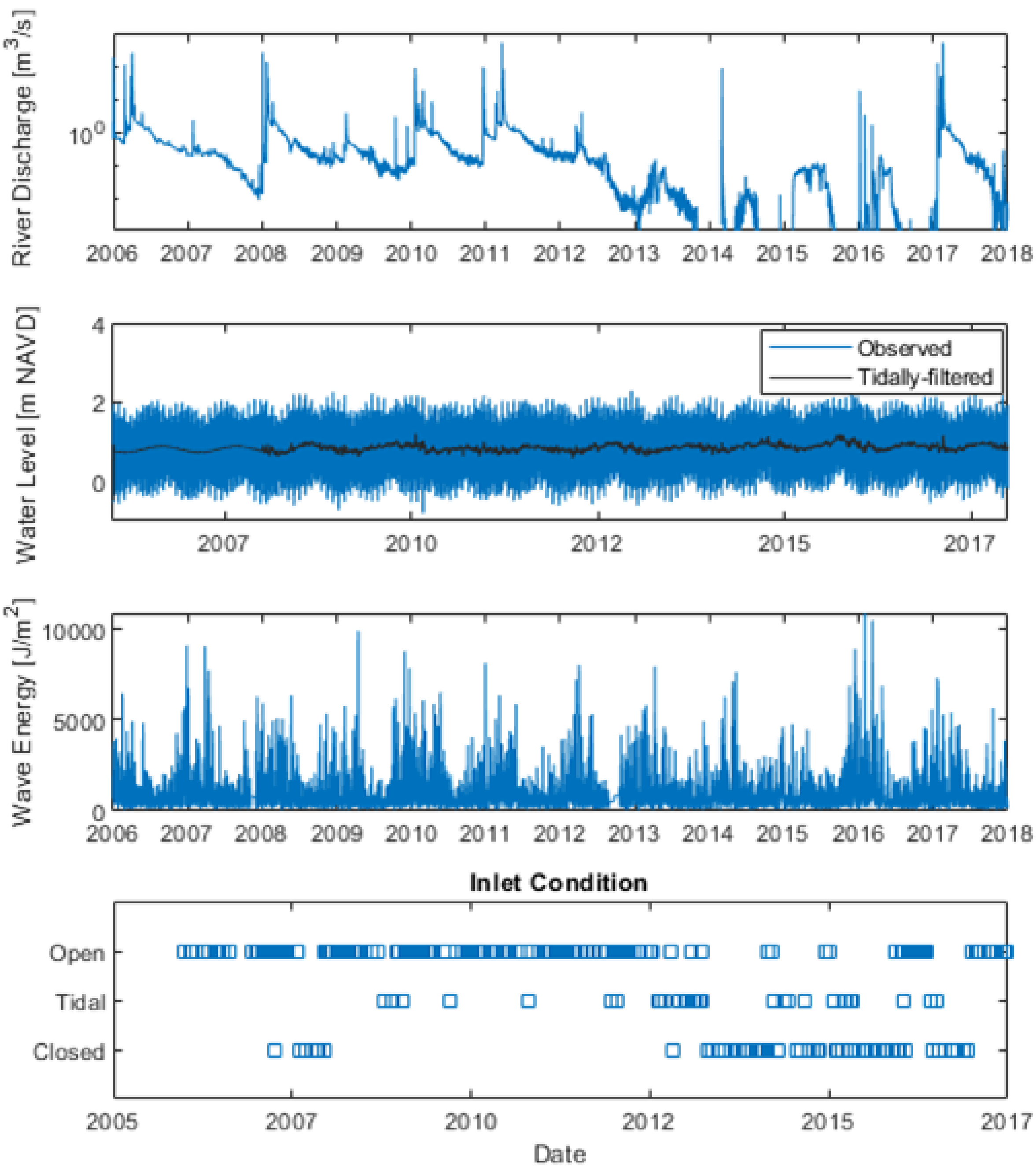


Figure 18. River Discharge (top), Raw and Tidally Filtered Water Level Observations (second panel), Observed Wave Energy (third panel), and Observed Inlet Conditions (bottom panel).

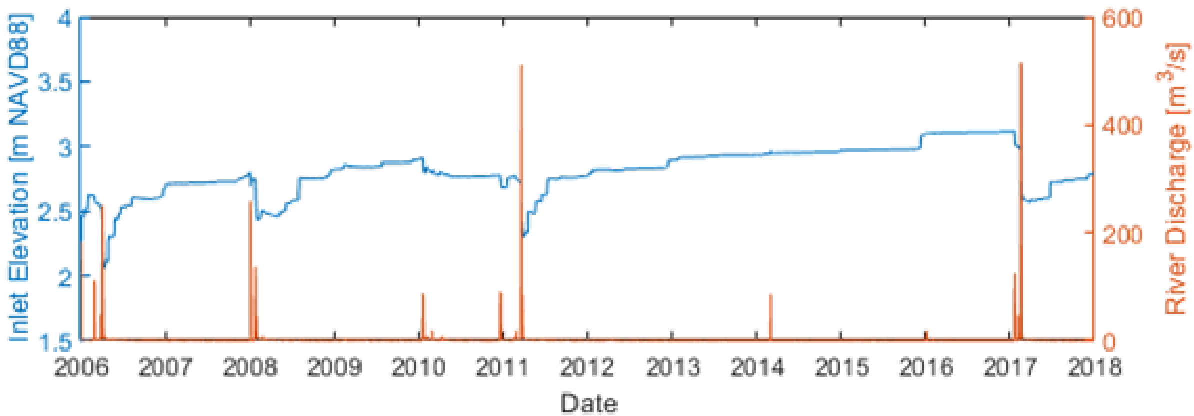


Figure 19. Inlet Elevation Erosion Due to River Discharge and Accretion.

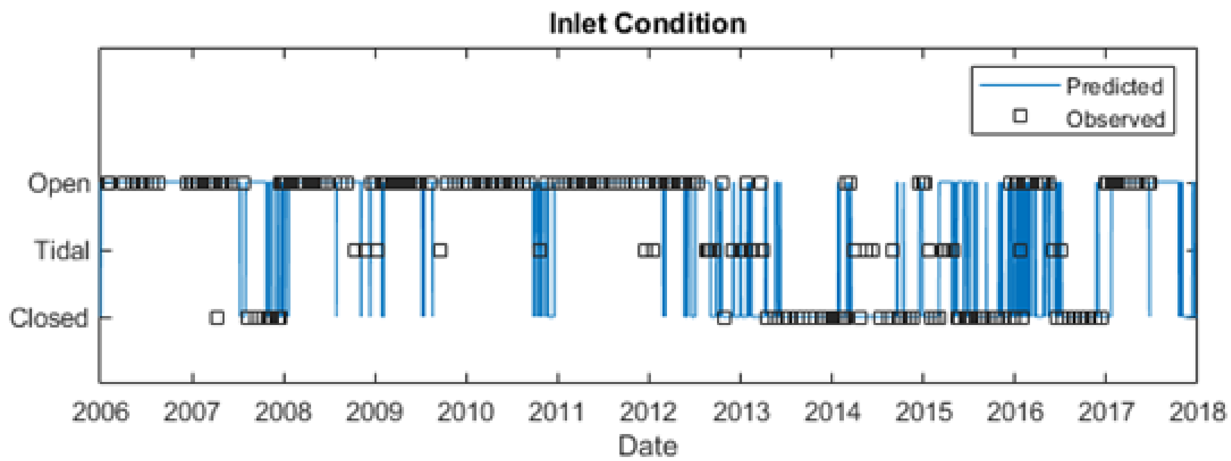


Figure 20. Comparison of Predicted and Observed Inlet Conditions.

4 COASTAL MODEL DEVELOPMENT

Characterization of sediment transport in the coastal ocean was conducted using two distinct models: a high-fidelity hydrodynamic and wave coupled coastal model (Delft3D/SWAN) as well as a long-term shoreline change model (COAST). The Delft3D/SWAN coastal model was used to simulate short-term events to accurately resolve transport of various grain sizes associated with large river releases, including dam removal and large return period events. In contrast, the long-term shoreline change model approximates complex wave and hydrodynamics to predict long-term (50-year) changes in shoreline position. The long-term model is informed by the high-fidelity, short-term modeling, but is able to incorporate long-term dynamics such as sea level rise.

4.1 COASTAL OCEAN MODEL (DELFT3D/SWAN)

Coastal ocean modeling was used to simulate event-based (i.e., days) transport of sediment from the Ventura River within the coastal ocean using high-fidelity modeling tools. Two distinct coastal ocean models were developed and validated: Delft3D/SWAN and XBeach. However, during evaluation of the two models, the XBeach coastal model was found to be inappropriate for this system because of the limitations in sediment grain sizes in the XBeach transport formulations. Although XBeach is a phase-resolved wave model that allows for slightly better resolution of wave dynamics, the inability of the model to transport coarse grain material (gravel and cobble) is a major limitation for this system in particular. Therefore, the coupled Delft3D and SWAN model (Delft3D/SWAN) was used to simulate transport from suspended sediment loading from Ventura River as well as deposited coarse grain material in the coastal region. The Delft3D/SWAN model is an open source model, which facilitates collaborative and transparent modeling efforts. The following describes the coastal ocean model domain and the diagnostic event chosen for qualitative model validation. Model development and validation is then described for the Delft3D/SWAN coastal model.

As described above, a coupled Delft3D/SWAN model was used to evaluate transport of suspended sediment from the Ventura River. The SWAN model simulates the offshore-to-nearshore wave propagation and transformation into the Ventura domain. The wave-induced radiation stresses from SWAN are incorporated into the Delft3D model to drive wave-induced currents and water levels. By forcing the Delft3D/SWAN models with offshore tidal, wind, and wave conditions, long-term simulations of waves, winds, water-levels, and local river flooding will be accurately simulated so that scenario-based hydrodynamics and sediment transport are quantified.

4.1.1 Model Development and Setup

The coastal ocean model extends from Emma Wood State Beach in the north to beyond Ventura Harbor in the south, with an offshore extent of approximately 4 km (Figure 21). Bathymetry over the model domain ranges from approximately 0 to 32 m water depth.

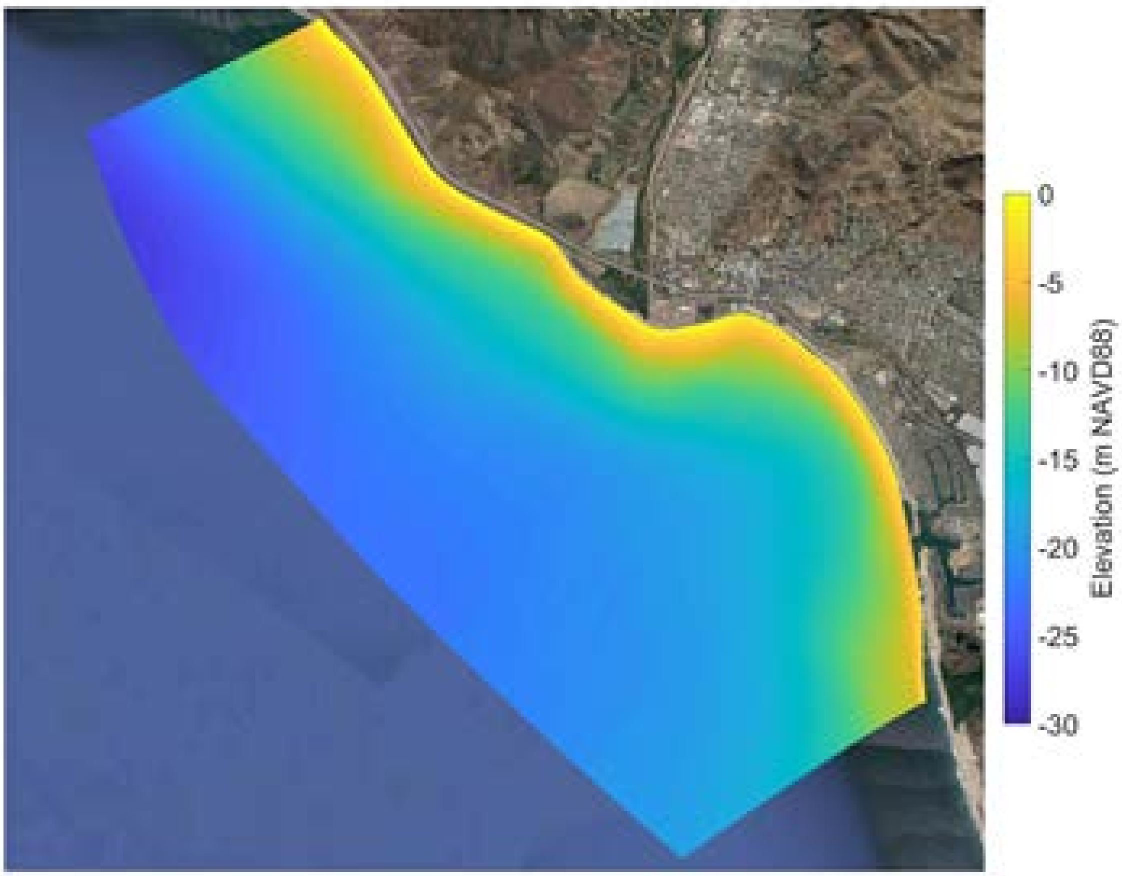


Figure 21. Overview of the Coastal Ocean Model Domain and Bathymetry.

The curvilinear, 2-dimensional Delft3D/SWAN model grid has varied resolution in order to better resolve the small-scale transport processes near the Ventura River mouth and in the nearshore region. The coastal model grid was refined such that the region near Surfer's Point (Figure 22) has the highest model resolution (16 m) while model resolution decreases (to 60 m) north of Surfer's Point and south of Ventura Pier. The nearshore region was resolved at 3 times the resolution of the offshore zone to better account for the smaller length scales of nearshore processes relative to the offshore zone. The water depth from the DEM (described above) was interpolated onto the model grid. While the bathymetry was smoothed in select locations to prevent numerical instabilities, important features and bathymetric gradients were retained.

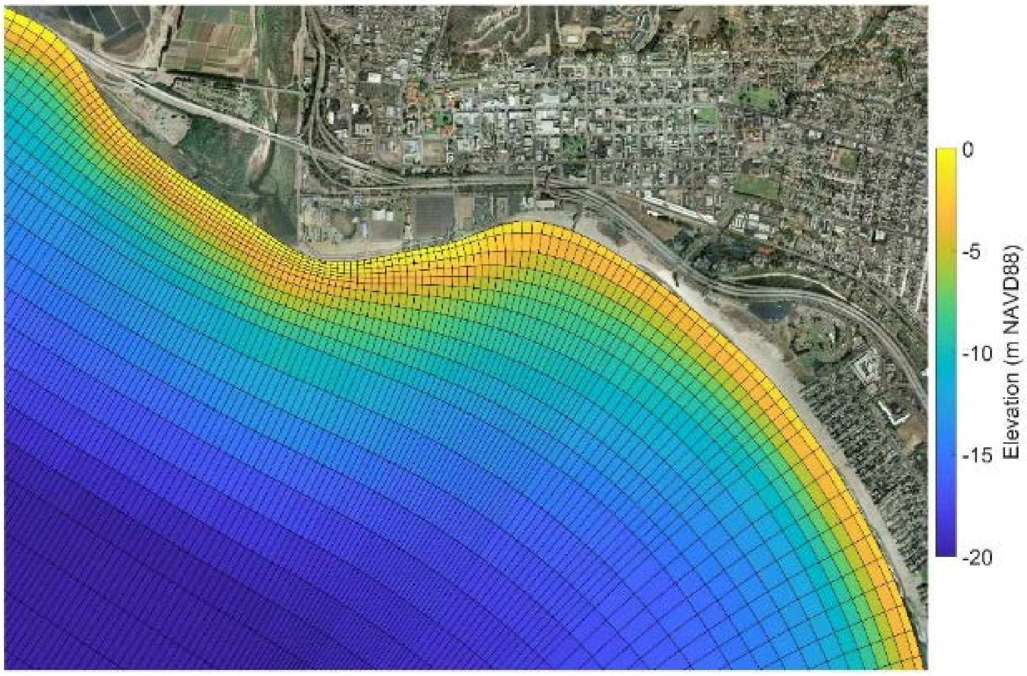


Figure 22. Close-up of the Ventura Coast Delft3D/SWAN Model Grid with Higher Resolution in the Nearshore and near the Estuary Mouth.

For the coastal model diagnosis and validation, a time period with both high river flow and high offshore waves was chosen. The January 17–18, 2019, flow and wave event (shown in Figure 23) was selected for the coastal simulations.[8] During this time period, the estuary was breached and the peak flow and sediment load on January 17, 2019, was followed by approximately 4 m (12 ft) offshore waves on January 18, 2019. These wave conditions can drive substantial sediment transport and the period provides ideal diagnostic conditions for the coastal ocean models to evaluate transport of river loading due to coastal ocean processes. Data for the event (shown in Figure 23) is from the USGS Ventura River gage station (11118500), the East Santa Barbara Channel CDIP buoy (46053), and the NOAA water level at Santa Barbara (9411340). The estimated silt, sand, and gravel loading from the river was computed using the sediment loading curves as a function of river discharge developed by AECOM and Stillwater (2016).

[8] The 5-year flood event on February 3, 2019, could not be simulated for the coastal ocean models because wave data from the CDIP buoys were unavailable as of March 10, 2019.

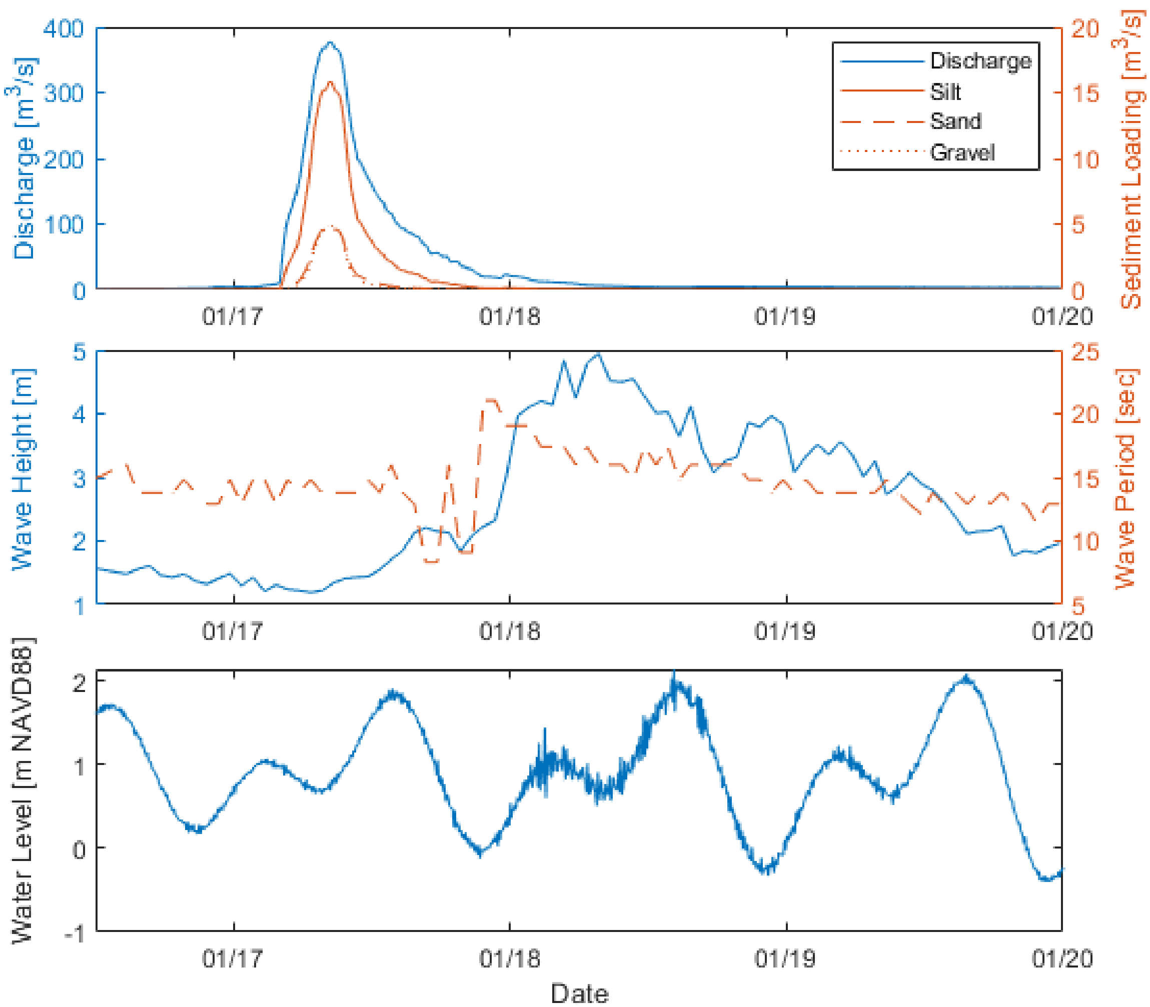


Figure 23. River Discharge and Sediment Loading (top panel), Wave Height and Period (middle panel), and Santa Barbara Water Level (bottom panel) Observed during the January 1718, 2019, Coastal Ocean Diagnostic Event.

Observed river and ocean forcing conditions over the event are shown in Figure 24. Measured ocean water levels from the Santa Barbara NOAA station (9411340) and the TPXO8 ocean tide model (Egbert et al. 2002) were applied at the open ocean boundaries to drive currents in the Delft3D hydrodynamic model. Measured offshore wave height, period, and direction from the NOAA East Santa Barbara buoy (46053) were applied to the north and west boundaries of the SWAN model grid to model the wave conditions incident to the model area.

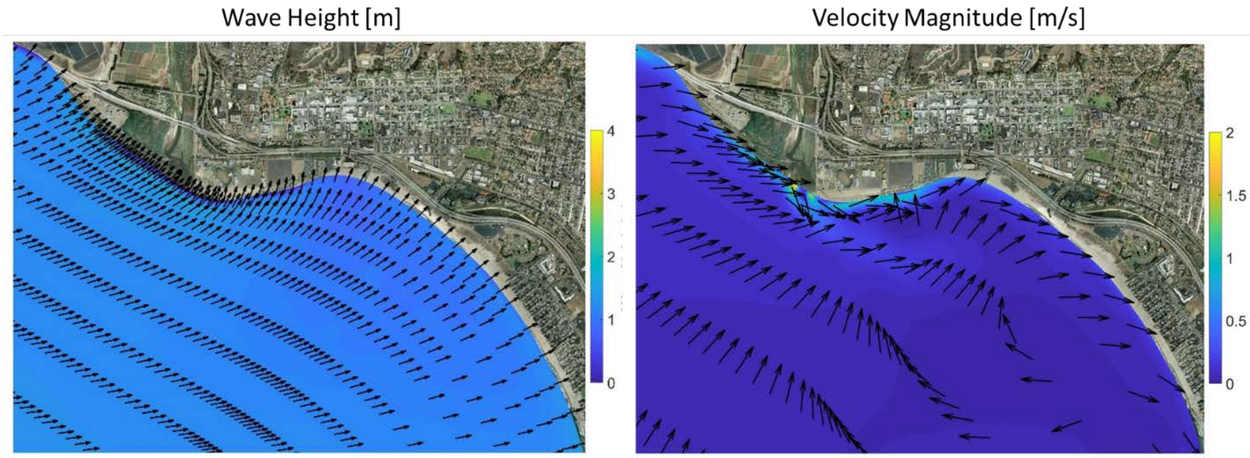


Figure 24. Wave Height and Direction (left) and Offshore Velocity and Direction (right) at 12:00 a.m. on January 17, 2019.

Sediment concentrations associated with river flowrates were derived from estimates developed by AECOM and Stillwater (2016). For the purposes of the Delft3D/SWAN diagnostic modeling here, it was assumed that no sediment is trapped in the estuary and the total sediment loading to the estuary is transported to the coastal ocean. The trapping in the estuary with realistic sediment loading to the coastal ocean will be included for final scenario simulations. The river flowrate and sediment loadings are applied to the coastal model at the location of the estuary breaches in the winter of 2019. The sediment size classes included for the diagnostic simulations include a 0.03 mm silt and a 0.35 mm sand. The sediment grain sizes for the dam and river release scenarios (described in the main report) are consistent with the estuary model. For the validation event, a coarse sand grain size was used based on observed offshore sand grain sizes (Mustain 2007).

The Delft3D/SWAN coupled model was run over the 2-day flow and high wave event. The wave simulations were conducted hourly and passed to the circulation model. The Delft3D circulation model was simulated for the entire 48-hour period with a 5-second time step. The wave conditions simulated in the SWAN model generate wave driven circulation (e.g., longshore transport) in the Delft3D hydrodynamic model.

4.1.2 Model Results and Validation

The Delft3D/SWAN model simulated a 48-hour January 2019 storm event. The river discharge and sediment loading are the highest at approximately 12:00 p.m. on January 17, 2019 (Figure 24). The period of peak river discharge coincides with small offshore wave heights (~ 1 m). Concurrently, the offshore currents are quite low, with the exception of velocities in excess of 1 m/s near the river mouth breach as seen in Figure 24. The nearshore transport is alongshore to the east and south even during these conditions of low waves. Figure 25 shows suspended silt and sand concentrations in the water column during the peak discharge. Consistent with the alongshore currents and anecdotal observations, a high concentration plume is transported to the south along the coast. The heavier sand particle transport predominantly as bedload and the total loading are much smaller than fine loading; therefore, the sand particles stay near the coast and are not transported as far as the silt particles. Overall the discharge plume transport is consistent with the CSM and observations in the area.

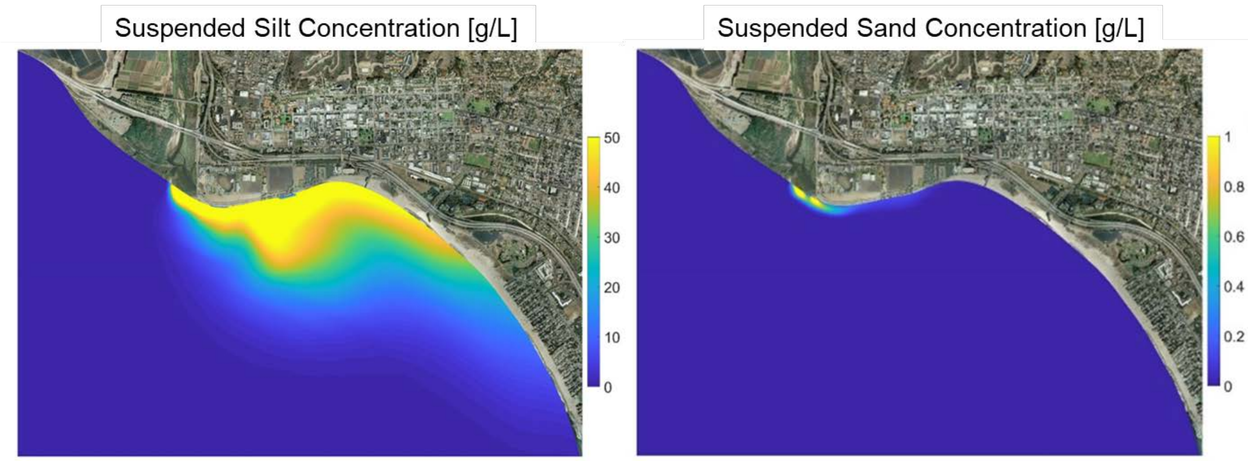


Figure 25. Suspended Silt (left) and Sand (right) Concentrations at 12:00 p.m. on January 17, 2019.

The maximum offshore wave height is approximately 4 m and occurs on January 18, after the peak discharge. Large waves during the simulation generate significant longshore transport in the nearshore (Figure 26). Velocities exceeding 1 m/s in the nearshore are consistent with anecdotal observations during large wave events. The sediment plumes associated with peak discharge have been transported alongshore and out of the region by the time the wave heights increase. Figure 27 shows the sediment mass deposited by the end of the event. The deposit is primarily sandy sediment from the river mouth and collects around the point where the wave heights and velocities decrease during the event. Overall, the modeled waves, currents, and sediment transport reproduce observed trends in the region, giving confidence that the Delft3D/SWAN modeling performs adequately for the next phases of the study. Improvements to the model based on additional observations may be made to increase model confidence and reduce uncertainty.

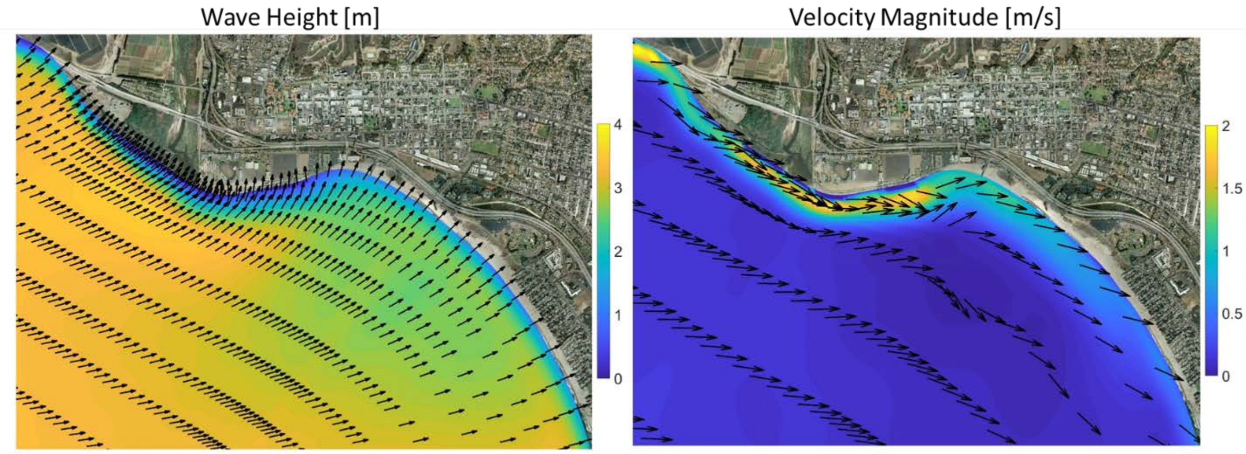


Figure 26. Wave Height and Direction (left) and Offshore Velocity and Direction (right) at 12:00 a.m. on January 19, 2019.

Figure 27. Sediment Mass Deposited from the River at 12:00 a.m. on January 19, 2019.

4.2 SHORELINE CHANGE MODEL (COAST)

The COAST long-term shoreline change model (Vitousek et al. 2017) has been developed and calibrated to the Ventura region and will be used to evaluate longer term coastal dynamics and morphology. The model is a one-line model to predict shoreline change over longer time scales using a combination of physics-based transport and data assimilation with available shoreline observations. The model computes the cross-shore shoreline location at a series of transect locations along the coastline. The shoreline change is a function of computed alongshore-sediment transport, a cross-shore equilibrium shoreline model, shoreline migration due to sea level rise, and long-term unresolved shoreline processes. A component of the COAST model is data assimilation of historical shoreline position to characterize a number of unresolved shoreline processes (such as unresolved sources or sinks of sediment including fluvial inputs, cliff failure, offshore transport, etc.). The model data will be used to evaluate the effects of long-term sediment loading from the Ventura River on beach and inter- and subtidal habitats.

4.2.1 Model Setup

The COAST model for the Ventura shoreline was developed with transects every 20 m along the coast. The transect locations form the model grid (Figure 28), where shoreline position is predicted at each model time step. Due to the presence of hardscape along the Ventura coastline, a non-erodible shoreline was also defined. The non-erodible shoreline sets the minimum allowable shoreline position predicted by the model.

Figure 28. COAST Model Grid with Transect Locations.

Offshore wave forcing for the long-term shoreline change model is from the CDIP buoy at Anacapa Passage,[9] which provides significant wave height, peak wave period, and dominant wave direction every 30 minutes. The offshore wave height, period, and direction were run through a wave refraction model (an enhancement to the COAST model) to predict nearshore wave angle relative to the shoreline angle at each transect location. The wave refraction model uses the shoreline angle, offshore wave angle, and Snell's law to iteratively estimate the nearshore wave angle.[10]

Additional COAST model forcing includes sediment loading from the Ventura River. For the purposes of model evaluation, we have used the upstream sediment loading curve (AECOM 2016) and have assumed that there is no sediment trapping in the estuary. This assumption will be updated once the suite of short-term, event-based modeling of the estuary and coastal ocean have been completed. The assumption is appropriate for the diagnostic modeling of shoreline change to ensure the model is able to reliably transport periodic sediment delivery from the river down the coast.

For the purposes of model evaluation and validation, the COAST model was set up for a 10-year simulation to coincide with a period of extensive shoreline sampling. The model was run with a 1-day time step beginning in October 2006 and running through October 2018. The model was run without data assimilation or sea level rise to evaluate the model's ability to predict observed shoreline positions. Data assimilation was subsequently used for the dam removal and sea level rise forecast model scenarios developed and described in the main report. Model forcing parameters including offshore wave height, offshore wave direction, and sediment loading from the river were applied over the simulation period (Figure 29).

[9] The CDIP buoy from East Santa Barbara channel was also initially used; however, the buoy was serviced with no available data for a long period in 2015.
[10] As described in the main report, the forecast simulations used available nearshore wave forecast from USGS. Nearshore wave data were unavailable during the period with the most available shoreline position observations (2005–2015). Therefore, the wave refraction model and offshore wave data were used in the validation case.

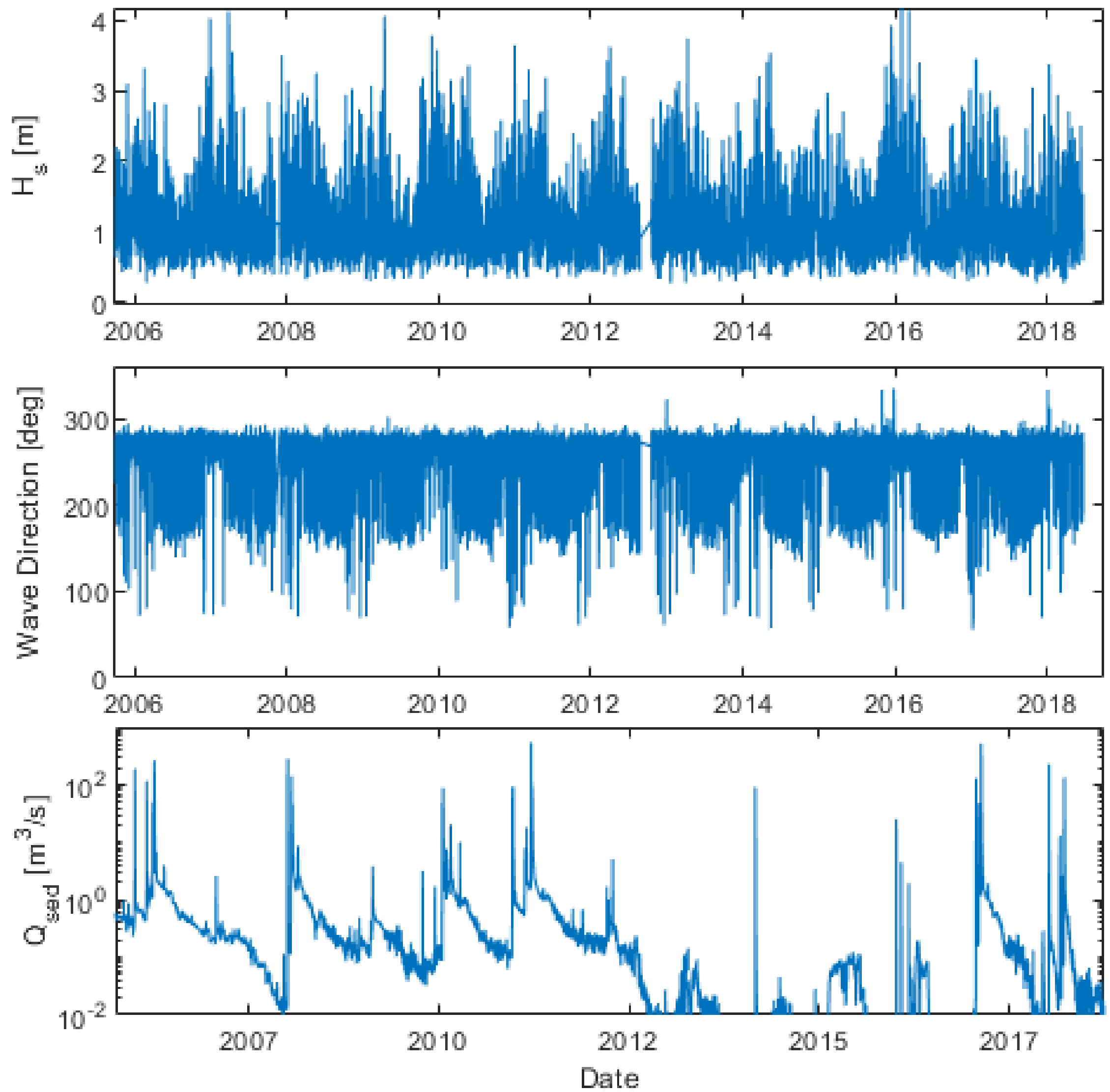


Figure 29. Wave Forcing (Wave Height and Direction) and Ventura River Sediment Loading (Q_{sed}) for the COAST Diagnostic Model Simulation.

4.2.2 Model Results

For the interim model evaluation, no data assimilation was used due to the limited period of available shoreline position data (2005-2017 shoreline position data from USGS). The shoreline observations were used to evaluate model performance in the model results presented here. However, data assimilation (using 2005-2017 shoreline observations from USGS) was included in the dam removal and sea level rise scenarios described in the main report. The model simulated shoreline change starting in October 2005 and ending in October 2017. The model-predicted mean shoreline positions over the model time period are shown along with observations of shoreline position in Figure 30. The 5th and 95th percentile model-predicted shoreline positions are also shown to bound the range of model predictions over the time period. The model is able to capture the range of observed shorelines without relying on data assimilation methods.

This model does not take into account dredging of the sand trap north of Ventura Harbor. Therefore, the model predicts continued accretion of sediment in the sand trap. The removal of sediment north of the harbor can be accounted for using dredge records of sediment removal or through data assimilation. Using dredge records, the mass of sediment can be intermittently removed from the shoreline in the sand trap. Alternatively, the model with data assimilation will estimate a long-term source or sink of sediment to account for the changing shoreline position.

Figure 30. Observed Shoreline Positions (white) Compared with Mean, 5th, and 95th Percentile Shoreline Predictions from COAST Model (black). Close-up maps are shown near the river mouth and Ventura Harbor.

4.3 SUMMARY

The processes associated with the Matilija Dam removal and long-term climate change will impact estuarine and marine habitats over a wide range of timescales from hours to decades. The range of time scales associated with the various processes requires careful consideration of representative model scenarios. For instance, sediment transport processes such as erosion and deposition are driven by water column turbulence and shear stresses, which can vary over seconds. At the other extreme, long-term climate change impacts occur over the course of decades.

The suite of modeling tools has been successfully developed and qualitatively validated with available data and observations. The models are reasonably predicting sediment transport dynamics across a wide range of sediment grain sizes. The short-term event models (estuary and coastal ocean) were qualitatively validated using two recent discharge events (January 17 and February 2, 2019). The two coastal ocean models were also shown to reasonably transport sediment downcoast associated with a river discharge event and a subsequent wave event.

The inlet model was shown to accurately reproduce inlet dynamics fluvial erosion and wave-driven accretion across the approximately 10-year period of inlet observations. The model-predicted inlet condition corresponds well to observed inlet conditions, and the model is able to produce seasonal opening as well as long-term variability in inlet dynamics associated with periods of drought. Finally, the long-term shoreline change model was developed for an approximately 10-year period that coincided with high-frequency shoreline observations. The model was run without data assimilation to compare the model-predicted shorelines to observed shoreline position. The model accurately resolved the range of predicted shorelines. A notable exception is the sand trap north of Ventura Harbor where annual dredging activity modified the available sediment, which has not been explicitly incorporated into the shoreline change model at this point. Overall, the set of short- and long-term modeling has reproduced available observations providing confidence that the models can be used to evaluate dynamics in the system.

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Appendix B

Supplemental Model Results

MATILIJA DAM REMOVAL ECOSYSTEM RESTORATION PROJECT

Appendix B: Supplemental Model Results

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November 2019

CONTENTS

LIST OF FIGURES

1 INTRODUCTION

This appendix provides model results for the model scenarios that were not included in the main report. Estuary and coastal modeling mapped results are presented, including additional dam removal scenarios, return period events, and coastal wave conditions. Also provided are results demonstrating model sensitivity to offshore water level, sediment loading, and sediment grain size. Details of the model scenarios presented in this appendix can be found in the main report.

2 VENTURA RIVER ESTUARY SUPPLEMENTAL RESULTS

Supplemental results from the Delft3D estuary modeling analysis are shown below. Results include all five dam removal scenarios, return period modeling events, and model sensitivity to offshore water level and sediment loading.

2.1 DAM REMOVAL SCENARIOS

The resulting sedimentation maps from dam removal scenarios (A–E) are shown below. Model sensitivity to offshore water level and sediment loading is also included.

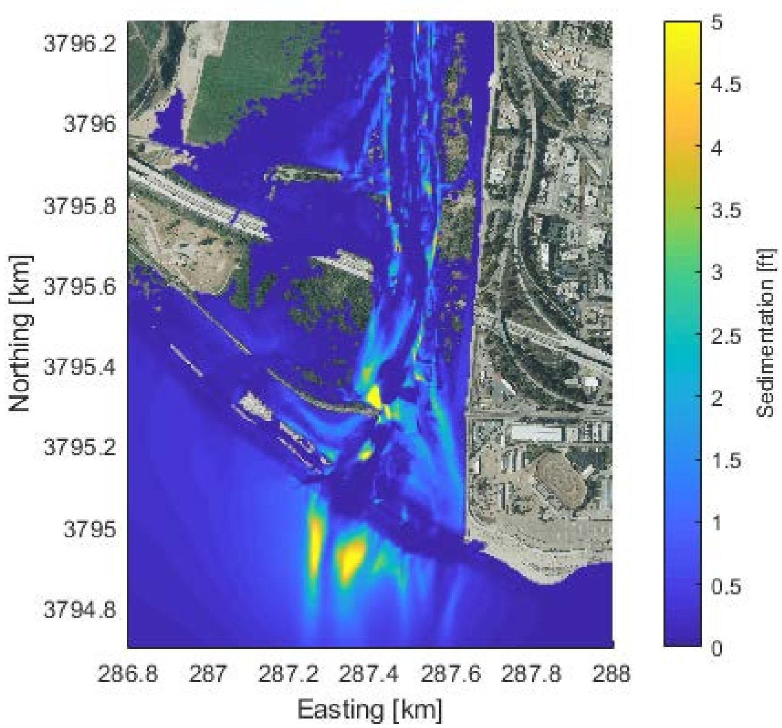

Figure 1. Sedimentation from Dam Removal Scenario A.

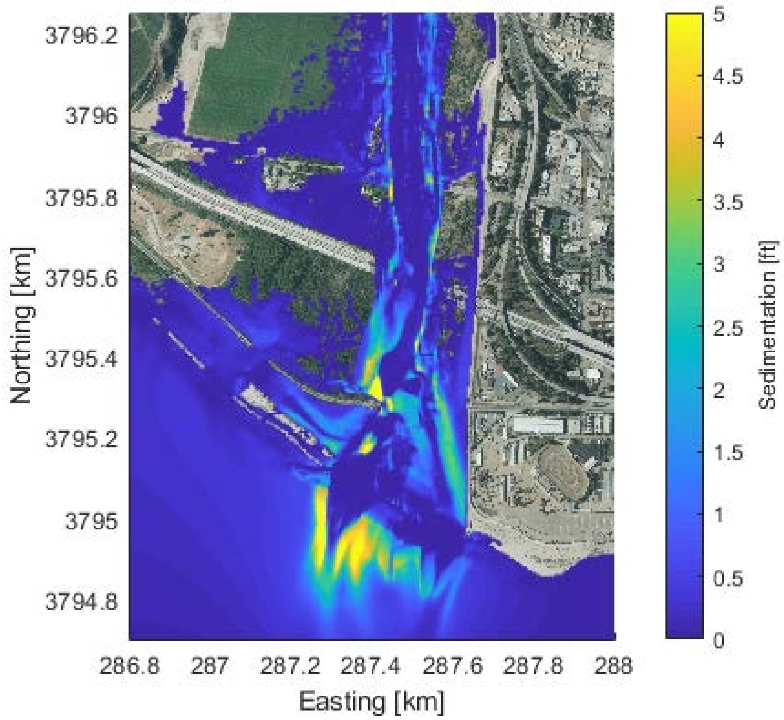

Figure 2. Sedimentation from Dam Removal Scenario B.

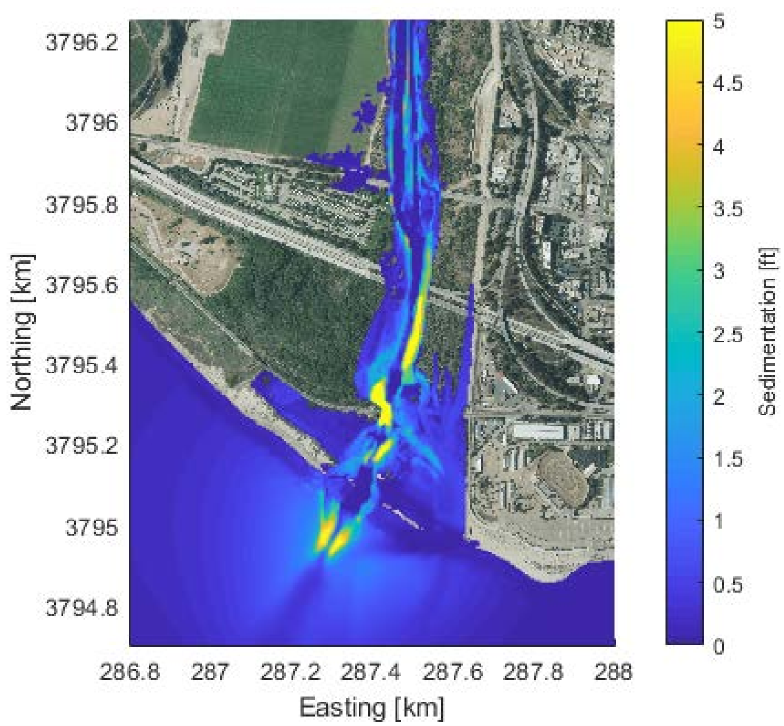

Figure 3. Sedimentation from Dam Removal Scenario C.

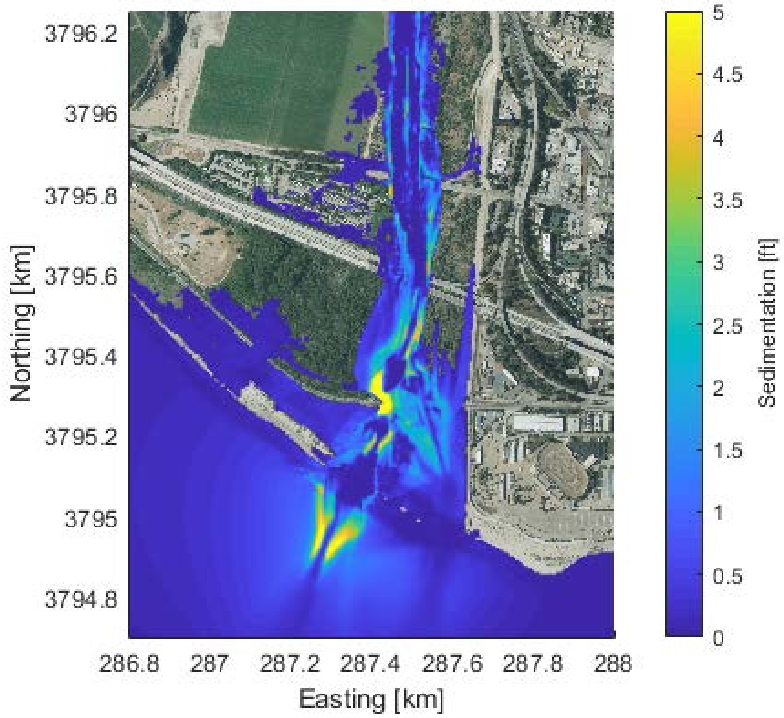

Figure 4. Sedimentation from Dam Removal Scenario D.

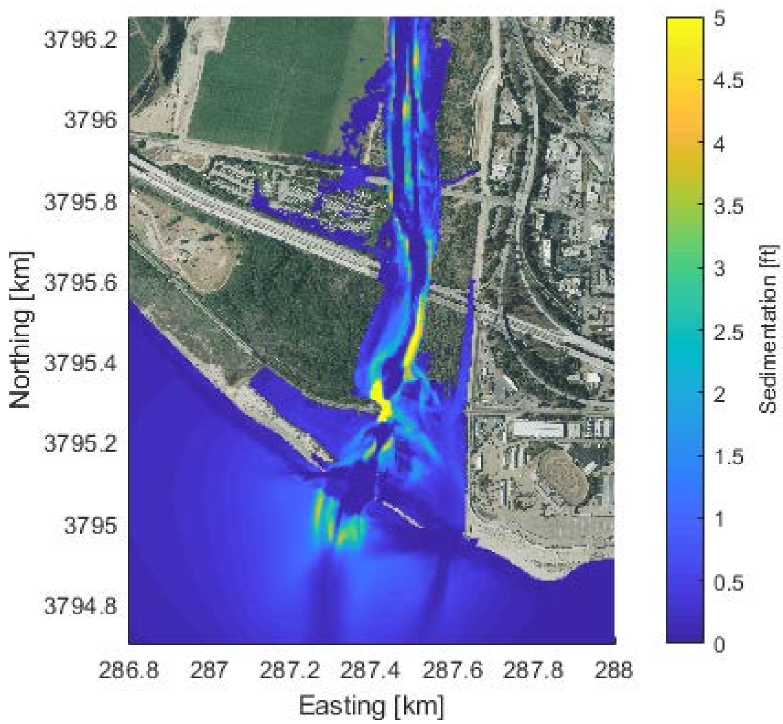

Figure 5. Sedimentation from Dam Removal Scenario E.

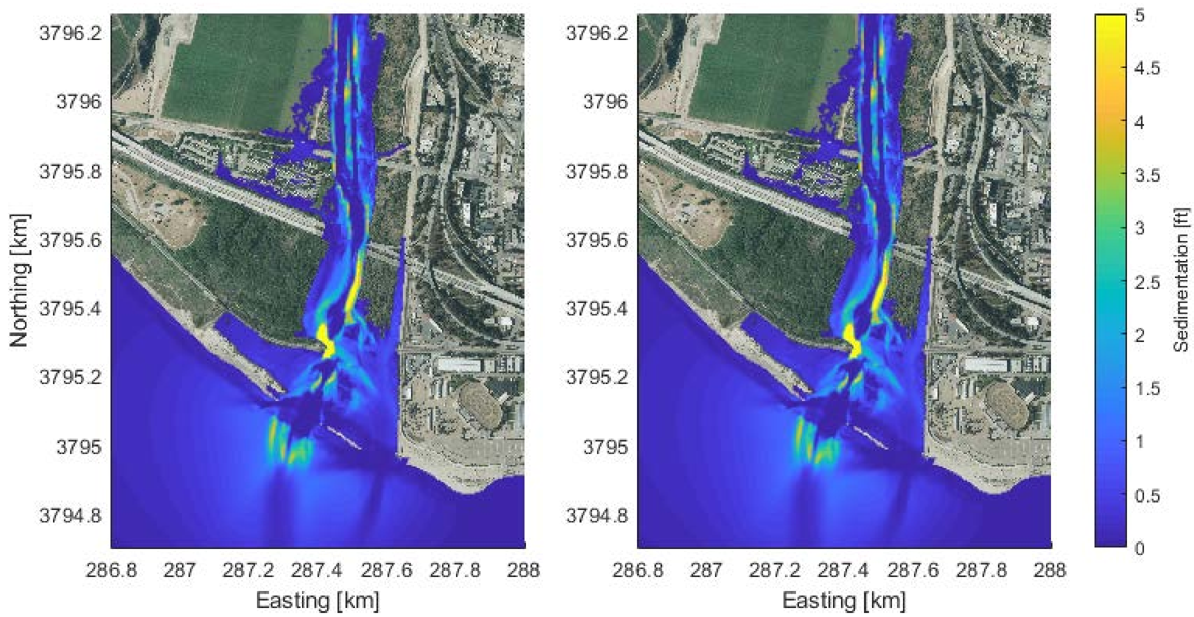

Figure 6. Dam Removal Scenario D during King High Tide (6.5 ft NAVD88; left panel) and during Low Tide (–0.3 ft NAVD88; right panel) to Illustrate Model Sensitivity of Offshore Water Level.

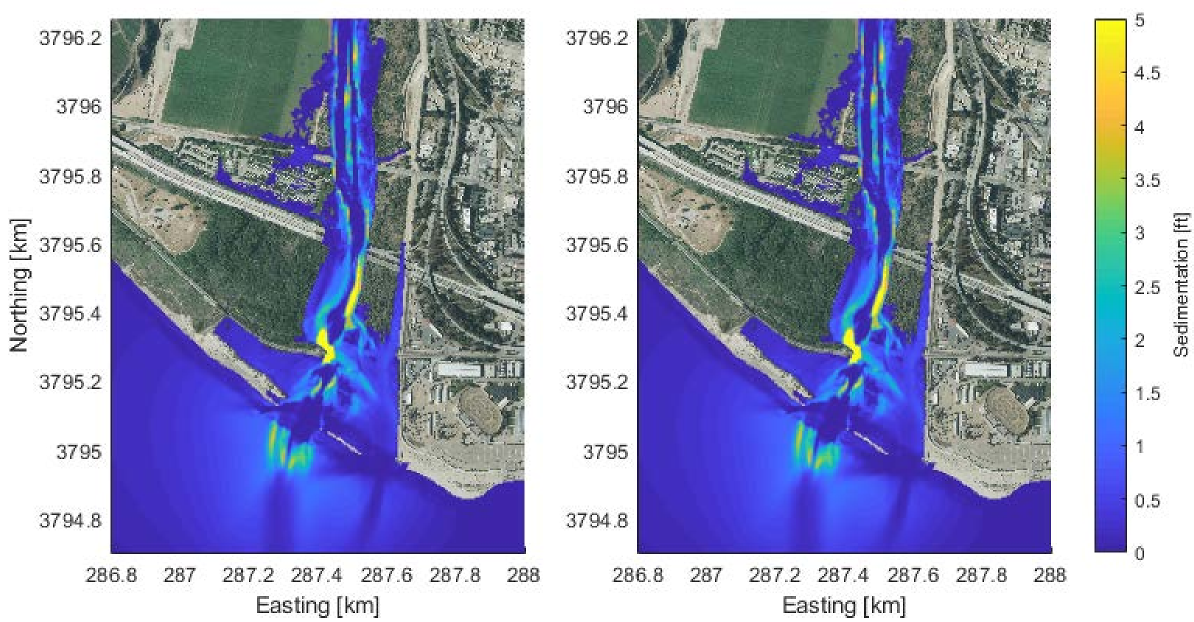

Figure 7. Dam Removal Scenario D with a 20 Percent Increase in Coarse (Gravel and Cobble) Sediment Loading to Illustrate Model Sensitivity to Uncertainty in DREAM-2 Model Results.

2.2 POST-DAM REMOVAL RETURN PERIOD SCENARIOS

Sedimentation and grain size distribution following the post-dam removal return period events are shown in Figures 8 through 20 below.

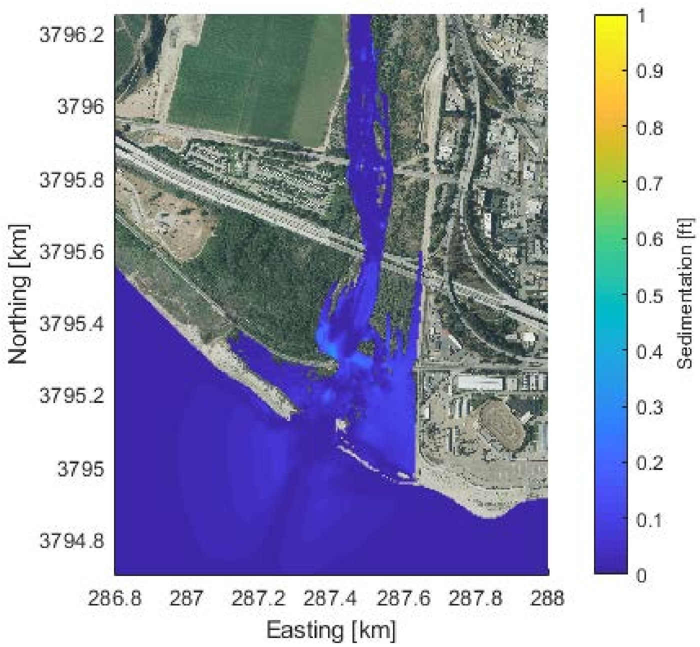

Figure 8. Total Sedimentation following 2-Year Return Period Event.

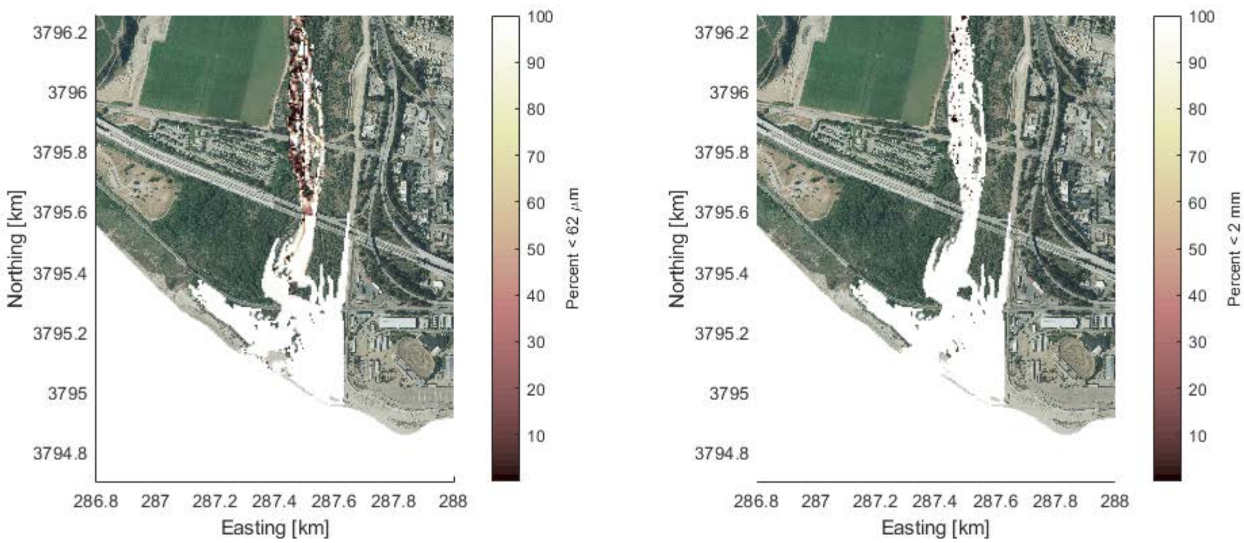

Figure 9. Sediment Grain Size Distribution for 2-Year Return Period Event Indicated by the Percent of Deposited Material Less Than 65 µm (left panel) and the Percent of Deposited Material Less Than 2 mm (right panel).

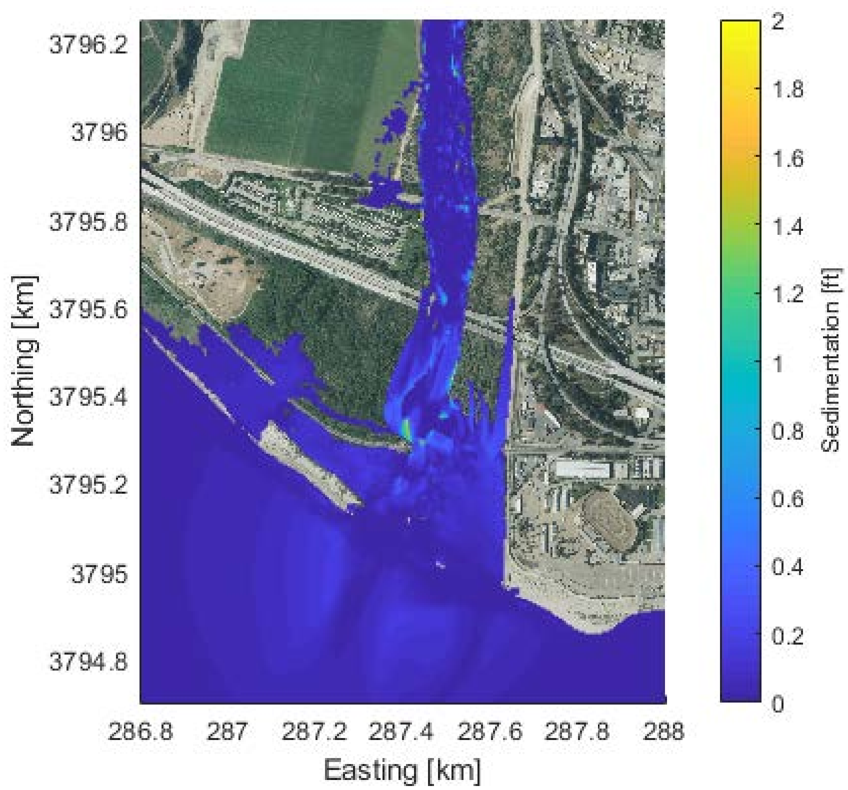

Figure 10. Total Sedimentation following 5-Year Return Period Event.

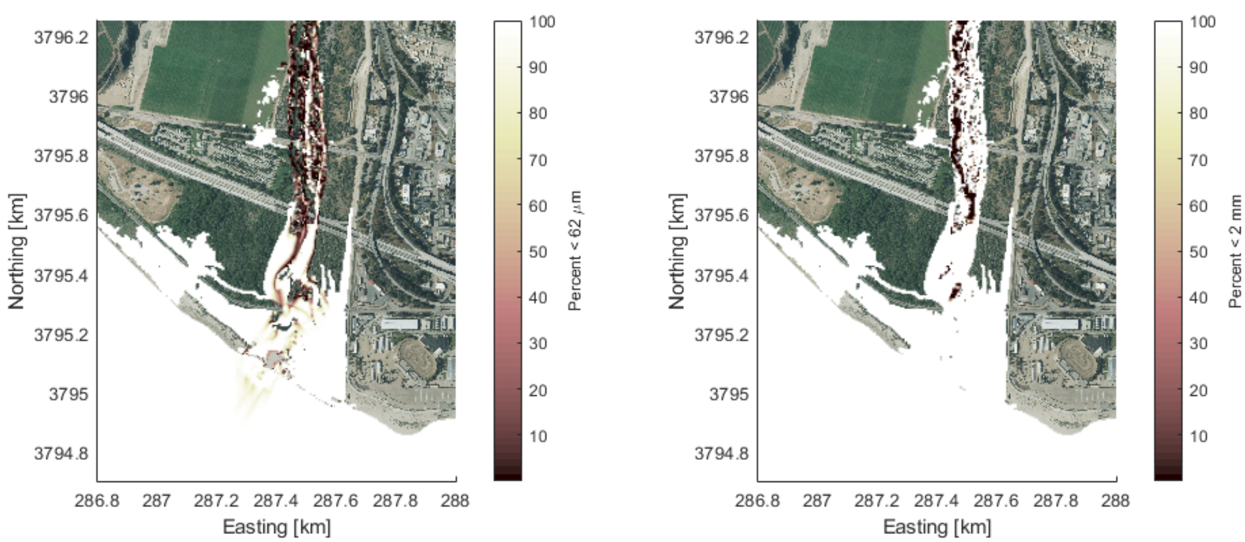

Figure 11. Sediment Grain Size Distribution for 5-Year Return Period Event Indicated by the Percent of Deposited Material Less Than 65 µm (left panel) and the Percent of Deposited Material Less Than 2 mm (right panel).

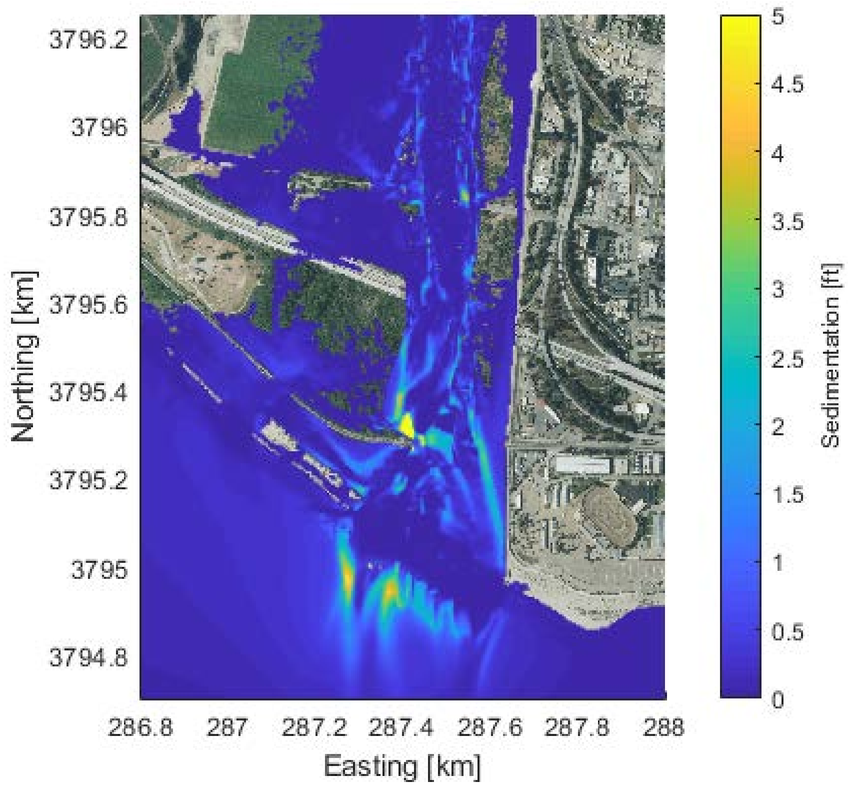

Figure 12. Total Sedimentation following 10-Year Return Period Event.

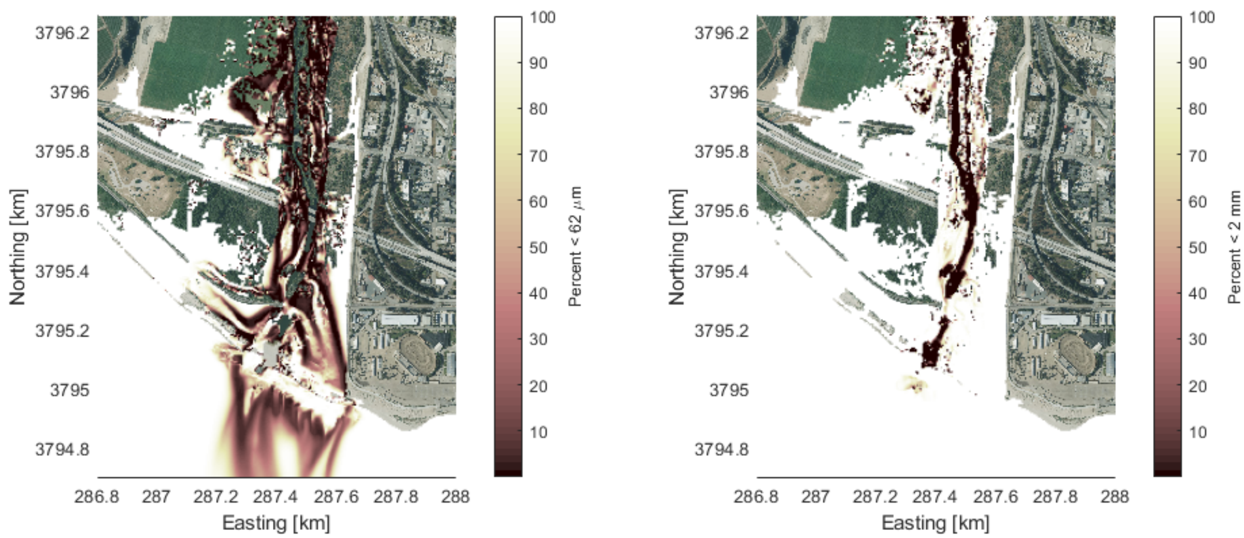

Figure 13. Sediment Grain Size Distribution for 10-Year Return Period Event Indicated by the Percent of Deposited Material Less Than 65 µm (left panel) and the Percent of Deposited Material Less Than 2 mm (right panel).

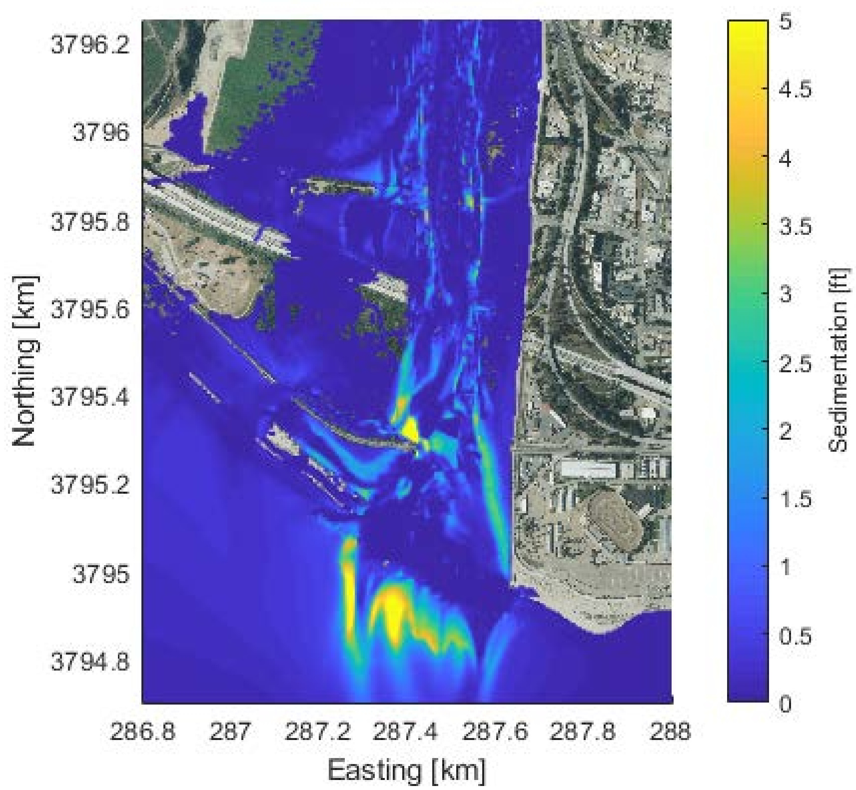

Figure 14. Total Sedimentation following 20-Year Return Period Event.

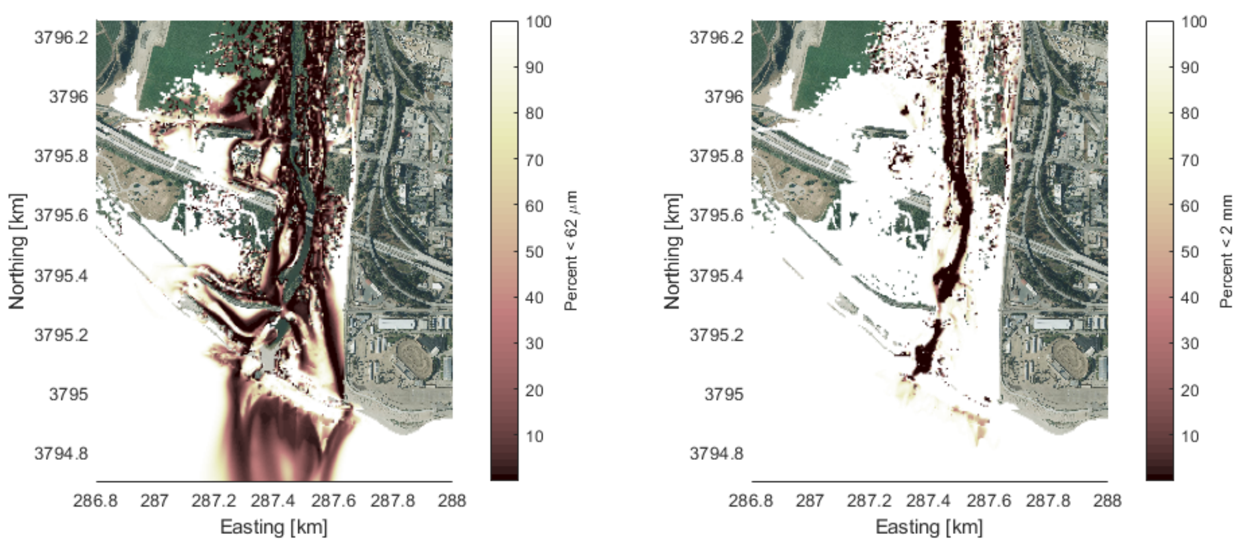

Figure 15. Sediment Grain Size Distribution for 20-Year Return Period Event Indicated by the Percent of Deposited Material Less Than 65 µm (left panel) and the Percent of Deposited Material Less Than 2 mm (right panel).

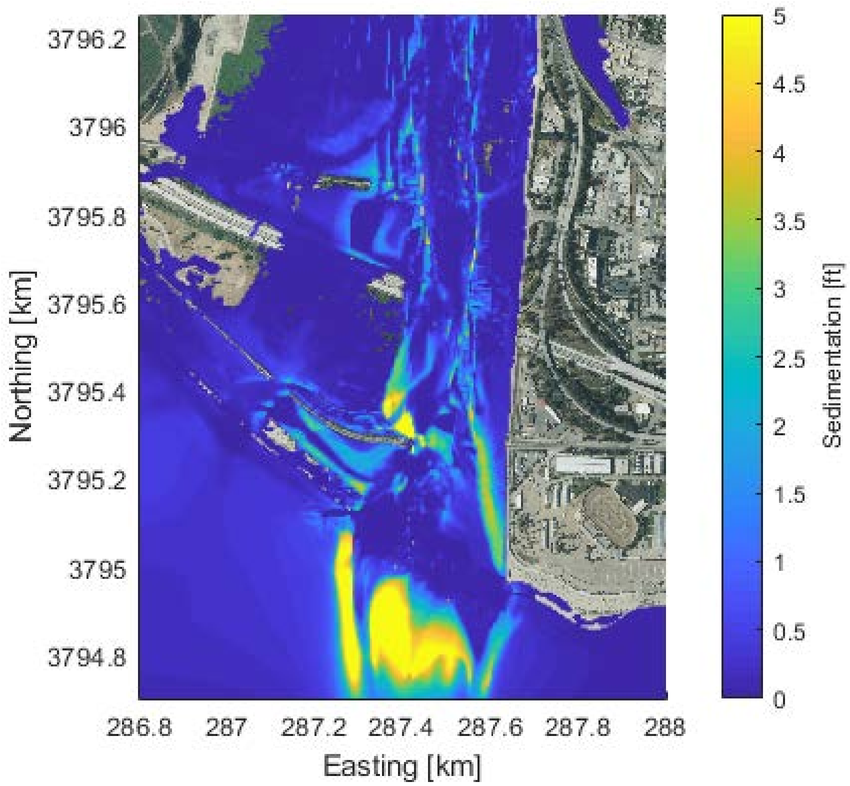

Figure 16. Total Sedimentation following 50-Year Return Period Event.

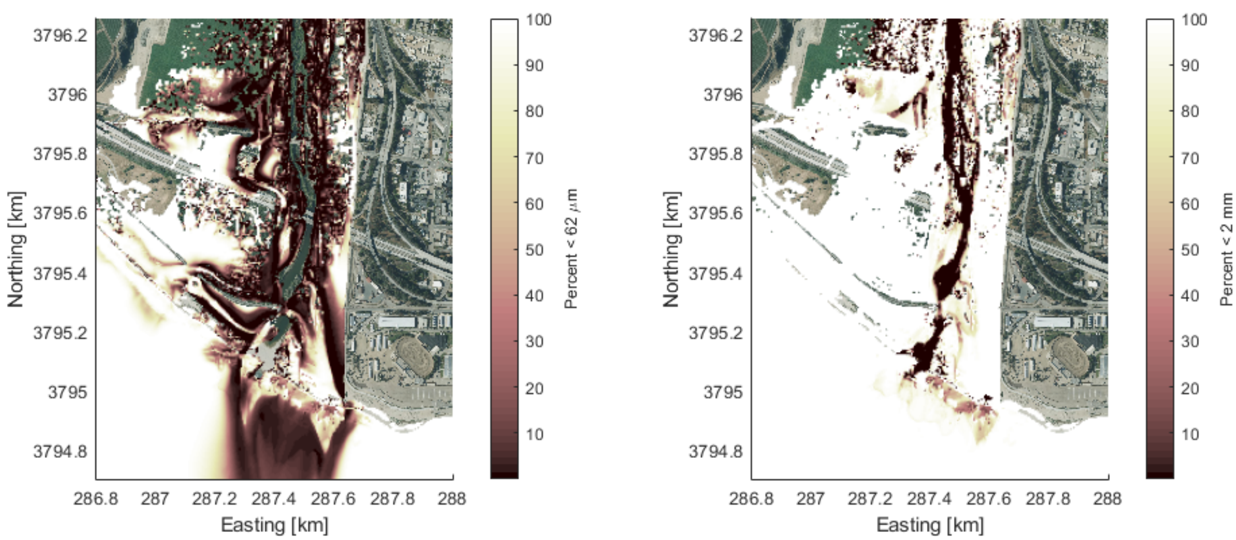

Figure 17. Sediment Grain Size Distribution for 50-Year Return Period Event Indicated by the Percent of Deposited Material Less Than 65 µm (left panel) and the Percent of Deposited Material Less Than 2 mm (right panel).

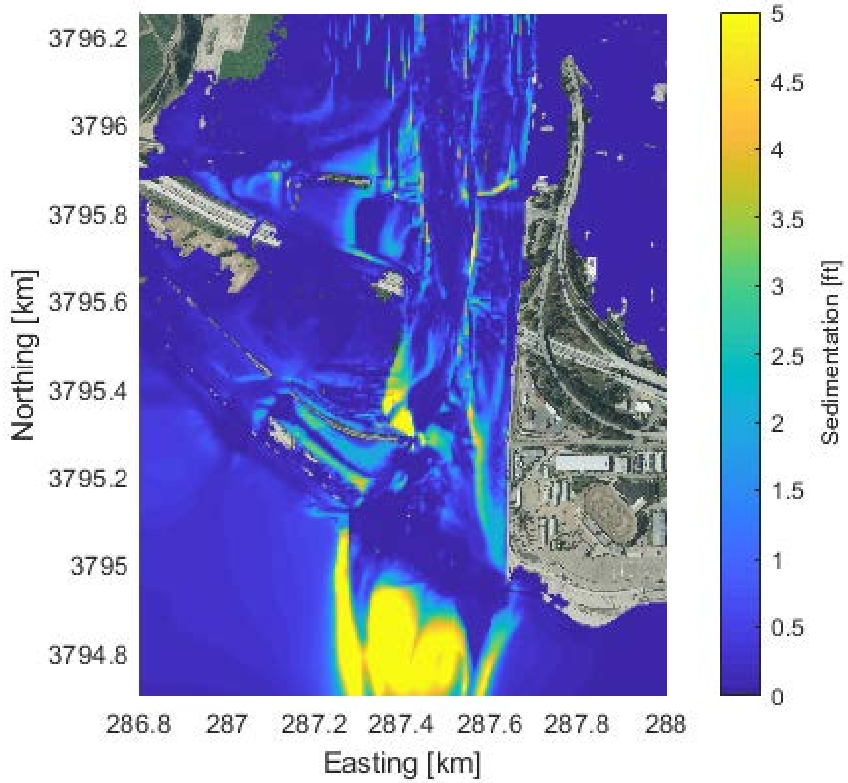

Figure 18. Total Sedimentation following 100-Year Return Period Event.

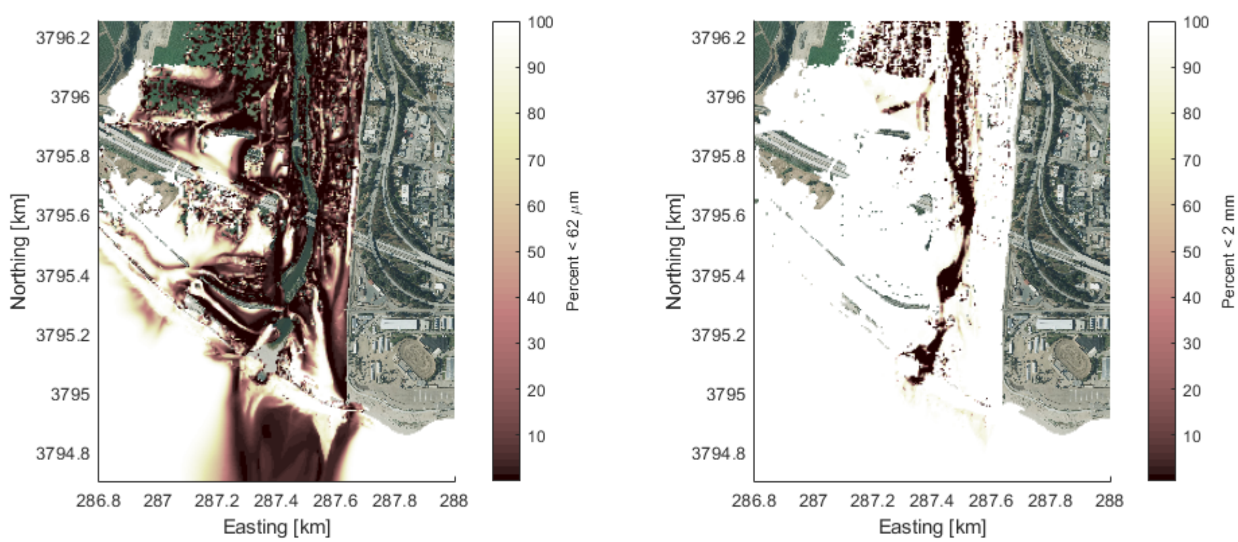

Figure 19. Sediment Grain Size Distribution for 100-Year Return Period Event Indicated by the Percent of Deposited Material Less Than 65 µm (left panel) and the Percent of Deposited Material Less Than 2 mm (right panel).

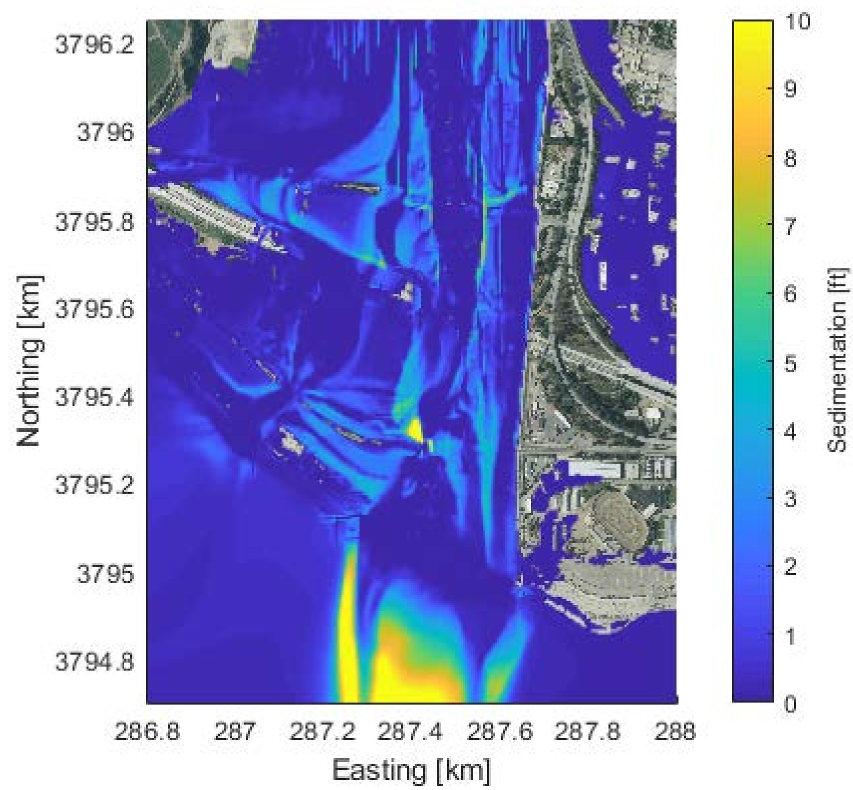

Figure 20. Total Sedimentation following 500-Year Return Period Event.

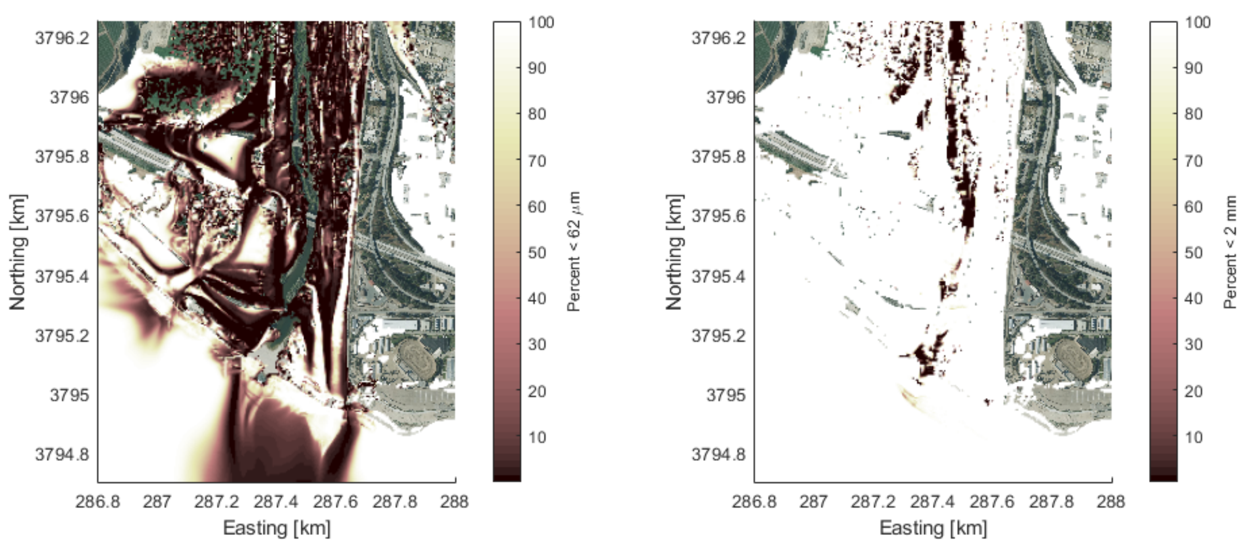

Figure 21. Sediment Grain Size Distribution for 500-Year Return Period Event Indicated by the Percent of Deposited Material Less Than 65 µm (left panel) and the Percent of Deposited Material Less Than 2 mm (right panel).

3 COASTAL OCEAN SUPPLEMENTAL RESULTS

3.1 DAM REMOVAL SCENARIOS

The coastal ocean modeling using Delft3D-SWAN simulated the maximum and minimum sediment loading to the coastal ocean (across the five dam removal scenarios). The offshore wave conditions were forced using a range of typical wave conditions based on observed offshore wave data. The suite of dam removal scenarios is described in Table 11 of the main report. Sedimentation results from all 10 dam removal scenarios are shown in the figures below.

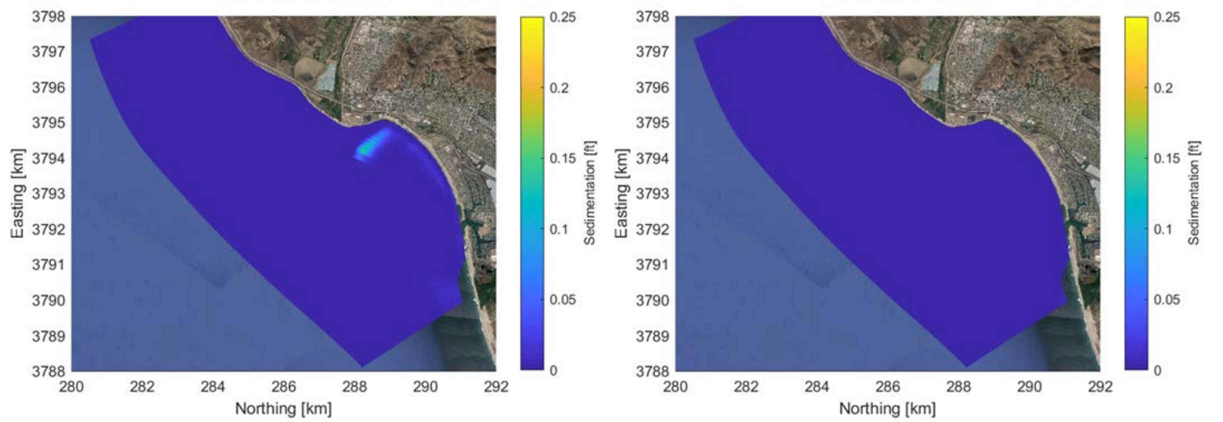

Figure 22. Maximum (left panel) and Minimum (right panel) Dam Removal Loading Scenario during a Large Winter Storm Event.

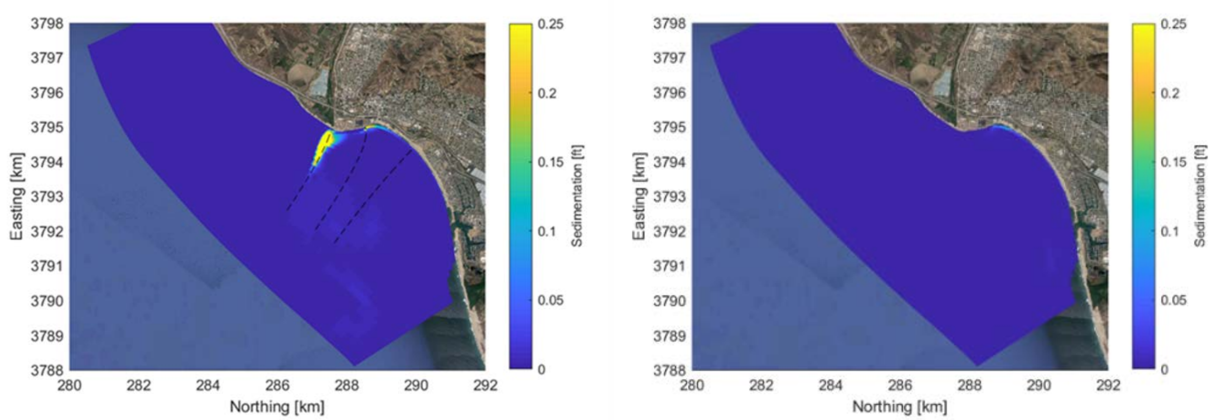

Figure 23. Maximum (left panel) and Minimum (right panel) Dam Removal Loading Scenario during Average Winter/Spring Offshore Wave Conditions.

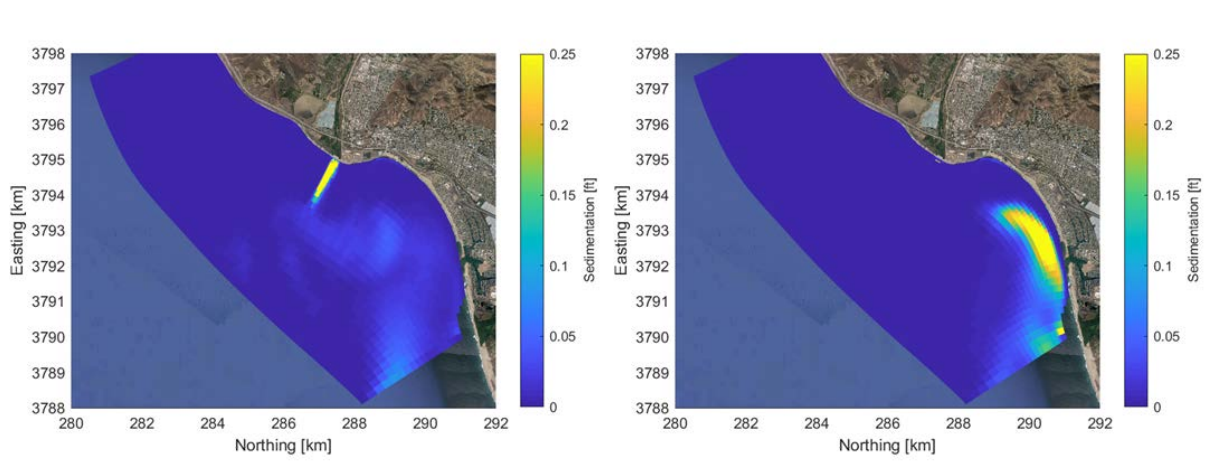

Figure 24. Maximum (left panel) and Minimum (right panel) Dam Removal Loading Scenario during Average Summer/Fall Westerly Swell Wave Conditions.

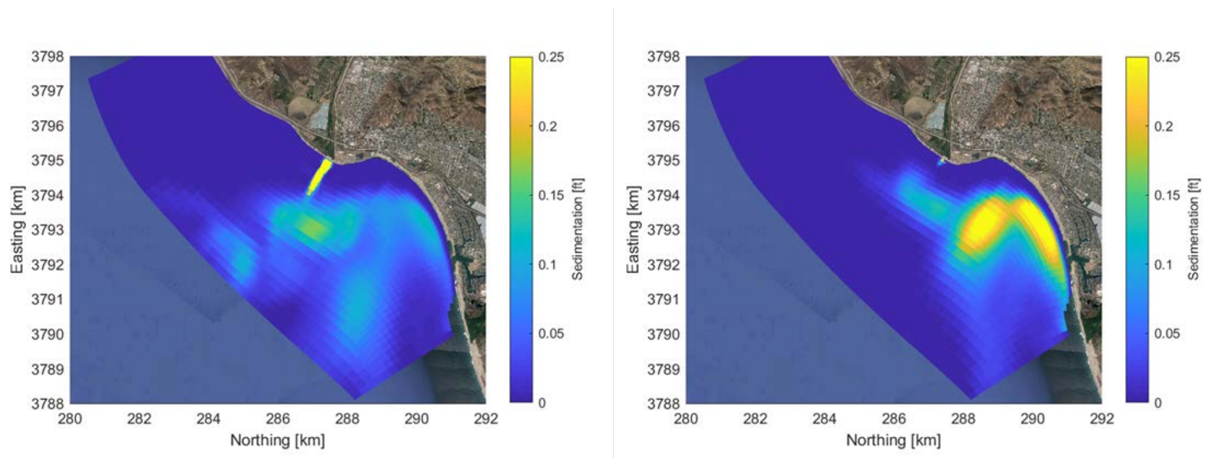

Figure 25. Maximum (left panel) and Minimum (right panel) Dam Removal Loading Scenario during Average Summer/Fall Southerly Swell Wave Conditions.

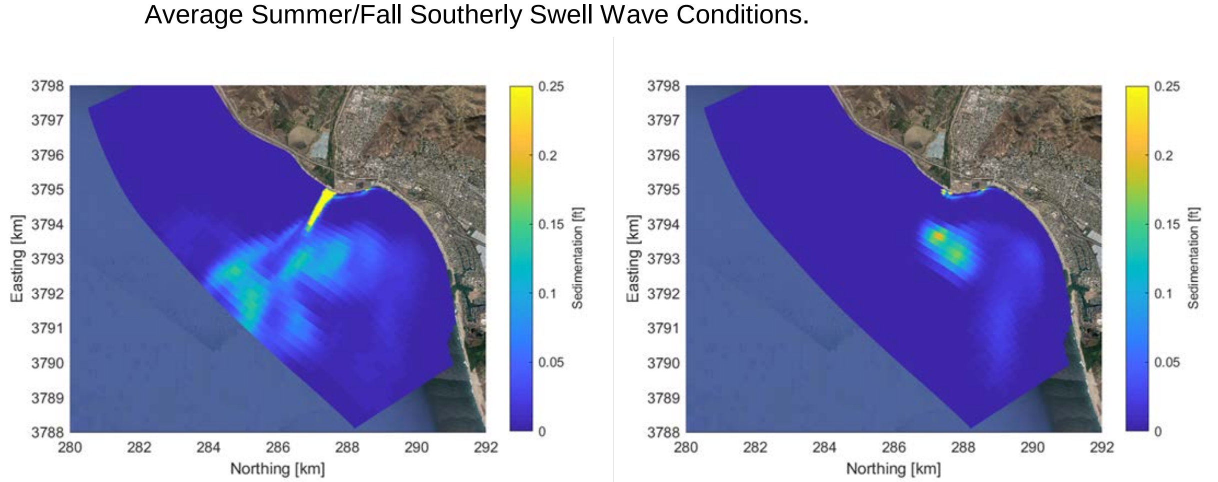

Figure 26. Maximum (left panel) and Minimum (right panel) Dam Removal Loading Scenario during Strong Summer/Fall Southerly Swell Wave Conditions.

3.2 MODEL SENSITIVITY

As described in the main report, the sand fraction associated with dam removal has the most significant effect on estuary and coastal sedimentation. The silt fraction is readily transported offshore, and the gravel and cobble fractions are a small proportion of the total load. Because of the importance of the sand fraction on sedimentation results, the model sensitivity to sand grain size was evaluated. Figure 27 below shows the resulting sedimentation maps associated with the maximum sediment loading dam removal scenarios and wave condition A (large winter storm) using two different sediment grain sizes (0.2 and 0.35 mm). The 0.2 mm sand is more readily transported offshore and deposits along deeper isobaths. In comparison, the 0.35 mm sand fraction is largely constrained to the nearshore coast and is transported downcoast by alongshore, wave-driven currents.

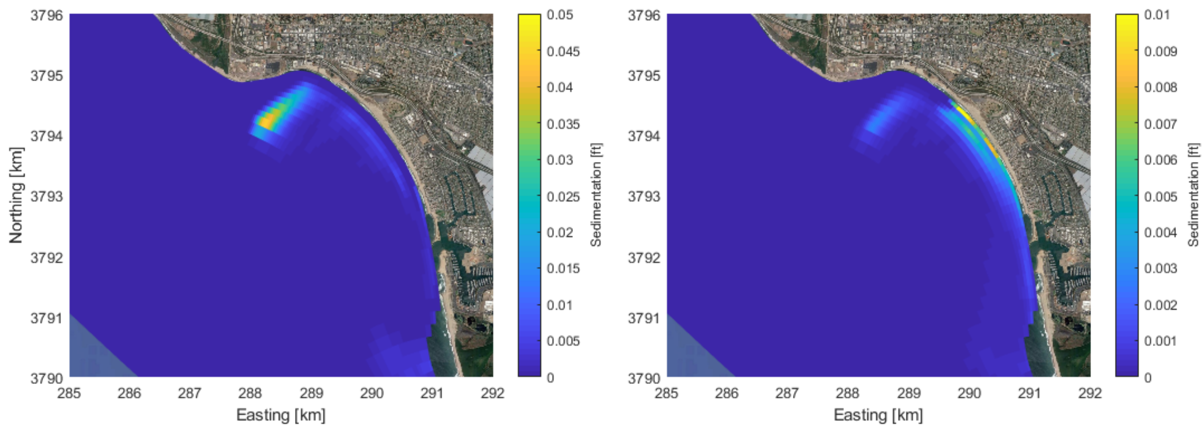

Figure 27. Sedimentation Associated with the Maximum Dam Removal Sediment Loading during a Large Winter Storm with 0.2 mm Sand (left panel) and 0.35 mm Sand (right panel).