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Appendix B

Engineering Appendix

Watsonville Slough Ecosystem Restoration Project
San Francisco District

Continuing Authorities Program (CAP), Section 1135

US Army Corps
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San Francisco District

DRAFT

Appendix B-1

Hydrology, Hydraulics & Climate (HH&C)

Watsonville Slough CAP 1135 Ecosystem Restoration Project
Santa Cruz County, California

July 2025

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ATTACHMENTS

Attachment A - Watsonville CAP 1135 Hydrology Technical Memorandum

Attachment B - HEC-RAS Results – Percent Time Inundated Raster Maps

Attachment C - Annualized Percent Time Inundated (PTI) Heat Maps

Attachment D - Lower Watsonville Slough Ecosystem Restoration – Lagoon Response Modeling Memorandum (Environmental Science Associates)

List of Abbreviations & Acronyms

AEP	Annual Exceedance Probability
CAP	Continuing Authorities Program
CIMIS	California Irrigation Management Information System
cfs	Cubic feet per second
ENSO	El Niño-Southern Oscillation
ESA	Environmental Science Associates
ET	Evapotranspiration
EWOP	Existing without project
FEMA	Federal Emergency Management Agency
FIS	Flood Insurance Study
FIRM	Flood Insurance Rate Map
FRM	Flood Risk Management
FWOP	Future without project
H&H	Hydrology and Hydraulics
HH&C	Hydrology, Hydraulics, and Climate
HEC-RAS	Hydrologic Engineering Center - River Analysis System
MFR	Memorandum For Record
MHHW	Mean Higher High Water
MLLW	Mean Lower Low Water
NAVD	North American Vertical Datum
NHC	Northwest Hydraulic Consultants
NLCD	National Land Cover Database
PDO	Pacific Decadal Oscillation
PDT	Project Delivery Team
PTI	Percent Time Inundated
PV Water	Pajaro Valley Water
QCM	Quantified Conceptual Model
RSLC	Relative sea level change
SLC	Sea level change
SPD	South Pacific Division
TWL	Total Water level
USGS	US Geological Survey
WSE	Water surface elevation

1. Study Description

1.1. Purpose and Scope

The goal of the Watsonville Slough CAP study is to enhance existing marsh habitat by restoring tidal/hydrologic connectivity within the study area. The scope of the Hydrology, Hydraulics, and Climate (HH&C) analysis for this study was primarily to support the quantification of ecosystem restoration benefits from proposed project alternatives over the course of the project design life. Ecosystem restoration benefits in this study are measured indirectly as increases in hydroperiod (or percent time inundated). Thus, the primary objective of the hydraulic modeling was to simulate percent time inundated throughout the marsh plain contained within the study area under various present and future scenarios.

1.2. Study Area

The Watsonville Slough CAP study area is located at the confluence of the Watsonville Slough with the Pajaro River, in southern Santa Cruz County. The project area is bordered inland by low-lying, active agricultural fields and on the ocean side by the Pajaro Dunes Community. The project area is bounded by Shell Road at the upstream end, and the Pajaro River and Lagoon at the downstream end (Figure 1).

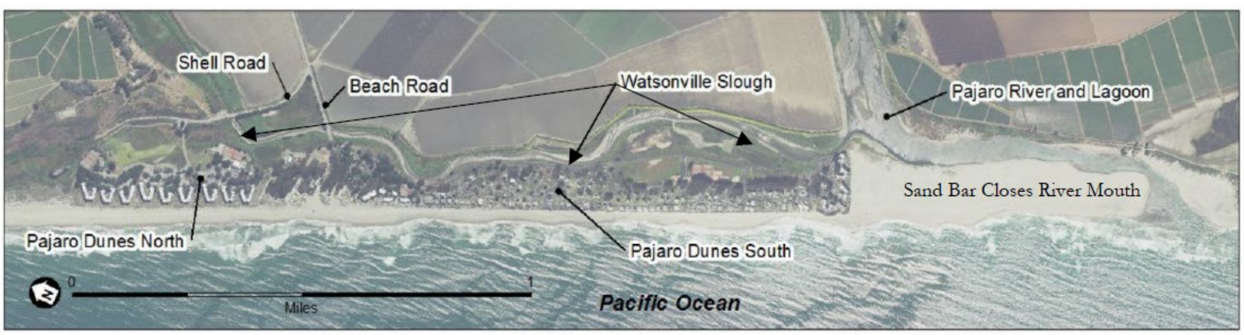


Figure 1: Map of the project area extents, showing the confluence of the Watsonville Slough and the Pajaro River at the Pajaro Lagoon (Source: Technical Memo from ESA, 2018).

The mouth of the Pajaro River watershed includes a lagoon and can be characterized as a bar-built estuary system, which experiences intermittent closures caused by the interplay of wave action and sediment transport. Wave runup deposits sand transported onshore and builds up a beach berm, which rises in elevation over time and “closes” the lagoon mouth. Closure events typically occur in the summer and fall. The lagoon stage can increase from wave run-up overtopping the beach or from watershed runoff and breach the berm, thus creating a new channel outlet to the ocean (Figure 2). While closed, lagoon water levels can spike rapidly with fluvial inputs and create a backwatering effect. Santa Cruz County actively manages the lagoon mouth state through a mechanical breaching program, to help prevent flooding of adjacent communities and roadway infrastructure.

This system (and its closure/breaching patterns) influences the upstream hydrology and water quality of Watsonville Slough and lower Pajaro River. When the lagoon mouth is open, water levels in Watsonville Slough and Pajaro River (up to Highway 101) are subject to tidal influence. When the lagoon is closed, the project area is effectively disconnected from tidal forcing, and water levels in the project area are determined predominantly by streamflow inputs and losses due to evapotranspiration and seepage/infiltration.

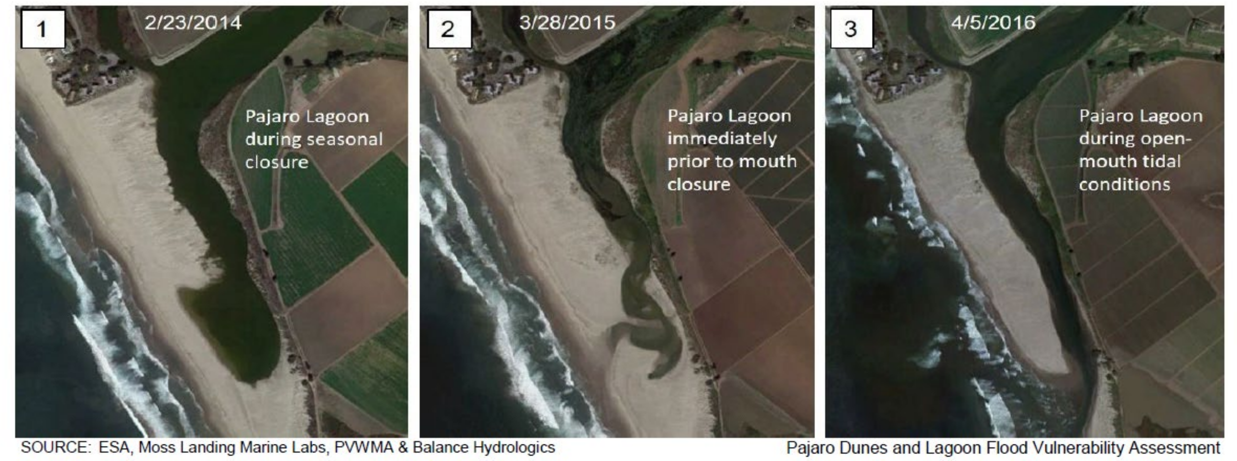


Figure 2: Pajaro Lagoon under open and closed conditions (Source: ESA, 2018).

1.3. Modeling Workflow Overview

The primary objective of the hydrology, hydraulics, and climate (HH&C) analyses described herein is to quantify the ecosystem restoration benefits of the proposed project scenarios. Given the complicated hydrologic nature of an intermittently closed estuary system, a multi-step modeling approach was employed. The approach aims to quantify changes to the annual hydroperiod that result from the proposed project scenarios in a "typical" hydrologic year. The modeling workflow steps are summarized as follows:

1) *Hydrologic Analysis:* Derive hydrologic boundary conditions for four different hydrologic regimes to be used in the hydraulic modeling. The four hydrologic regimes are (1) Open Lagoon, Dry Season; (2) Open Lagoon, Wet Season; (3) Closed Lagoon, Dry Season; (4) Closed Lagoon, Wet Season. The hydrologic boundary conditions consist of 1-month duration streamflow hydrographs and total water level hydrographs that are representative of the respective hydrologic regime in a "typical" year. Derivation of these hydrographs is described in Chapter 2 of this analysis.

2) *Hydraulic Modeling:* Run HEC-RAS 2D simulations for all combinations of hydrologic regimes, project scenarios (Chapter 3), and future conditions modeling time horizons (Section 4.2). Generate Percent Time Inundated (PTI) rasters for each of the HEC-RAS simulations. Details of the hydraulic modeling are described in Chapter 4 of this analysis.

3) *Post-Processing of Hydraulic Model Results:* Use a parametric lagoon model called Lagoon QCM (Behrens et al., 2015) to determine the fraction of a typical year during which the Pajaro Lagoon is in each of the four hydrologic regimes. Use the outputs from Lagoon QCM to combine the PTI rasters from Step (2) into an annual weighted average PTI map. These annual PTI maps are then used to quantify the increases in marsh hydroperiod within the project area that result from the project scenarios. Lagoon QCM and the derivation of annual PTI maps are described in Section 4.6 of this analysis.

2. Hydrology

A detailed hydrologic assessment for the Watsonville Slough CAP study was prepared as a Memorandum for Record (MFR), dated 7 November 2022. That assessment underwent District Quality Control and Agency Technical Review as part of USACE South Pacific Division's (SPD) requirement for Hydrology Certification. The SPD-certified Hydrologic Assessment MFR is included as an attachment to this analysis. The key information and findings from that MFR are summarized below.

2.1. Hydrologic Regimes in Pajaro Lagoon

The hydrologic forcings of this system are streamflow from Watsonville Slough, streamflow from the Pajaro River, and tidal forcing from Monterey Bay. The hydrology in the project area is complicated by the fact that the mouth of the Pajaro Lagoon periodically closes, due to the formation of a barrier beach that is formed by wave-driven sand transport during low river flows.

When the lagoon is closed, the project area is effectively disconnected from tidal forcing, and water levels in the project area are determined predominantly by streamflow inputs and losses due to evapotranspiration and seepage/infiltration. When the lagoon is open, both streamflow and tide stage play a role, with tidal fluctuations having a more significant impact on water levels in the lagoon.

Given this set of circumstances, to appropriately characterize this hydrologic system, it was determined that four distinct hydrologic regimes should be modeled. Those four regimes are: (1) Open Lagoon, Dry Season; (2) Open Lagoon, Wet Season; (3) Closed Lagoon, Dry Season; and (4) Closed Lagoon, Wet Season.

For each of the four regimes, a one-month duration time series of representative hydrologic boundary conditions was developed. A simulation duration of one month was selected so that the hydraulic model simulation is long enough to capture a wide range of tidal conditions, but not so long as to cause prohibitively long model runtimes.

Open lagoon hydrologic boundary conditions are described in Section 2.2., closed lagoon hydrologic boundary conditions are described in Section 2.3., and extreme event hydrology is discussed briefly in Section 2.4.

2.2. Open Lagoon Boundary Conditions

2.2.1. Available Data

The relevant data available for this analysis consists of a short-term (WY2016 to WY2021) observed flow record in Watsonville Slough approximately 1.5 miles upstream of the project area at San Andreas Road, a long-term (1908 to present) precipitation gage approximately 5 miles inland from the project area, and a relatively long-term (1973 to present) NOAA tide gage in Monterey Bay (Station ID: 9413450).

2.2.2. General Approach

The goal of the H&H modeling for this study is to quantify the annual hydroperiod of the marsh plain in the project area over the course of a "typical" hydrologic year. It was decided that one-year-long simulations were too computationally expensive for this study, and instead, one-month-long simulations that are representative of the four different hydrologic regimes would be run, and then a subsequent step would be used to translate those month-long simulation results into an annual weighted average.

Thus, the purpose of the hydrologic analysis is to derive representative one-month-long time series of typical hydrologic conditions for the wet season and the dry season. The analysis used to derive these “typical” hydrologic conditions is based on a duration analysis of monthly accumulated flow volume. Given that the observed flow record is only six years long and the observed precipitation record is 112 years long, it was decided to convert the observed monthly precipitation depths into equivalent monthly flow volumes using a linear regression. This approach allowed us to synthetically extend the flow record, and better define what is typical for this system. Assumptions justifying this simplified approach are provided in Attachment A.

For the sake of this analysis, “typical” was defined as the 50th percentile monthly flow volume. The streamflow hydrographs corresponding to these 50th percentile flow volumes are then combined with coincident tide hydrographs that span a representative range of tide conditions for the wet season and dry season to comprise the hydrologic boundary conditions that are fed into the hydraulic model.

2.2.3. Streamflow Analysis

The goal of the analysis was to select the hydrologic conditions that capture the range and variability of inundation that can occur over the course of a typical year. In the context of this hydrologic assessment, it was decided to define “typical” as the 50th percentile (median) flow volume from the precipitation-based duration analyses. For the dry season, the median flow volume based on the long-term precipitation record is approximately 2.2 acre-feet. For the wet season, the median flow volume is approximately 569 acre-feet.

To ensure that the flow hydrographs selected as the hydrologic boundary conditions have realistic temporal patterns, the representative months are selected from the observed flow record. I.e., a month with an accumulated flow volume close to 2.2 acre-feet and a month with an accumulated flow volume close to 569 acre-feet were selected from the observed flow record.

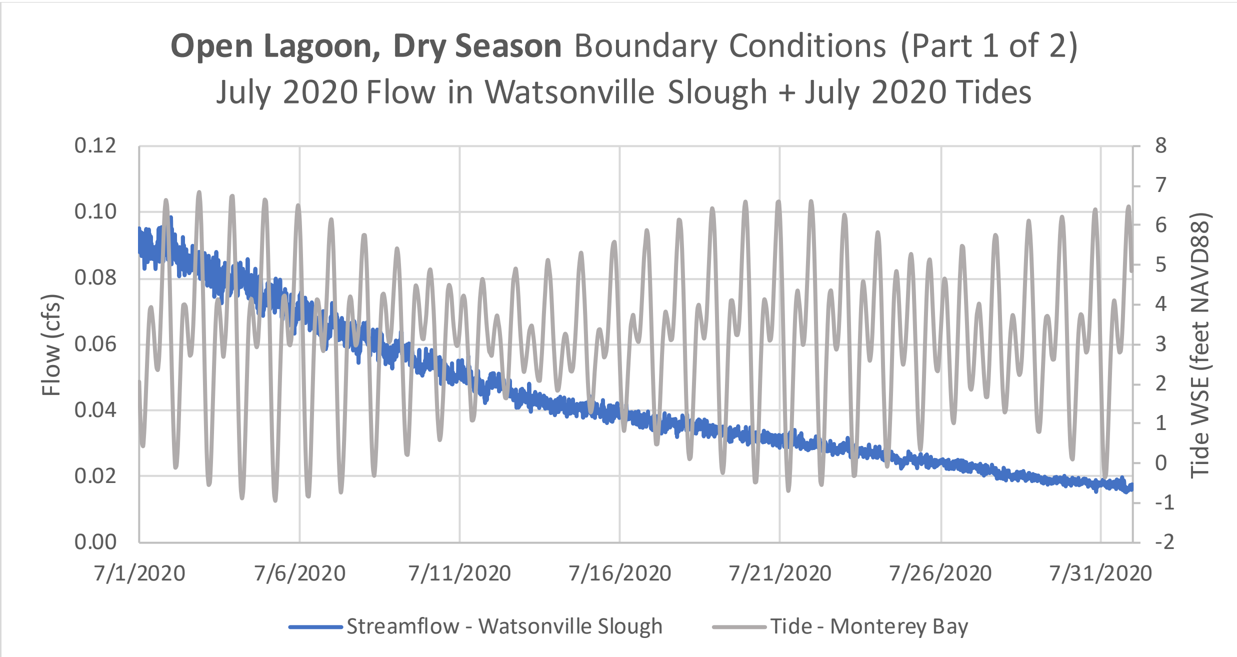
Another constraint for selecting representative months was to select from the time period during which there is a flow record on the Pajaro River at Watsonville (USGS Gage ID: 11159500). Streamflow data at this gage is only available after February 2019. Note, there is a longer-term flow record at a USGS gage upstream of Watsonville at Chittenden, however there are complex patterns of flow loss and gain that occur in the Pajaro River between these two gages, making the flow record at the Chittenden gage suboptimal for our modeling purposes.

The month that best satisfies these criteria for the dry season is July 2020, which has an accumulated flow volume of 2.69 acre-feet. The month that best satisfies these criteria for the wet season is January 2020, which has an accumulated flow volume of 667.5 acre-feet.

2.2.4. Selected Hydrographs

The Open Lagoon, Dry Season hydrologic boundary conditions consist of the July 2020 observed streamflow hydrograph in Watsonville Slough, the July 2020 observed streamflow hydrograph in the Pajaro River, and the July 2020 observed TWL hydrograph in Monterey Bay (Figure 3).

The Open Lagoon, Wet Season hydrologic boundary conditions consist of the January 2020 observed streamflow hydrograph in Watsonville Slough, the January 2020 observed streamflow hydrograph in the Pajaro River, and the January 2019 observed TWL hydrograph in Monterey Bay (Figure 4). January 2019 was selected instead of January 2020 for the TWL hydrograph because it contains slightly higher water levels during the highest tides of the month, making it more useful in evaluating the marsh plain hydrology under a broader range of conditions. See Attachment A for more details.



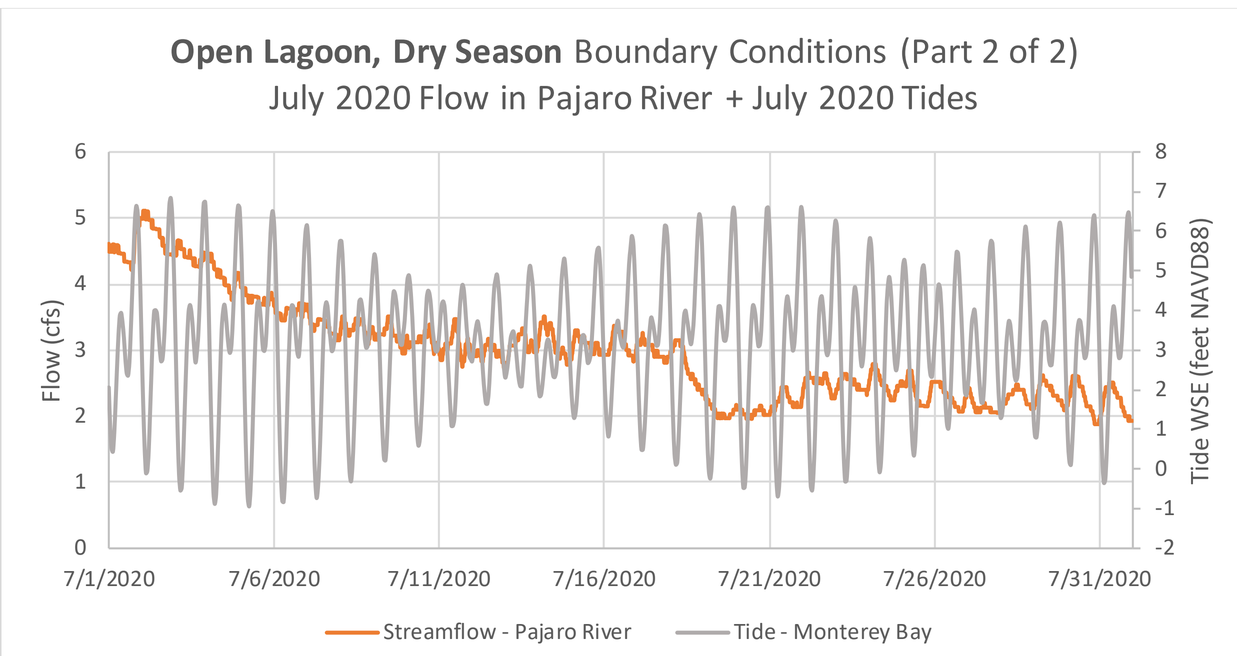
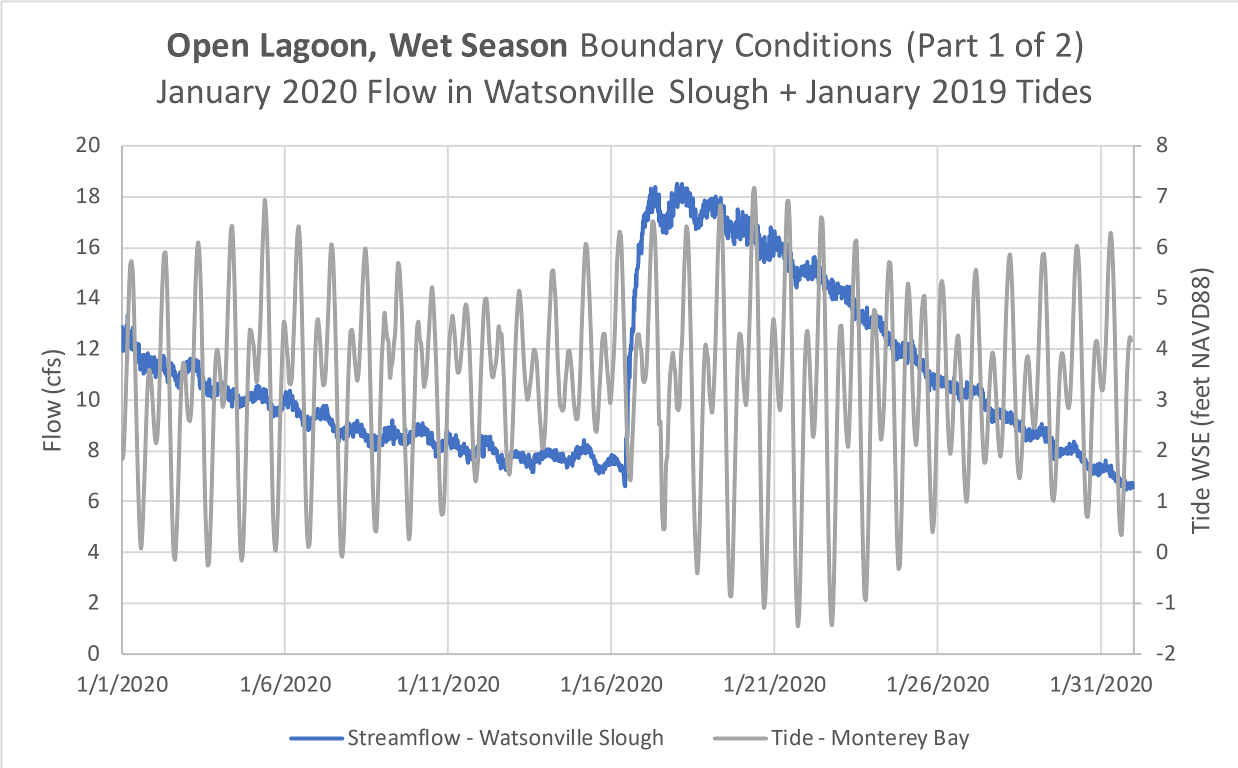


Figure 3: Hydrologic boundary conditions selected as representative of the Open Lagoon, Dry Season hydrologic regime.



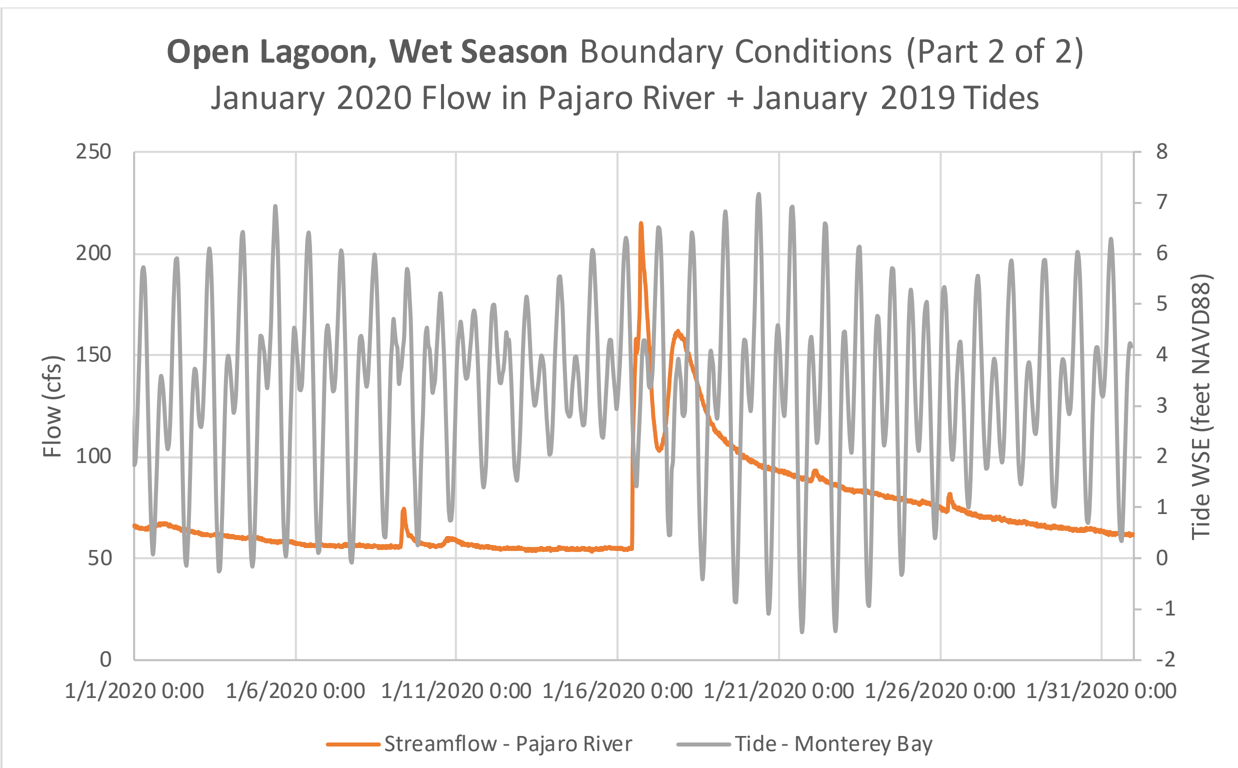


Figure 4: Hydrologic boundary conditions selected as representative of the Open Lagoon, Wet Season hydrologic regime.

2.3. Closed Lagoon Boundary Conditions

As with the Open Lagoon mouth state, the Closed Lagoon state is separated into dry season and wet season. Unlike for the Open Lagoon state, however, the modeling approach is significantly different for the wet season and the dry season in the Closed Lagoon state. Thus, the derivation of the boundary conditions is also quite different. Each approach and the resulting boundary conditions are described separately in the sections below.

2.3.1. Wet Season

For the Closed Lagoon, Wet Season, an actual closure event from the historic record is simulated. Lagoon water level data and a lagoon closure record is available from 2011 to present. During that period of record, there were eight total closure events. Of those eight candidate events, many of which are unsuitable for hydraulic modeling with HEC-RAS. Reason that a closure event might be unsuitable include:

- The lagoon temporarily opened and then closed again during the closure period (e.g., due to a coastal storm/wave overwash). This scenario can't be modeled as a continuous simulation in HEC-RAS.
- The lagoon was closed for too short a time (less than 1 month). The HEC-RAS model results would thus be nonrepresentative of a "typical" closure event
- The lagoon was closed for too long (greater than 3 months), resulting in too long of model runtimes.

The Nonfederal Sponsor's consultant (ESA) has produced a figure that compiles the available record for lagoon water levels, inflows, and ocean total water levels, and indicates thereon the closure events and breaches (Figure 5). Reviewing the closure record and taking into consideration the aforementioned limitations of modeling a closure event, the selected event is the closure period between approximately November 2017 and January 2018 (identified with the red box in Figure 5).

The Wet Season closure event that was selected as representative for modeling purposes spans more than two months. However, in order to keep model runtimes down and be consistent with boundary conditions for the other hydrologic regimes for the sake of combining results into an annual weighted average, the desired time series duration is one month. To compress this two-month time series into a one-month time series that captures the same range of water levels (and marsh inundation pattern), certain blocks of days where water levels in the lagoon remained steady were clipped out of the time series. After compressing the time series, the start date for the selected hydrographs were artificially set to January 1st, 2018. The resulting set of hydrologic boundary conditions used in the Closed Lagoon, Wet Season hydraulic model are presented in Figure 6.

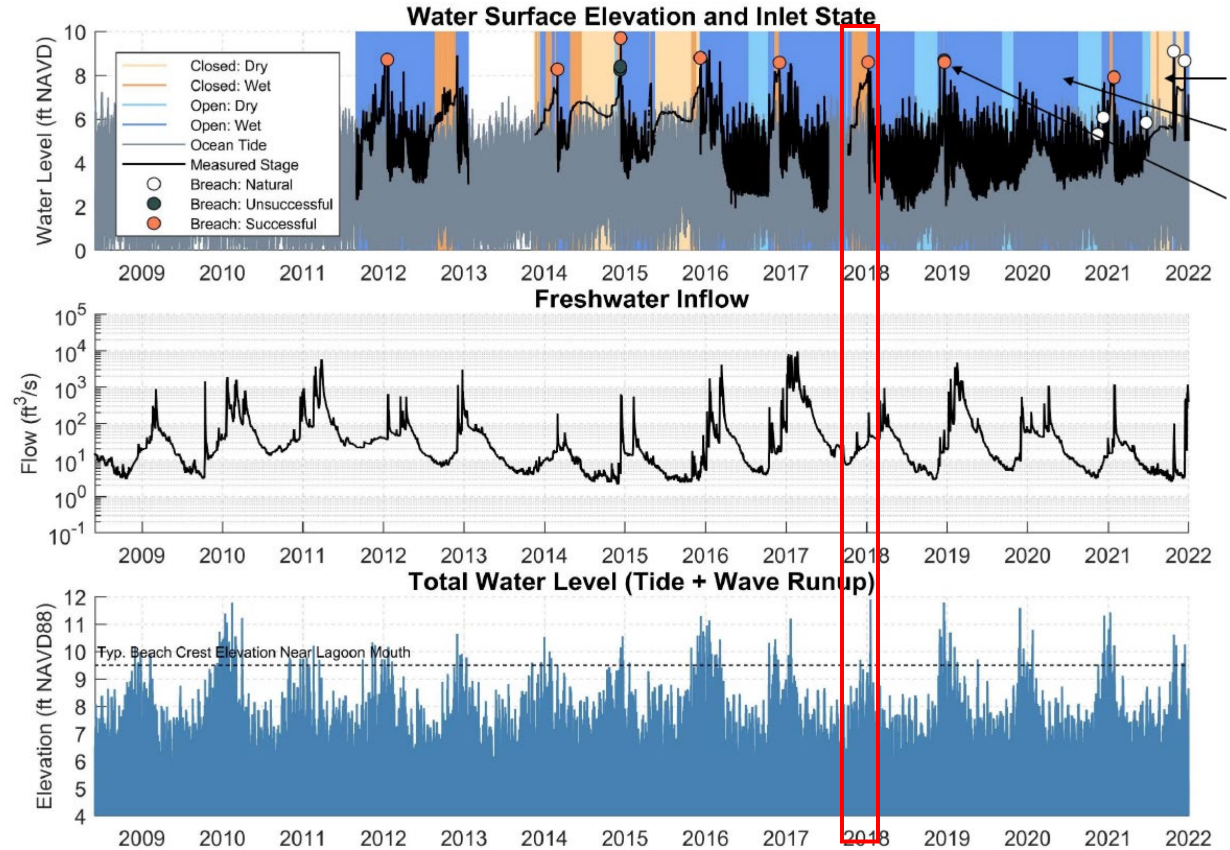


Figure 5: Historical record of water levels in Pajaro Lagoon, freshwater inflow into the lagoon, and total water level in Monterey Bay, with lagoon closure state and breach events indicated. The red box highlights the closure period that was selected for hydraulic modeling for the Watsonville CAP feasibility study. Figure adapted from preliminary results provided by ESA.

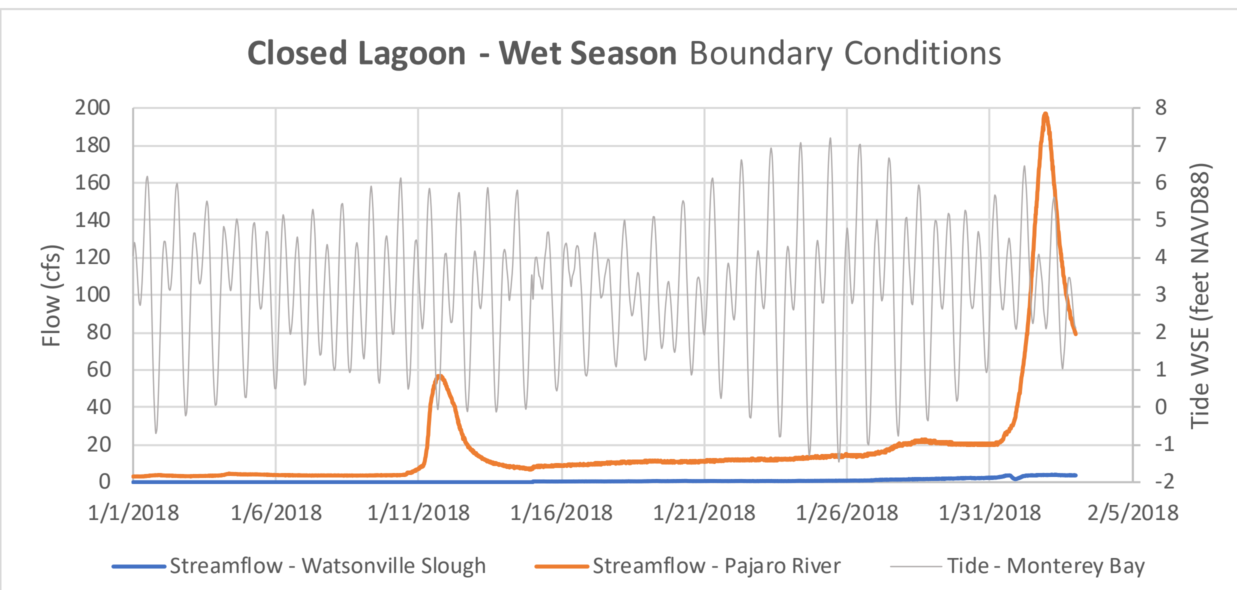


Figure 6: Hydrologic boundary conditions selected as representative of the Closed Lagoon, Wet Season hydrologic regime.

2.3.2. Dry Season

For the Closed Lagoon, Dry Season, a simplified modeling approach is employed. Rather than run a hydraulic model to simulate a dry season closure event, a static water surface profile is assumed across the entire slough system. This simplifying assumption was deemed acceptable because in the dry season closure events, the lagoon water level is consistently less than 6 feet NAVD88 (see lagoon water level record in Figure 5). At WSEs less than or equal to 6 feet, water is confined to the slough channel and does not reach up onto the marsh plain. Therefore, in the post-processing of hydraulic model results for the purposes of quantifying annual hydroperiod (described in Section 4.6 of this analysis), the Closed Lagoon, Dry Season hydraulic model results were synthetically generated to have 100% time inundated within the slough channel at elevations less than 6 feet NAVD88, and 0% time inundated for the areas adjacent the slough channel that are at elevations greater than 6 feet NAVD88.

2.4. Extreme Event Hydrology

This project uses values from the FEMA Flood Insurance Study (FIS) for the extreme event streamflow. The information contained in the FIS is considered authoritative. The FIS that covers the project area is Study #06087CV001C, Santa Cruz County and Incorporated Areas, Effective Date: 29 September 2017. The peak discharges published in the FIS for Watsonville Slough and for the Pajaro River are reproduced in Table 1.

The FEMA FIRM shows that the entire project area is located in Zone AE, much of it in the Regulatory Floodway, with a base flood elevation between 13 and 15 feet NAVD88. At a water surface elevation of 15 feet, the entire project area is submerged by at least 5 feet of water, and it is expected that there will be no measurable flood impacts due to the proposed project scenarios. Nevertheless, extreme event discharges were modeled with HEC-RAS to evaluate any potential flood impacts from the proposed scenarios.

Table 1: Peak flows in Watsonville Slough and Pajaro River as published in the Effective FEMA FIS.

Annual Exceedance Probability (AEP)	Peak Discharge in Watsonville Slough, below confluence with Struve Slough (cfs)	Peak Discharge in Pajaro River, downstream of confluence with Salsipuedes Creek (cfs)
10%	1,320	14,250
2%	2,980	32,500
1%	3,910	43,600
0.2%	6,400	76,200

3. Development of Project Scenarios

In addition to the No Action alternative, three distinct project scenarios were developed for the State and County-owned parcels upstream of the W. Beach Road crossings. The names and brief descriptions of the scenarios are as follows:

1) *No Action (Figure 7)*- The No-Action alternative assumes no federal project in the study area.

2) *Crossing Improvements (Figure 8)* – This alternative consists of replacing the existing Beach Road pipe culverts with a larger, taller, culvert and raising the elevation of Beach Road. It also includes the replacement of a smaller culvert in an agricultural ditch that runs parallel to Beach Road with a more robust culvert fitted with a mechanical flap gate. This scenario allows higher water surface elevations (WSEs) in the Pajaro Lagoon that inundate the associated marsh plain during the closed lagoon state having dangerous road flooding at the crossing trigger the County to mechanically breach the beach berm to avoid flood impacts. In the existing conditions, the beach berm is breached by the County when water levels in the lagoon reach approximately 8 feet NAVD88, before the inundation reaches much of the marsh plain. If the Crossing Improvement scenario is implemented, water levels in the lagoon could rise to approximately 9.2 feet NAVD88 before significant flood impacts to infrastructure occur, allowing the marsh plain experience more natural inundation periods.

   The higher conveyance capacity and increased road profile elevations associated with the Crossing Improvements scenario will decrease the frequency and duration of road closures. However, the proposed culvert and road improvements are not intended to prevent the road from overtopping or road closures. The proposed crossing improvements are only designed to benefit the ecosystem restoration project performance.

3) *Earthwork (Figure 9)* – This scenario consists of excavation of three dendritic tidal channel alignments and breaching of existing slough-side berms in nine locations. The purpose of this scenario is to provide pathways for water to more readily escape the main slough channel and spread onto the marsh plain, thereby increasing frequency and extent of marsh inundation.

4) *Crossing Improvements + Earthwork (Figure 10)* – This alternative is a combination of scenarios 2 and 3.

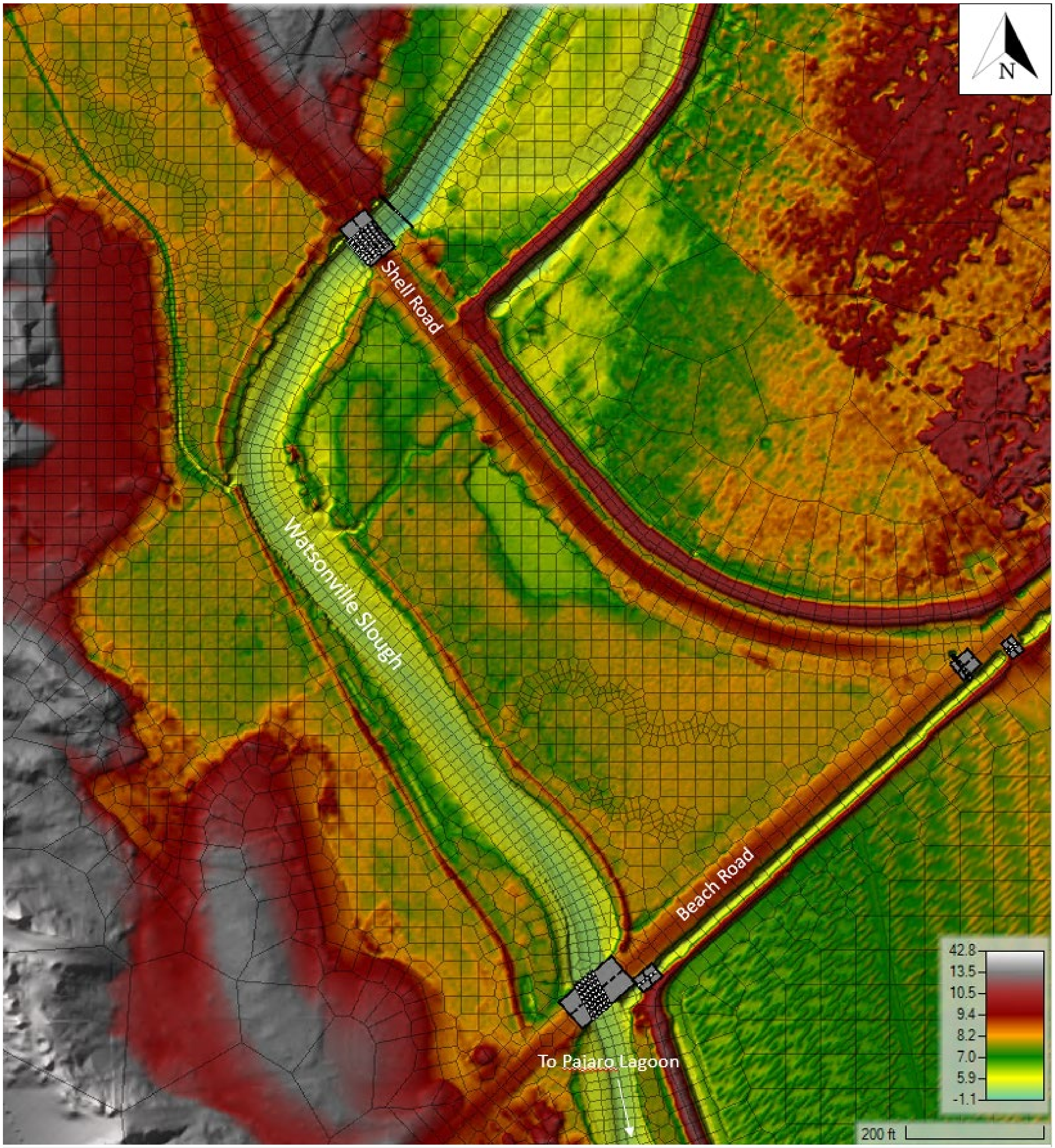


Figure 7: No Action project alternative.

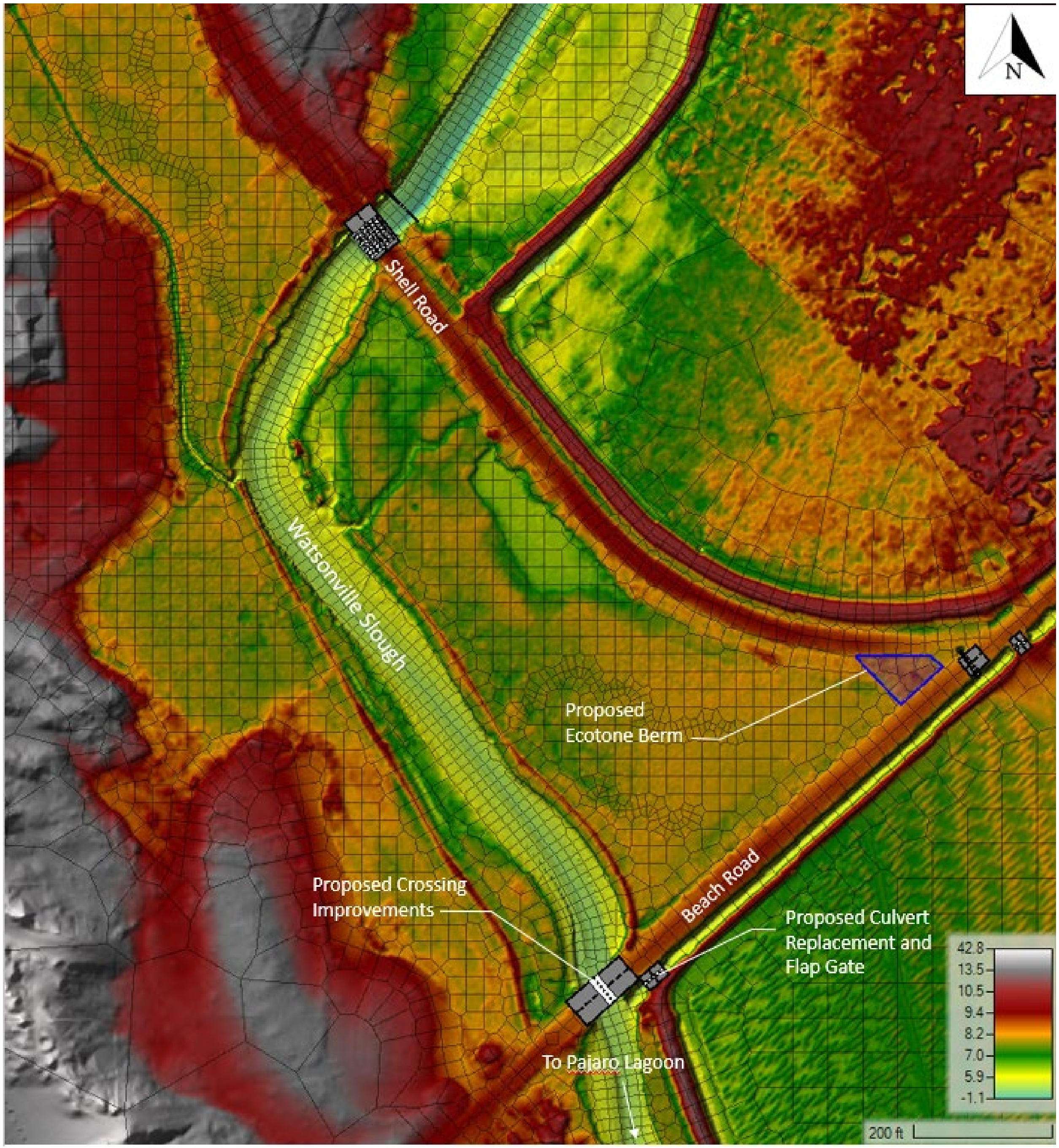


Figure 8: Crossing Improvements project scenario.

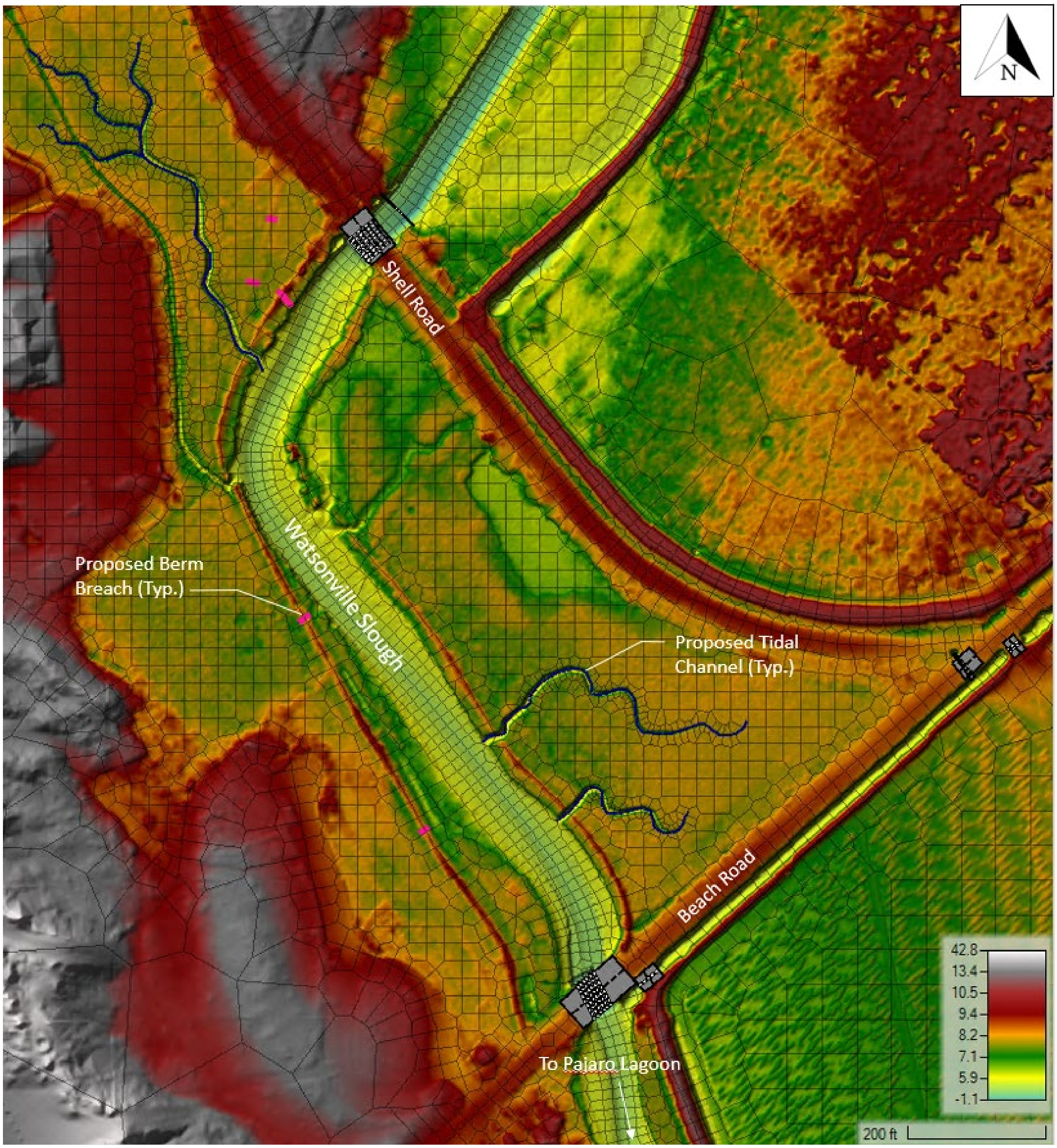


Figure 9: Earthwork project scenario.

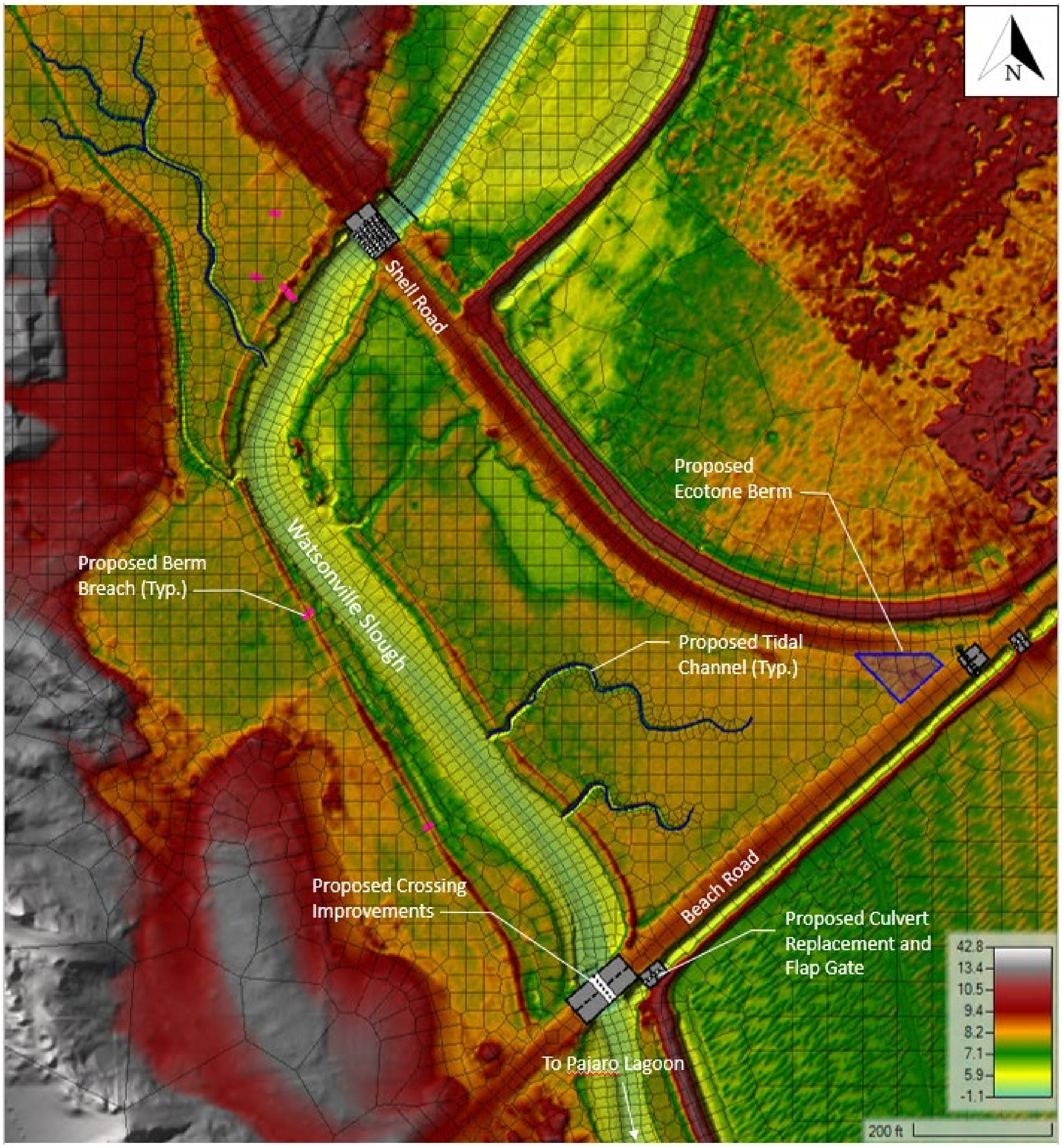


Figure 10: Crossing Improvements + Earthwork project scenario.

3.1. Crossing Improvements Design Considerations

There are two key design considerations with respect to the Crossing Improvements measures: (1) determining the appropriate culvert size, and (2) identifying the new closed lagoon County breach threshold that is enabled by raising the culvert and roadway.

3.1.1. Culvert Size

The primary consideration for sizing the proposed culvert was to improve the hydraulic conveyance compared to existing conditions. It was not possible to design the culvert according to a flood conveyance criteria (e.g., passage of the 1% AEP flow) due to the flood prone nature of the project area. Given the low-lying topography and its proximity to the Pacific Ocean and mouth of the Pajaro River, the entire project area is situated in the FEMA 100-year floodplain. According to the FEMA FIS, the WSE in the project area is 13 feet NAVD during a 1% AEP event and 10.5 feet during a 10% AEP event, both of which exceed the elevation of the marshplain and all nearby roads, including Beach Road (FEMA, 2017).

The conveyance area of the existing Beach Road culvert is approximately 60 square feet, and hydraulic model results indicated the existing culvert configuration is not causing a significant hydraulic constriction under normal flow and tidal conditions. Analysis results indicate a single culvert size of 18-feet width by 7-feet height aligned perpendicular to the road centerline (i.e., at a skew angle of approximately 30 degrees) would not result in flow constriction or excess velocity/shear under any of the test flow cases. The flow conditions that were tested consisted of the 1-month-duration hydrographs described in Chapter 2, as well as combinations of steady-state MHHW and steady-state MLLW for the downstream boundary condition, and 40 cfs (the 99^{th} percentile flow duration value), 300 cfs (the channel capacity flow value), 1,320 cfs (the 10% AEP flow from the FEMA FIS) for the upstream boundary condition. As the width of the existing configuration of pipe culverts exceeds 18 feet, the PDT has also discussed the potential to install two wide-span culverts to span the entire width of the Slough channel. For the purposes of the Feasibility Study, a single wide-span culvert was modeled in the Crossing Improvements scenario. Additional refinements to the culvert size and configuration will be examined during Design phase.

3.1.2. Selection of a Revised County Breach Threshold Elevation

In the current conditions, the County of Santa Cruz has a breaching protocol in place to mechanically breach the beach closure at the mouth of the Pajaro Lagoon to prevent flood impacts to W. Beach Road. The W. Beach roadway crossing effectively acts as an infrastructural trigger for breaching when water levels in the lagoon reach approximately 8 feet NAVD88.

In formulating the Crossing Improvements scenario, the PDT and County reviewed the Pajaro Dunes and Lagoon Flood Vulnerability Assessment (ESA 2018), which identified flooding thresholds for various infrastructure near the project area, in order to select a new breach threshold elevation that would avoid critical impacts (e.g. life safety or major system damage with no possible workaround) and also allow for a longer hydroperiod on the marsh plain. A summary matrix from that report is included as Figure 11. The 2018 study found that farm field levees adjacent to the Slough channel would be overtopped at water levels exceeding 9.7 ft NAVD, which could result in life safety impacts. Assets between the County's existing typical breach elevation of 8.0 ft NAVD and 9.7 ft NAVD were carefully reviewed to characterize the nature of impacts and the potential for retrofit and adaption. The total count of surveyed features exposed to various still water flooding elevations is shown in Figure 12. The PDT assumed a revised breach threshold elevation of 9.2 feet NAVD88 for the project scenarios that include the Crossing Improvements measures, as the number of features exposed to nuisance flooding were determined to not be threatening to life safety and could be mitigable through the project.

FLOODING THRESHOLDS FOR VARIOUS FEATURES IN AND AROUND PAJARO DUNES

ID	Name	Flooding Threshold (ft at Beach Rd gauge)	Flooding Threshold (ft NAVD88)	Surveyed Feature	Location
1	Staff gauge	3.84	6.34	3.0' reading	Watsonville Slough & Pajaro River
2	Puffin Ln sewage pump station (#3)	7.1	9.60	Adjacent hatch	River Road at Puffin Lane
		7.13	9.63	Electrical Box	
		8.97	11.47	Top of flood barrier	
3	Dunes Hall	7.62	10.12	Door threshold	at Sandpiper Center
4	Drainpipe at playfield	4.12	6.62	Top of culvert pipe	between Sandpiper and Willets
5	Sewage pump station (#2)	8.18	10.68	Adjacent hatch	River Rd @ Sanderling Cir
		8.35	10.85	Door threshold	
		8.52	11.02	Electrical box	
6	PG&E Transformer T 1693	6.48	8.98	Electrical Box	River Rd near Firehouse
		6.9	9.40	Adjacent hatch	
7	South Gatehouse	6.87	9.37	Door threshold	2661 Beach Rd Bldg 1
8	Cable box w electrical	8.18	10.68	Top of flood barrier	next to gatehouse pump station
		6.34	8.84	Ground within barrier	
9	Gatehouse sewage pump station (#1)	6.48	8.98	Door threshold	entrance to River Road
		7.46	9.96	Raised hatch	
10	Telephone box	6.24	8.74	Top of conc. footing	North side Beach Rd @ River Rd
11	Park Ranger residence south	6.6	9.10	Driveway	Palm Beach State Park
12	Park Ranger residence north	6.55	9.05	Driveway	Palm Beach State Park
13	Staff gauge	6	8.50	6.0' reading	Watsonville Slough @ Beach Rd
14	Beach Rd at Watsonville Slough	6	8.50	Center of road	Beach Rd at Watsonville Slough
15	Agricultural property	7.21	9.71	Berm Crest	South of Beach Rd
16	Drain inlet @ intersection	5.52	8.02	Grate	Beach Rd and Shell Drive
17	Coastal Distribution System Station	5.38	7.88	Ground at system	East Corner of Beach & Rio Boca
18	Stage gauge	4.14	6.64	3.0' reading	Watsonville Slough at Shell Rd
19	Flapgates	2.87	5.37	Top of lowest flapgate	Watsonville Slough at Shell Rd
20	Shell Drive at Watsonville Slough	6.37	8.87	Road Center	Watsonville Slough at Shell Rd
21	Watsonville Slough pumphouse	6.31	8.81	Pumphouse Deck	Watsonville Slough at Shell Rd
22	Pumphouse staff gauge	6.31	8.81	9.0' reading	Watsonville Slough at Shell Rd
23	Well 13 (Drinking Water)	7.78	10.28	Ground next to well	600 Shell Road
24	Sunset Booster Station (Drinking Water)	7.44	9.94	Ground next to well	800 Shell Road
25	North Gatehouse	8.19	10.69	West door threshold	101 Shell Drive
26	Road at lagoon culvert	6.93	9.43	Road center	PD North
27	Staff gauge	5.91	8.41	3.0' reading	PD North Lagoon
28	Cypress House	7.55	10.05	Ground outside door	South end of PD North
29	Storm drain	5.63	8.13	Grate	Front of Rental/Sales Office
30	North sewage pump station (#4)	8.06	10.56	Adjacent hatch	next to 105 Shell Road
		7.85	10.35	Door threshold	
31	Shed Village	6.76	9.26	Asphalt	PD North
32	History Center	6.74	9.24	Door threshold	At T-junction in PDN
33	Roadway within Pajaro Dunes North	6.56	9.06	Road Center	PD North
34	Lagoon House	8.09	10.59	Deck outside door	PD North
35	Low point culvert	5.26	7.76	Path center low point	PD North

Figure 11: Flooding thresholds for various features in and around Pajaro Dunes (ESA, 2018).

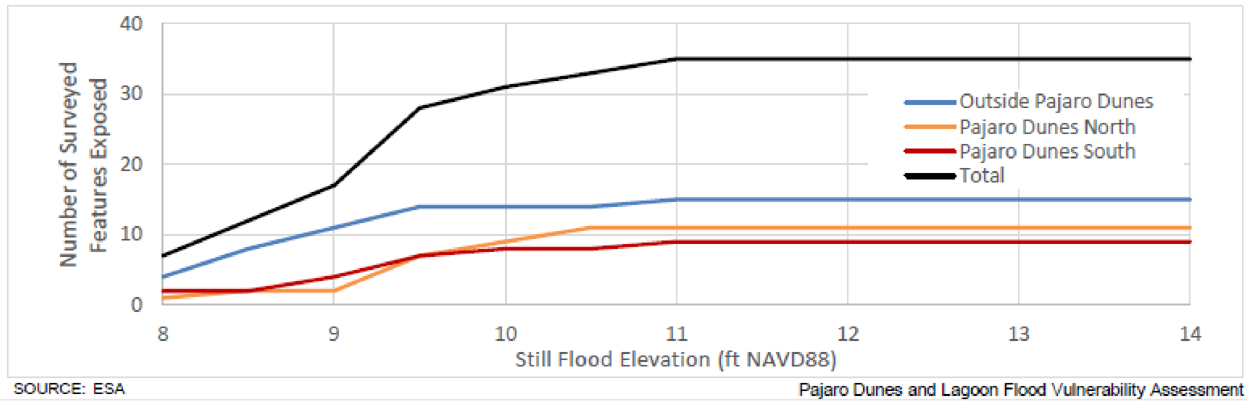


Figure 12. Total number of surveyed features exposed by range of still water flooding elevations (ESA, 2018)

3.1.3 Flood Risk Mitigation Measures

The revised breach threshold elevation of 9.2 feet NAVD88 exceeds several of the flooding threshold elevations listed in Figure 11. The PDT and County investigated the nature of any changes in flood extents to determine flood risk reduction measures that should be included as part of the Crossing Improvements scenario. In some cases, some features are meant to be exposed to water (e.g. staff gauge) and others have an existing flood barrier component that would be sufficient to protect the utility (e.g. top of door threshold). Some feature, such as the PG&E transformer and telephone box, would reasonably be at risk for flooding during King Tides with an open lagoon mouth (future without project conditions) and sea level change would increase risk of damage in the future. Therefore, the PDT assumed that utility owners would be floodproofing these low-lying assets. Table 2 summarizes the features exposed to nuisance flooding from the revised breach threshold and descriptions for adaptation/mitigation actions.

Table 2 Features Exposed to Nuisance Flooding from Revised Breach Threshold of 9.2 ft NAVD88

Feature ID	**Name**	**Flooding Threshold (ft NAVD)**	**Surveyed Feature**	**Notes**
6	PG&E Transformer T 1693	8.98 9.40	Electrical Box Adjacent Hatch	Assume utility owner will floodproof
10	Telephone Box	8.74	Top of conc. footing	Assume utility owner will floodproof
11	Park Ranger residence south	9.10	Driveway	Nuisance flooding anticipated from revised breach threshold. See additional discussion in Section 3.1.3.
12	Park Ranger residence north	9.05	Driveway	See note for ID 11
16	Drain inlet @ intersection	8.02	Grate	Feature is located upstream in agricultural ditch connection, where high water levels from backwatering are undesirable.

Feature ID	Name	Flooding Threshold (ft NAVD)	Surveyed Feature	Notes
17	Coastal Distribution System Station	7.88	Ground at system	Feature is located upstream in agricultural ditch connection, where high water levels from backwatering are undesirable.
20	Shell Drive at Watsonville Slough	8.87	Road Center	County confirmed that this is an isolated low point in the road. Road elevation at Shell Drive exceeds 9.2 ft.
21	Watsonville Slough pumphouse	8.81	Pumphouse Deck	
S22	Pumphouse staff gauge	8.81	9.0' reading on gauge	Feature is meant to be exposed to water
27	Staff gauge	8.41	3'0 reading on gauge	Feature is meant to be exposed to water
29	Storm drain	8.13	Grate	Feature is protected by higher elevation between location and Slough channel.
33	Roadway within Pajaro Dunes North	9.06	Road Center	Feature is protected by higher elevation between location and Slough channel.
35	Low point culvert	7.76	Path center low point	Feature is protected by higher elevation between location and Slough channel.

The review of vulnerable assets informed the development of auxiliary flood risk reduction measures that should be included as part of the Crossing Improvements measure to avoid potential flooding effects from raising the County's breach threshold to 9.2 feet. These are as follows:

(1) The replacement of an existing corrugated metal pipe culvert with a reinforced concrete pipe culvert with a flap gate in an agricultural drainage ditch immediately downstream and to the east the Beach Road slough crossing, to prevent backwatering up the ditch that could lead to overflow into agricultural fields to the east and into hydraulic connections underneath Shell Road-Beach Road intersection (Feature IDs 16 and 17); and

(2) The placement of an ecotone berm in the east corner of the State-owned parcel, adjacent the Shell Road-Beach Road intersection, to protect the low-lying western corner of the intersection.

(3) Flood risk reduction measures by the entrance of the Palm Beach State Park and lower elevation parking lot to prevent nuisance flooding and maintain drainage of runoff towards the Slough (e.g. paving, grading berms by the Slough side, etc.)

The aforementioned measures and roadway raise extent will be further refined during Design phase to ensure a smooth transition on the west end of W. Beach Road crossing by the Palm Beach State Park driveway and Pajaro Dunes entrance.

3.2. Earthwork Design Considerations

Tidal channel geometry (e.g., top width, channel depth, slopes) for the restoration design were evaluated at a conceptual level using empirical hydraulic geometry relations relating tidal channel size to marsh drainage area (Williams et al, 2002) and estimates of channel sizing from other similar-scale marsh systems in Central California. Locations of tidal channels were selected based on historic survey/mapping of the area, which revealed the presence of a historic channel at one location and identified additional existing flow pathways through low areas of the marsh. Marsh drainage areas were identified across all parcels and used to calculate the hydraulic geometry.

4. Hydraulic Modeling

The hydraulic modeling for this study was completed with HEC-RAS version 6.2. HEC-RAS is developed and maintained by the U.S. Army Corps of Engineers Hydrologic Engineering Center. The capabilities of HEC-RAS that were utilized in this study include two-dimensional unsteady flow simulations and georeferenced, two-dimensional animations of inundation.

4.1. Existing Conditions Model Setup

4.1.1. Model Geometry

The HEC-RAS model includes both Watsonville Slough and the Pajaro River. The upstream boundary for the model on Watsonville Slough is just downstream of San Andreas Road, where a streamflow gage operated by Pajaro Valley (PV) Water is located. The upstream boundary on the Pajaro River is the USGS gage at Main Street (Gage ID 11159500). Since gage data is available at these locations, they are ideal model boundaries. The downstream boundary for the model is the Pacific Ocean. The model is fully 2D (floodplain and channels). The extent of the 2D domain and location of boundary conditions are shown in Figure 13.

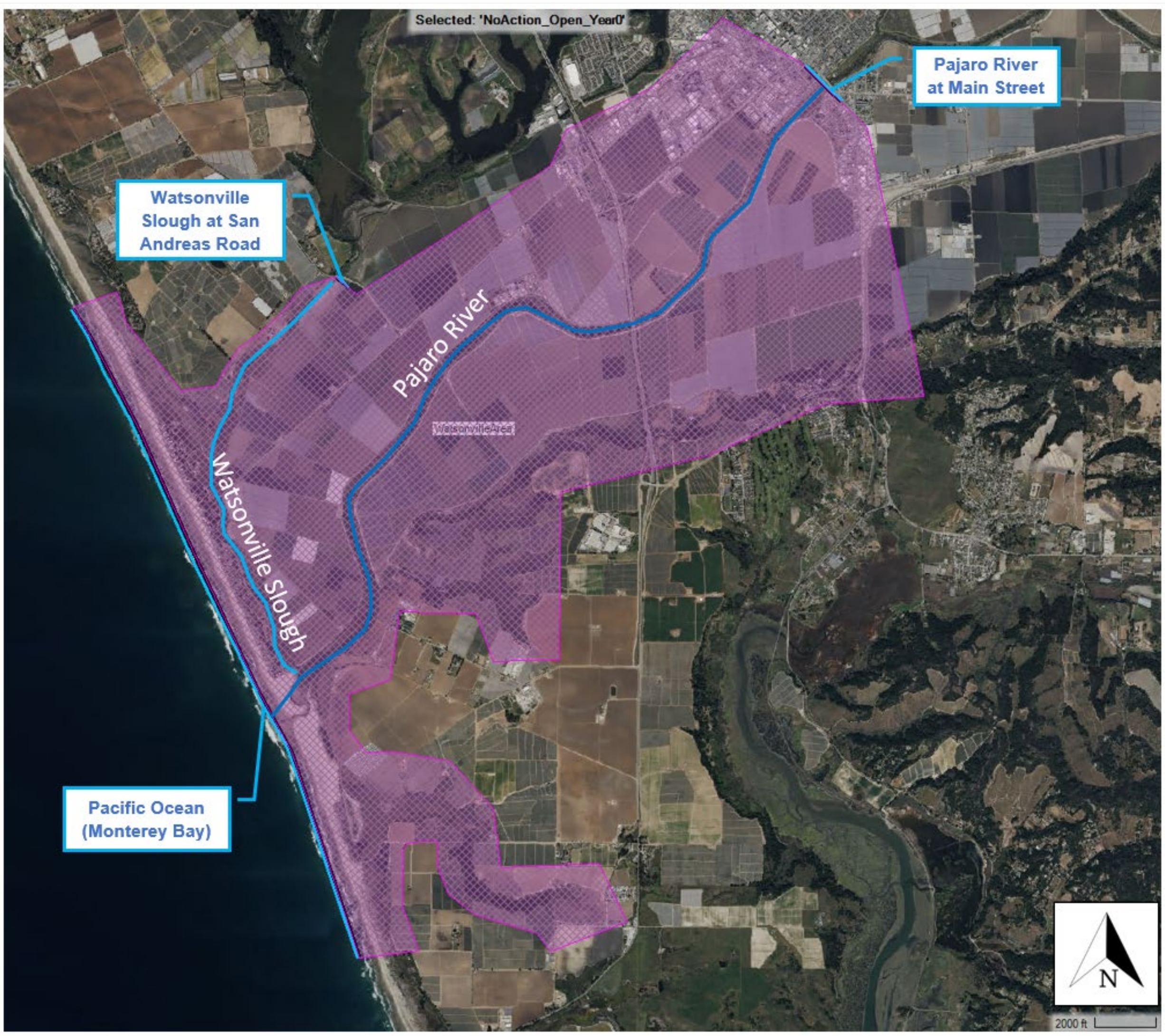


Figure 13: Extents of HEC-RAS model domain with upstream and downstream boundary conditions identified.

4.1.1.1. Terrain

There were several pre-existing models of the study area which were used as the basis for the development of the terrain and geometry for this Watsonville Slough CAP study. Each of these previous models focused on different portions of the study area and they used different topographic and bathymetric data.

The most recent 2D HEC-RAS model of the project area was completed by Peterson Brustad Inc. (PBI) for the USACE Pajaro River Flood Risk Management Project (Pajaro FRM model). The terrain used for the Pajaro FRM model, which is based on 2018 USGS Lidar data, was used as a primary data source for the floodplain areas in the CAP model. A flood vulnerability assessment performed by Environmental Science Associates (ESA) in 2018 used bathymetric data in Watsonville Slough from Shell Road downstream to the lagoon area, and this bathymetry was used for the current CAP study. For bathymetric data upstream of Shell Road to San Andreas Road, cross-section data from the 2014 Watsonville Slough Hydrology Study 1D HEC-RAS model (2014 1D HEC-RAS model) completed for the Resource Conservation District of Santa Cruz County was utilized. Those cross-sections are based on 2012 survey data.

Channel bathymetry in the Pajaro River in the CAP model is based on the latest bathymetric data surveyed by Northwest Hydraulic Consultants (NHC) in 2020, which covers the northern area of the Pajaro River lagoon to just upstream of Highway 1. Upstream of this reach, the Pajaro River channel elevations utilize the cross-sections from the latest Pajaro FRM model. Additional survey data from the Santa Cruz County's 2021 Pajaro River Mouth Monitoring Report, specifically data surveyed on 22 November 2019 and 19 February 2020, is incorporated for lagoon/mouth area elevations. Finally, USGS 2017 bathymetry is used for the ocean bathymetry. Figure 14 shows the approximate boundaries of the various data sources used in the development of the HEC-RAS terrain for this Watsonville Slough CAP study.

Additional modifications were made to the terrain for cuts at Beach Road and Shell Road crossings to ensure that the terrain was lower than the culvert inverts. Additionally, the connection to the ocean was lowered to match the lowest elevation upstream in the lagoon of 0.8 feet; this was done to allow for a better connection between the ocean and the lagoon and to improve model calibration for the Open Lagoon model runs, as described in Section 4.1.3.

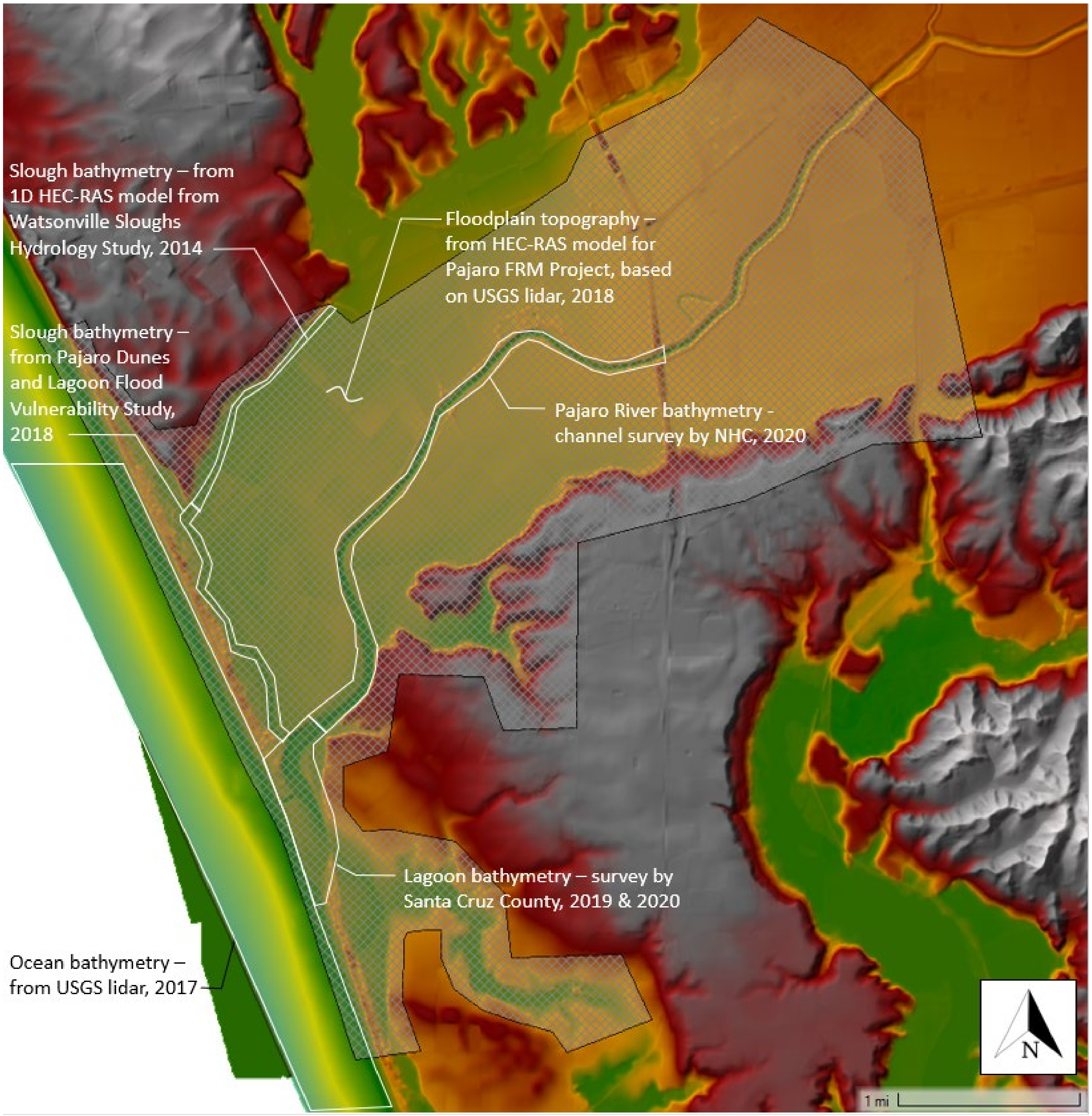


Figure 14: Data sources for HEC-RAS terrain. Boundaries shown are approximate.

Closed Lagoon Modifications

For the closed lagoon model runs, some modifications to the Open Lagoon terrain were necessary. This is because the lagoon closure event that was used for calibration of the closed lagoon model occurred in November 2017 to January 2018, and the configuration of the lagoon mouth was different at this time than during 2020. Figure 15 shows side-by-side aerials of the lagoon in 2018 and 2020. The lagoon-to-ocean connection portion of the RAS terrain was modified using the “Terrain Modification” tool in RAS Mapper to better match the 2018 USGS lidar and 2018 aerial imagery.

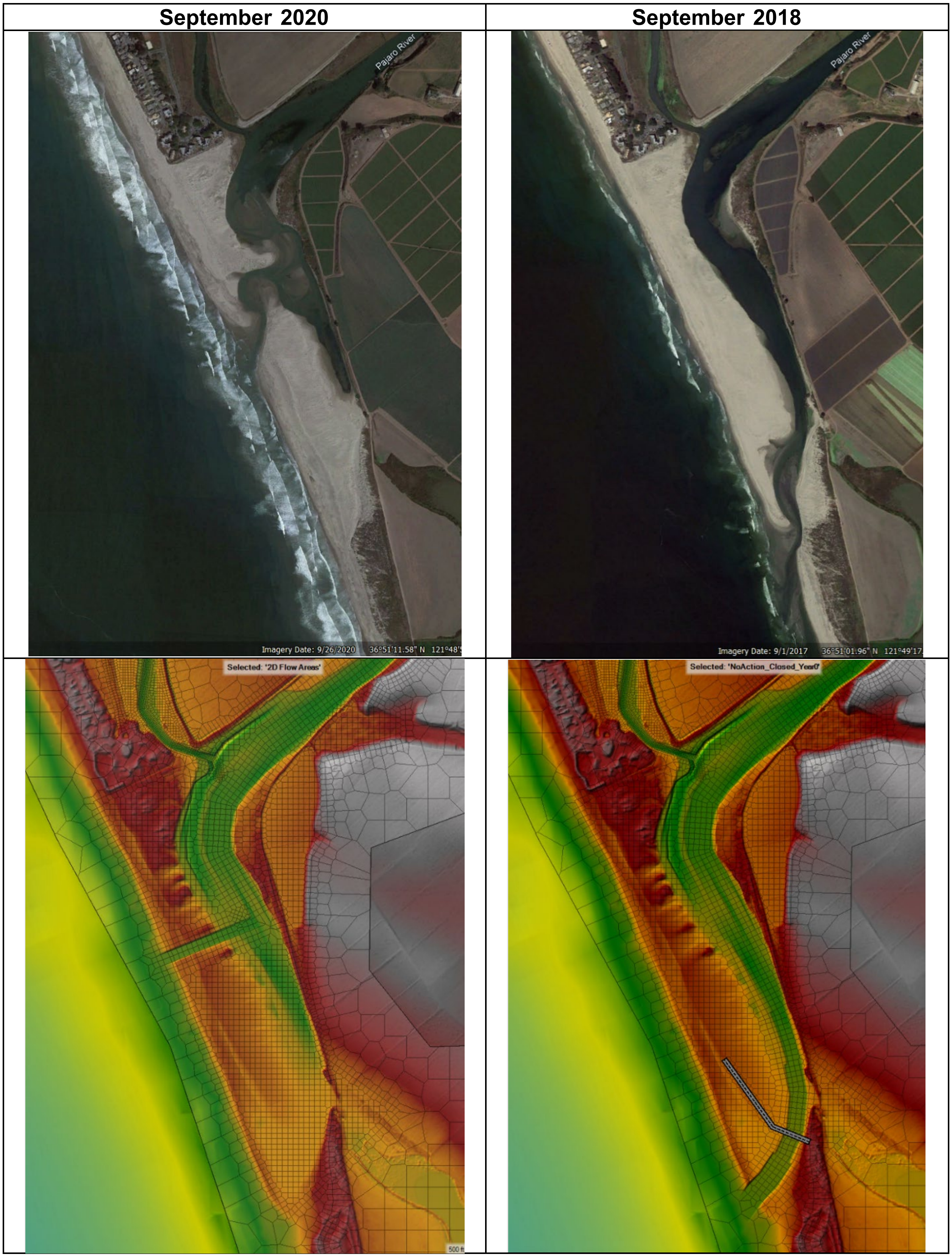


Figure 15: Lagoon aerials obtained from Google Earth and HEC-RAS terrains for the Open Lagoon model based on 2020 conditions (left panels) and the Closed Lagoon model based on 2018 conditions (right panels).

4.1.1.2. 2D Mesh and Computation Options

The model developed for this analysis is a two-dimensional hydraulic (2D) model (floodplain and channels). The 2D mesh has the highest resolution in Watsonville Slough and the adjacent marsh plain, which is the primary area of interest with respect to ecosystem restoration. Mesh cell sizes are 10 feet in the slough channel, 25 feet in the marsh plain areas, 50 feet in the Pajaro River channel, and up to 200 feet in the broader floodplain.

The HEC-RAS shallow water equations solver was used in this analysis. This solver is appropriate for tidally influenced areas. A computation timestep of 5 seconds was used, as this was the largest timestep that computed stable model results. For the simulation duration of 1 month, model runtimes were approximately 10 hours per run.

4.1.1.3. Hydraulic Structures

There are two road crossings on Watsonville Slough within the CAP study area. The Beach Road crossing is the furthest downstream crossing and is located about 1.3 miles upstream of the confluence with the Pajaro River. The Shell Road crossing is located about 0.25 miles upstream of Beach Road crossing.

The Beach Road crossing, shown in Figure 16, includes six 48-inch diameter reinforced concrete pipes. Both field observations and modeling show that this crossing rarely, if ever, controls flow rates in the system and, in fact, is frequently inundated during periods of extended rainfall or high winter tides (Balance 2014). This crossing is important for emergency access to/from the Pajaro Dunes South community.

The Shell Road crossing is the most important crossing in relation to drainage control within the watershed. The crossing, shown in Figure 17 and Figure 18, includes eight 48-inch diameter reinforced concrete pipes that pass under the road and an old flow control weir that is no longer functional or pertinent to current drainage conditions. Each pipe is equipped with a flap gate on their downstream ends to prevent ocean water from flowing upstream, as Shell Road is intended to be the demarcation point between the freshwater channels and sloughs upstream and the tidally-influenced environment that characterizes the system downstream to the mouth of the Pajaro River. The crossing also includes a pump station on the upstream side, operated by the County of Santa Cruz (Balance 2014). The pump station at the Shell Road crossing conveys water from the upstream side to the downstream side, to increase channel capacity for agricultural drainage. There is also a vent array that spans the crossing above the flap gates, at elevation 7 feet NAVD88. During very high tides, when tide stage exceeds 7 feet NAVD88, water can enter the vent array from the downstream side and pass through the vents to the upstream side of Shell Road.

The 2014 1D HEC-RAS model prepared as part of the Watsonville Sloughs Hydrology Study (Balance, 2014) served as the basis for the culverts and pump station geometry and operating rules in the 2D HEC-RAS model that was prepared for this analysis. The Sponsor was consulted regarding the pump station operation and capacity, and the Sponsor confirmed that the values obtained from the one-dimensional HEC-RAS model represented the best available data for the pumps.

For the structures on the Pajaro River, bridge deck elevations were obtained from the latest 2018 lidar and structure geometries are based on the HEC-RAS model that was developed by

PBI for the USACE Pajaro River Flood Risk Management Project in 2021. This model underwent USACE review in the form of DQC and ATR in 2021 and 2022.

For the Shell Road crossing, a gate was added to the model to represent the vent array above the culverts. An operational condition was applied to the gate to only allow flow in the upstream direction.

Figure 16: Beach Road crossing at Watsonville Slough – view of downstream side looking west.

Figure 17: Shell Road crossing at Watsonville Slough – view of downstream side with 8 culverts with flap gates and vent array above the culverts.

Figure 18: Shell Road crossing at Watsonville Slough – looking upstream from the road. View of pump station and old flow control weir.

Closed Lagoon Modifications

An additional structure was added to the HEC-RAS geometry for the Closed Lagoon model runs to simulate the fact that the lagoon and slough system are cut off from the downstream tidal fluctuations and impound water, slowly filling with inflows from Watsonville Slough and the Pajaro River. This structure consists of a weir/embankment SA/2D connection with top width of 50 feet and top elevation of 10 feet NAVD88. There is an outflow rating curve associated with this structure to simulate seepage losses through the berm and underlying beach, which is discussed in more detail in Section 4.1.2.3. This structure is set to breach at a water surface elevation of 8 feet NAVD88, in accordance with the historical record of mechanical breaches and Santa Cruz County's established mechanical breaching protocol.

4.1.1.4. Manning's n values

Land Cover (NLCD 2016) data was imported using tools from within RAS Mapper. Classification polygons were then added for the Watsonville main channel, side channels (along Watsonville Slough), Watsonville overbank areas, beach (sand), and Pajaro Main channel. The Manning's n values used are shown in Figure 19 and were based on values from the PBI update for the Pajaro FRM study, except for the classification polygons (IDs 1-5 in Figure 19), which were determined by considering the n values from the Pajaro FRM model and a review of aerial imagery.

Classification Parameters

Selected Area Edits

ID	Name	ManningsN	Percent Impervious
0	NoData	0.04	
21	Developed, Open Space	0.04	
42	Evergreen Forest	0.16	
22	Developed, Low Intensity	0.1	
23	Developed, Medium Intensity	0.12	
43	Mixed Forest	0.16	
71	Grassland-Herbaceous	0.035	
52	Shrub-Scrub	0.1	
82	Cultivated Crops	0.035	
24	Developed, High Intensity	0.15	
90	Woody Wetlands	0.12	
81	Pasture-Hay	0.03	
11	Open Water	0.04	
95	Emergent Herbaceous Wetlan...	0.07	
31	Barren Land Rock-Sand-Clay	0.025	
41	Deciduous Forest	0.16	
1	WatsonvilleMainChannel	0.045	
2	SideChannels	0.045	
3	WatsonvilleOverbank	0.07	
4	Sand	0.025	
5	PajaroMainChnl	0.045	

Figure 19: Manning's n values per land cover for the 2D model domain.

4.1.2. Boundary Conditions

The boundary conditions for the model consist of two flow hydrographs at the upstream end and one stage hydrograph at the downstream end. The location of the boundary conditions with respect to the model domain are shown in Figure 13. The hydrographs and their derivation are presented in Chapter 2. Additional information about the boundary conditions in the HEC-RAS model are described below.

4.1.2.1. Streamflow

The observed streamflow hydrographs presented in Chapter 2 were slightly modified for input into the HEC-RAS model to account for additional hydrologic information about the study area. One of these modifications was the addition of a baseflow to the Watsonville Slough inflow hydrograph. The magnitude of the baseflow term was 1.5 cfs and it was added to every timestep in the time series. This baseflow term represents agricultural return flows, and the value of 1.5 cfs was provided to the PDT by the Nonfederal Sponsor's consultant, based on information that they had received from a 2019 USGS study.

4.1.2.2. Tides

The observed total water level hydrographs from the Monterey tide station, as presented in Chapter 2 of this analysis, were used directly as downstream boundary conditions in the HEC-RAS models.

In the case of the Closed Lagoon model runs, the downstream boundary is disconnected from the lagoon system by the weir/embankment SA/2D connection called “Lagoon Closure”. That SA/2D connection is eventually breached when the lagoon water level upstream of the embankment reaches the predefined breach threshold. And once breached, the tidal downstream boundary condition influences water levels in the study area.

4.1.2.3. Evapotranspiration and Infiltration

Given the nature of the topography and the hydraulics in the project area, there are portions of the marsh plain that are isolated, localized depressions that pond once a high tide recedes. Because the benefits quantification methodology for this study relies on the percent time inundated metric, it was necessary to simulate infiltration and evapotranspiration (ET) of this ponded water, so that it doesn’t reside in the marsh plain depressions indefinitely.

ET and infiltration were lumped into a single term and applied uniformly across the entire model domain in the HEC-RAS model. This was done because the infiltration module in HEC-RAS, which allows for spatially variable infiltration rates, is only applicable to precipitation (“rain-on-grid”) inputs. To estimate the magnitude of infiltration, the PDT reviewed soil properties published in the National Resource Conservation Services Web Soil Survey and the Integrated Hydrologic Model of Pajaro Valley, Santa Cruz and Monterey Counties, California (USGS, 2014). The USGS report used a vertical hydraulic conductivity of 0.0 ft/day for Watsonville Slough, and the Web Soil Survey shows that the predominant soil type in the project area is Clear Lake clay, which has a hydrologic soil group classification of ‘D’, corresponding to a very slow infiltration rate. Communication with PV Water staff and the Nonfederal Sponsor also indicated that infiltration rates in the slough are thought to be quite low.

To estimate ET, observed data was obtained from the California Irrigation Management Information System (CIMIS) station #209. To simplify HEC-RAS inputs, a constant hourly ET rate was applied to the full simulation, as opposed to an ET time series. To derive the value for this constant ET rate, a simple average of the CIMIS data for the simulation period was calculated. When the constant ET rate was lumped with the estimate for infiltration, the loss rate used in the HEC-RAS model was 0.01 inches/hour. The same ET/infiltration loss rate was used for all model runs.

Closed Lagoon Modifications

In the case of the Closed Lagoon model runs, there are additional infiltration losses that result from the increased hydraulic head as water levels rise behind the closed beach berm. To account for these additional losses, a rating curve was provided by the Nonfederal Sponsor’s consultant that related water surface elevation in the lagoon to outflow from the lagoon in the form of infiltration/seepage. This rating curve was derived from their Lagoon QCM water balance analysis and it is calculated as the losses from the lagoon that could not be attributed to ET. The rating curve is applied in the HEC-RAS model as an outlet rating curve at the SA/2D connection called “Lagoon Closure” (Figure 20). Because this outflow term accounts for all losses due to infiltration, the lumped ET/infiltration term in the HEC-RAS model is reduced from 0.01 inches/hour in the Open Lagoon runs to 0.003 inches/hour in the Closed Lagoon runs.

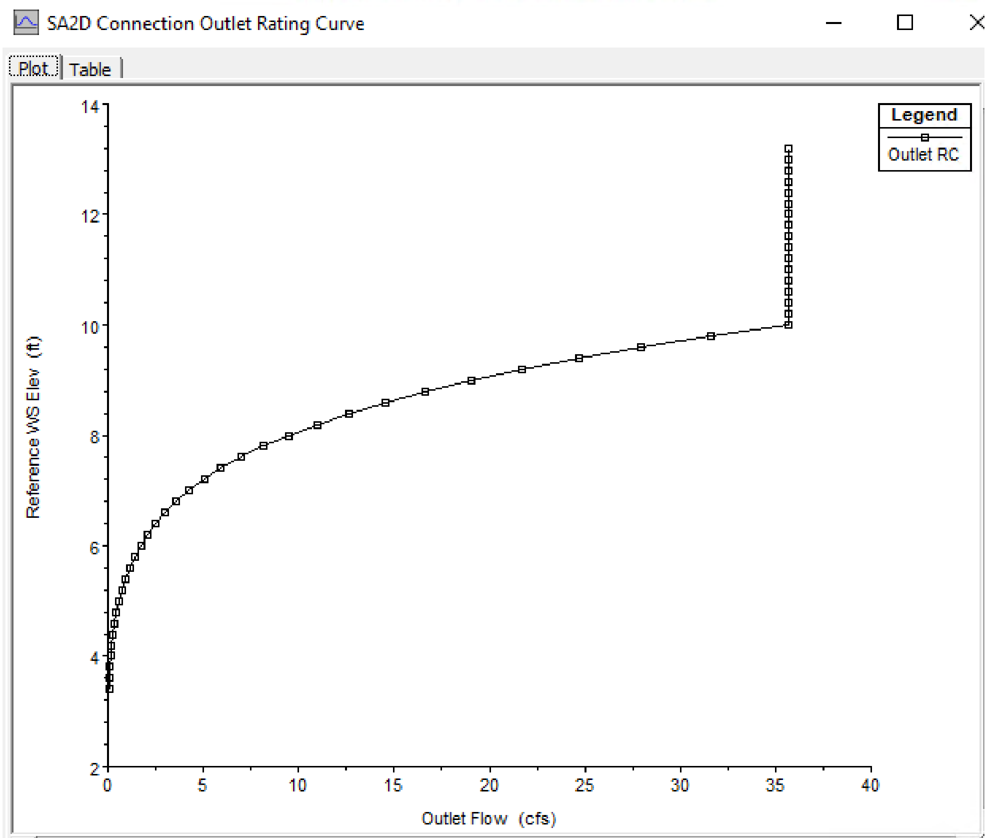


Figure 20: Rating curve for infiltration and seepage losses for the Closed Lagoon model runs.

4.1.3. Calibration

Calibration of the HEC-RAS model was performed using a water level gage located in Watsonville Slough just downstream of Shell Road. This gage is maintained by PV Water and has been in operation since Water Year 2016.

Calibration was performed for the open lagoon model and closed lagoon model separately, as different parameters were found to be more influential to model results in each of these two lagoon states. For the open lagoon model, model results were found to be most sensitive to the terrain at the lagoon to ocean connection. For the closed lagoon model, model results were found to be most sensitive to infiltration/evapotranspiration losses and lagoon hypsometry.

Open Lagoon

Calibration was performed for an Open Lagoon, Dry Season model run (June - July 2020), and subsequently evaluated for an Open Lagoon, Wet Season model run (April 2020). Note that the Open Lagoon, Wet Season calibration run is different than the selected representative hydrologic boundary conditions for the ecosystem restoration modeling. This is because the selected representative boundary conditions consisted of January 2020 flows combined with January 2019 tides, and was therefore not an observed, calibratable event. The plots showing the final calibration for the Open-Dry and Open-Wet EWOP model runs are shown in Figure 21 and Figure 22, respectively.

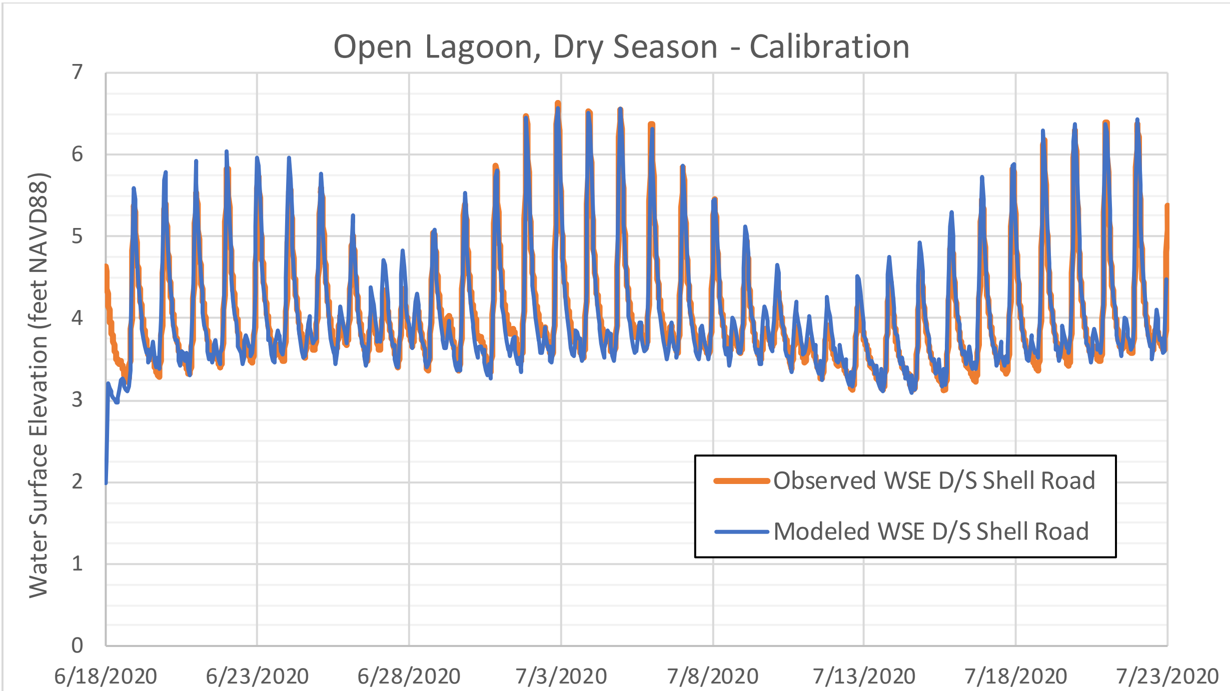


Figure 21: Observed vs. Modeled water surface elevation downstream of Shell Road for Open Lagoon model for June to July 2020.

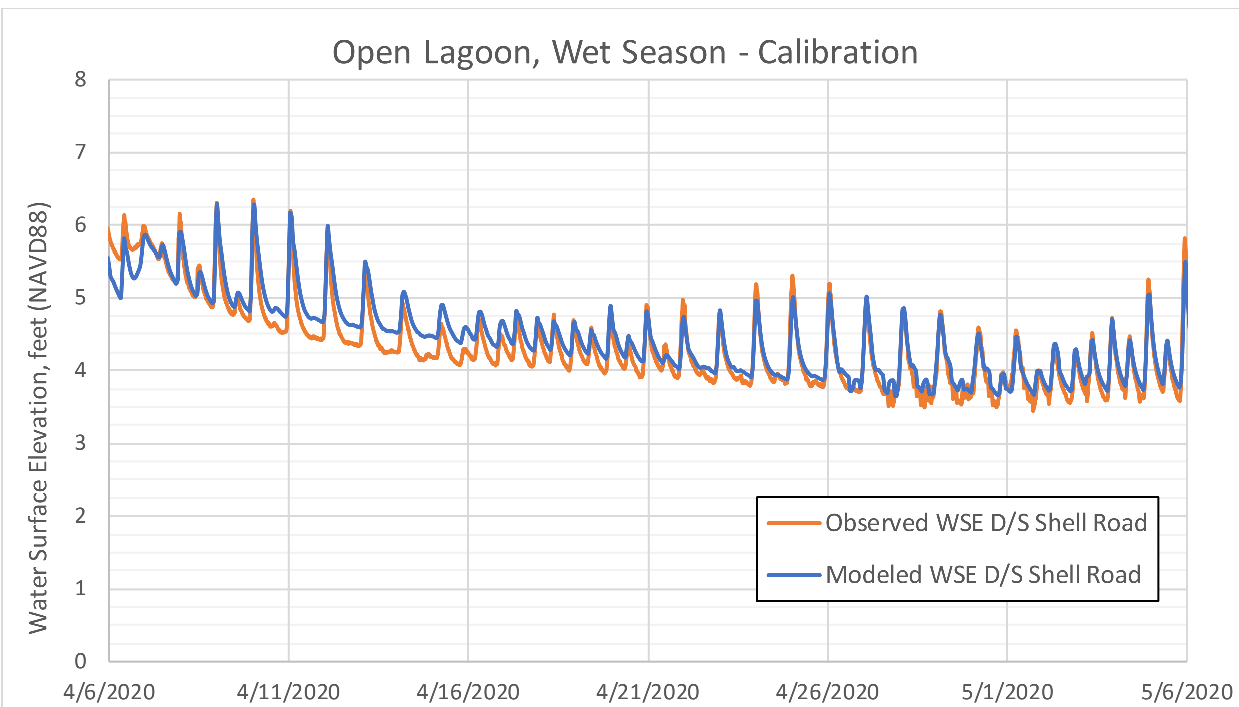


Figure 22: Observed vs. Modeled water surface elevation downstream of Shell Road for Open Lagoon model for April 2020.

Closed Lagoon

The Closed Lagoon, Wet Season model was calibrated to the full 70-day closure period of November 2017 through January 2018. The results of the final calibration are presented in Figure 23.

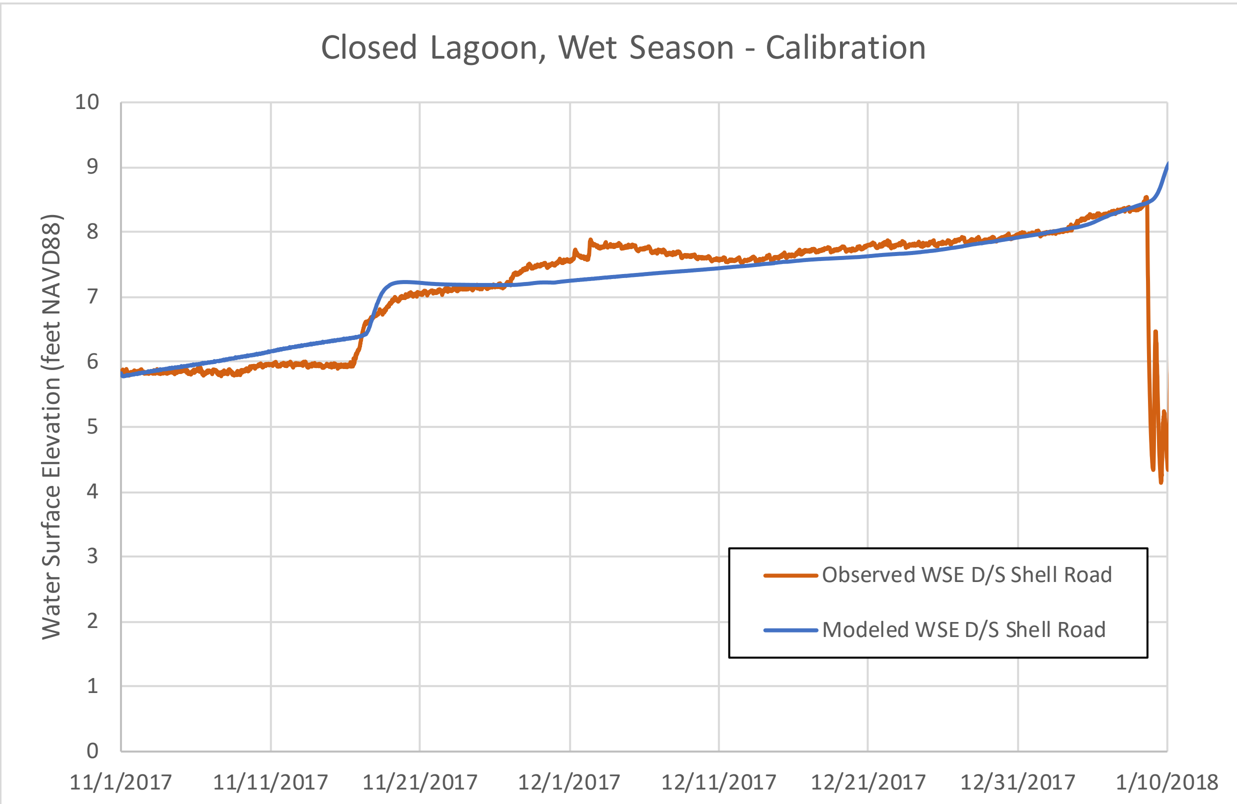


Figure 23: Observed vs. Modeled water surface elevation downstream of Shell Road for Closed Lagoon model for November 2017 to January 2018 closure event.

4.2. FWOP Model Setup

4.2.1. Future Conditions Time Horizons

In order to quantify benefits across the full project life cycle of 50 years, three different time horizons were modeled. Those time horizons were (1) Year 0 (i.e., immediately following project implementation), which was assumed to be the year 2025; (2) Year 25, or calendar year 2050; and (3) Year 50, or calendar year 2075.

The Year 0 future without project (FWOP) model setup is equivalent to the existing conditions model setup. The Year 25 and Year 50 FWOP model setups were altered in two different aspects: (1) the downstream boundary conditions were modified to reflect expected sea level change and (2) the model terrain was modified to reflect expected marsh accretion.

4.2.2. Modifications to Existing Conditions Boundary Conditions

Section 6.3 of this analysis presents the sea level change (SLC) analysis performed for this study. The findings of that analysis that are relevant for modifying the downstream boundary conditions in the hydraulic model are the estimates of the magnitude of SLC in 2050 (Project Year 25) and in 2075 (Project Year 50). There are two components to be considered in the total magnitude of SLC: relative sea level change and interannual variability (i.e., the effects of ENSO and PDO climate patterns).

With respect to relative sea level change (RSLC), it was determined that the USACE Intermediate SLC curve was the most appropriate for the study area. Applying that curve to the Monterey Bay tide station resulted in RSLR estimates of +0.34 feet from Year 0 to Year 25, and +0.79 feet from Year 0 to Year 50. With respect to the contribution of interannual variability to SLC, the frequency and intensity of ENSO effects are expected to increase into the future. A review of historic effects of ENSO on total water levels at the Monterey tide gage led to an estimate of +0.5 feet of SLC over Year 0 for both Year 25 and Year 50.

To incorporate these SLC estimates into the FWOP hydraulic model, the stage hydrographs used as downstream boundary conditions for each of the hydrologic regimes were shifted by +0.84 for the Year 25 model runs and +1.29 for the Year 50 model runs.

4.2.3. Modifications to Existing Conditions Terrain

Section 5.4 of this analysis describes the assumptions made concerning marsh accretion in the Watsonville Slough and Pajaro Lagoon in response to rising sea levels into the future. According to the assessment described in Section 5.4, the magnitude of marsh accretion in the slough and lagoon system is assumed to be 50% of the magnitude of sea level change. This translates to +0.17 feet in Year 25 and +0.395 feet in Year 50. These numbers, however, define the *maximum* amount of marsh accretion that we assume in the system. At higher elevations in the lagoon, less accretion is expected, because these areas will be submerged less often, and therefore have less opportunity to receive new sediment from the water column.

To account for this gradient of accretion, a linear relationship between accretion magnitude and ground surface elevation was assumed. For elevations less than 2 feet NAVD88, the maximum accretion magnitude of 50% of RSLR was applied. For elevations greater than 10 feet NAVD88, marsh accretion was set equal to zero. For elevations between 2 and 10 feet, marsh accretion was applied to the terrain according to a linear interpolation. This linear marsh accretion function was applied to the Year 0 RAS terrains using a Raster Calculator functions in ArcGIS to obtain the respective Year 25 and Year 50 FWOP terrains.

Figure 24 shows the ground elevations in the HEC-RAS model that represent marsh accretion. This figure shows one section taken just upstream of Beach Road. Marsh accretion, or ground elevation increases, was applied to the HEC-RAS terrain in Watsonville Slough beginning upstream of Shell Road and ending at Pajaro River. Marsh accretion was applied to all future conditions model scenarios.

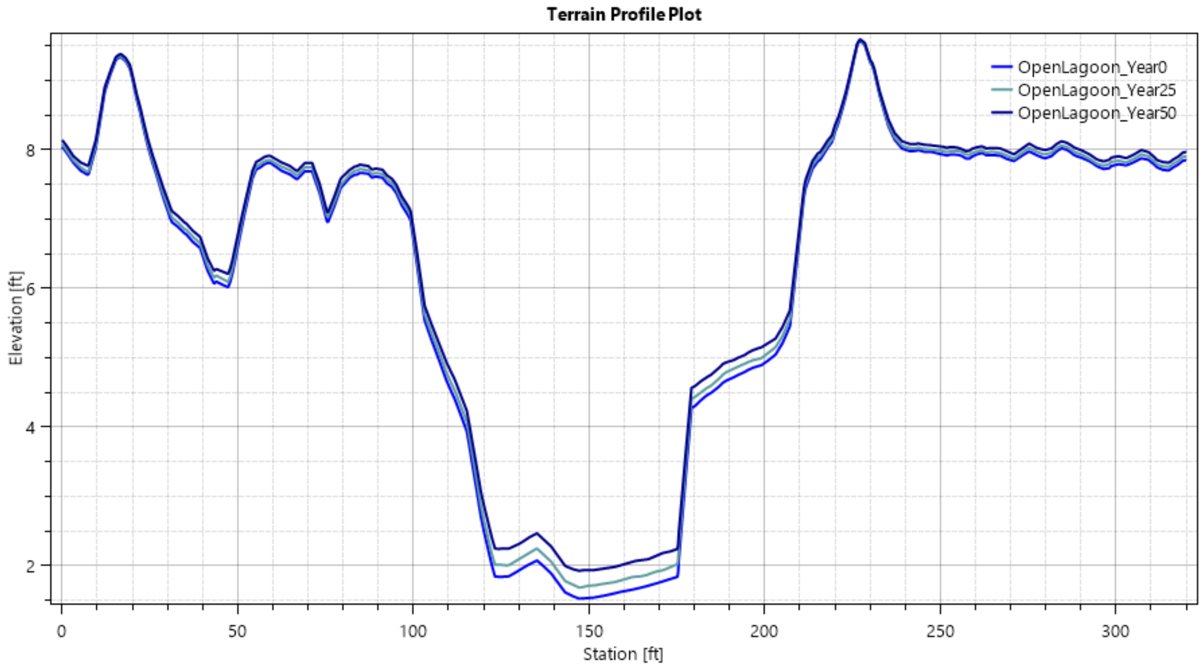


Figure 24: Cross section of HEC-RAS terrains for Project Year 0, Year 25, and Year 50 immediately upstream of the Beach Road crossing, demonstrating how marsh accretion was applied in the model.

4.3. With-Project Model Setup

4.3.1. Crossing Improvements Scenario

To represent the Crossing Improvements project scenario in the HEC-RAS model, modifications were made to both the model geometry and the model terrain. Changes to the model geometry consisted of replacing the six pipe culverts with a single wide-span culvert at the SA/2D connection named "Beach Road" and the addition of a flap gate allowing no negative flow at the SA/2D connection titled "Ag. Drainage Ditch Culvert".

Changes to the EWOP and FWOP terrains included the addition of an ecotone berm in the eastern corner of the State parcel and the raising of Shell Road to elevation 9.2 feet NAVD88. These modifications were made to the EWOP and FWOP terrains using the Terrain Modification tool in RAS Mapper.

4.3.2. Earthwork Scenario

To represent the Earthwork project scenario in the HEC-RAS model, modifications were made only to the terrain. These terrain modifications consisted of "burning in" the three dendritic tidal channels and the nine berm notches throughout the project area. The Terrain Modification tool in RAS Mapper was used for these edits. For the future time horizon terrains, the Earthwork channels and berm breaches were burned into the Year 0 terrain first, and then that modified Year 0 terrain was exported from RAS Mapper into ArcGIS, where the marsh accretion geoprocessing described in Section 4.2.2 was applied. This order of operations meant that the proposed tidal channels and berm breach excavations in the future conditions terrains also received marsh accretion.

4.3.3. Crossing Improvements + Earthwork Scenario

The Crossing Improvements + Earthwork project scenario combined the terrain and geometry edits to the EWOP and FWOP model setups described in Sections 4.3.2 and 4.3.3.

4.4. Summary of Ecosystem Restoration Model Runs

A total of 48 PTI rasters were developed in order to characterize typical conditions across the full range of hydrologic conditions and the full project life cycle. 36 of those 48 rasters were developed via one-month-long simulations in HEC-RAS 2D, and the other 12 (i.e., Closed Lagoon, Dry Season) were developed in ArcGIS by assuming a static water level of 6 feet NAVD88 for the one-month duration. Table 3 lists the 48 different combinations of project alternative, hydrologic regime, and time horizon. Figure 25 presents a sample PTI raster for Simulation 1 (No Action; Year 0; Open Lagoon, Dry Season). The complete set of HEC-RAS generated PTI rasters are included as Attachment B. These component one-month duration PTI rasters are combined into an annual PTI raster, which then serves as the basis for ecosystem restoration benefit quantification, as described in Section 4.6.

Figure 26 and Figure 27 show cross sections of the maximum computed water surface elevation upstream and downstream of the Beach Road crossing for two of the 48 model runs.

Table 3: List of hydraulic model simulations used for quantification of ecosystem restoration benefits.

Simulation Number	Project Scenario	Time Horizon	Hydrologic Regime
1	No Action	Year 0	Open, Dry
2	No Action	Year 0	Open, Wet
3	No Action	Year 0	Closed, Dry
4	No Action	Year 0	Closed, Wet
5	No Action	Year 25	Open, Dry
6	No Action	Year 25	Open, Wet
7	No Action	Year 25	Closed, Dry
8	No Action	Year 25	Closed, Wet
9	No Action	Year 50	Open, Dry
10	No Action	Year 50	Open, Wet
11	No Action	Year 50	Closed, Dry
12	No Action	Year 50	Closed, Wet
13	Crossing Improvements	Year 0	Open, Dry
14	Crossing Improvements	Year 0	Open, Wet
15	Crossing Improvements	Year 0	Closed, Dry
16	Crossing Improvements	Year 0	Closed, Wet
17	Crossing Improvements	Year 25	Open, Dry
18	Crossing Improvements	Year 25	Open, Wet
19	Crossing Improvements	Year 25	Closed, Dry
20	Crossing Improvements	Year 25	Closed, Wet
21	Crossing Improvements	Year 50	Open, Dry
22	Crossing Improvements	Year 50	Open, Wet
23	Crossing Improvements	Year 50	Closed, Dry
24	Crossing Improvements	Year 50	Closed, Wet
25	Earthwork	Year 0	Open, Dry
26	Earthwork	Year 0	Open, Wet

27	Earthwork	Year 0	Closed, Dry
28	Earthwork	Year 0	Closed, Wet
29	Earthwork	Year 25	Open, Dry
30	Earthwork	Year 25	Open, Wet
31	Earthwork	Year 25	Closed, Dry
32	Earthwork	Year 25	Closed, Wet
33	Earthwork	Year 50	Open, Dry
34	Earthwork	Year 50	Open, Wet
35	Earthwork	Year 50	Closed, Dry
36	Earthwork	Year 50	Closed, Wet
37	Crossing Improvements + Earthwork	Year 0	Open, Dry
38	Crossing Improvements + Earthwork	Year 0	Open, Wet
39	Crossing Improvements + Earthwork	Year 0	Closed, Dry
40	Crossing Improvements + Earthwork	Year 0	Closed, Wet
41	Crossing Improvements + Earthwork	Year 25	Open, Dry
42	Crossing Improvements + Earthwork	Year 25	Open, Wet
43	Crossing Improvements + Earthwork	Year 25	Closed, Dry
44	Crossing Improvements + Earthwork	Year 25	Closed, Wet
45	Crossing Improvements + Earthwork	Year 50	Open, Dry
46	Crossing Improvements + Earthwork	Year 50	Open, Wet
47	Crossing Improvements + Earthwork	Year 50	Closed, Dry
48	Crossing Improvements + Earthwork	Year 50	Closed, Wet

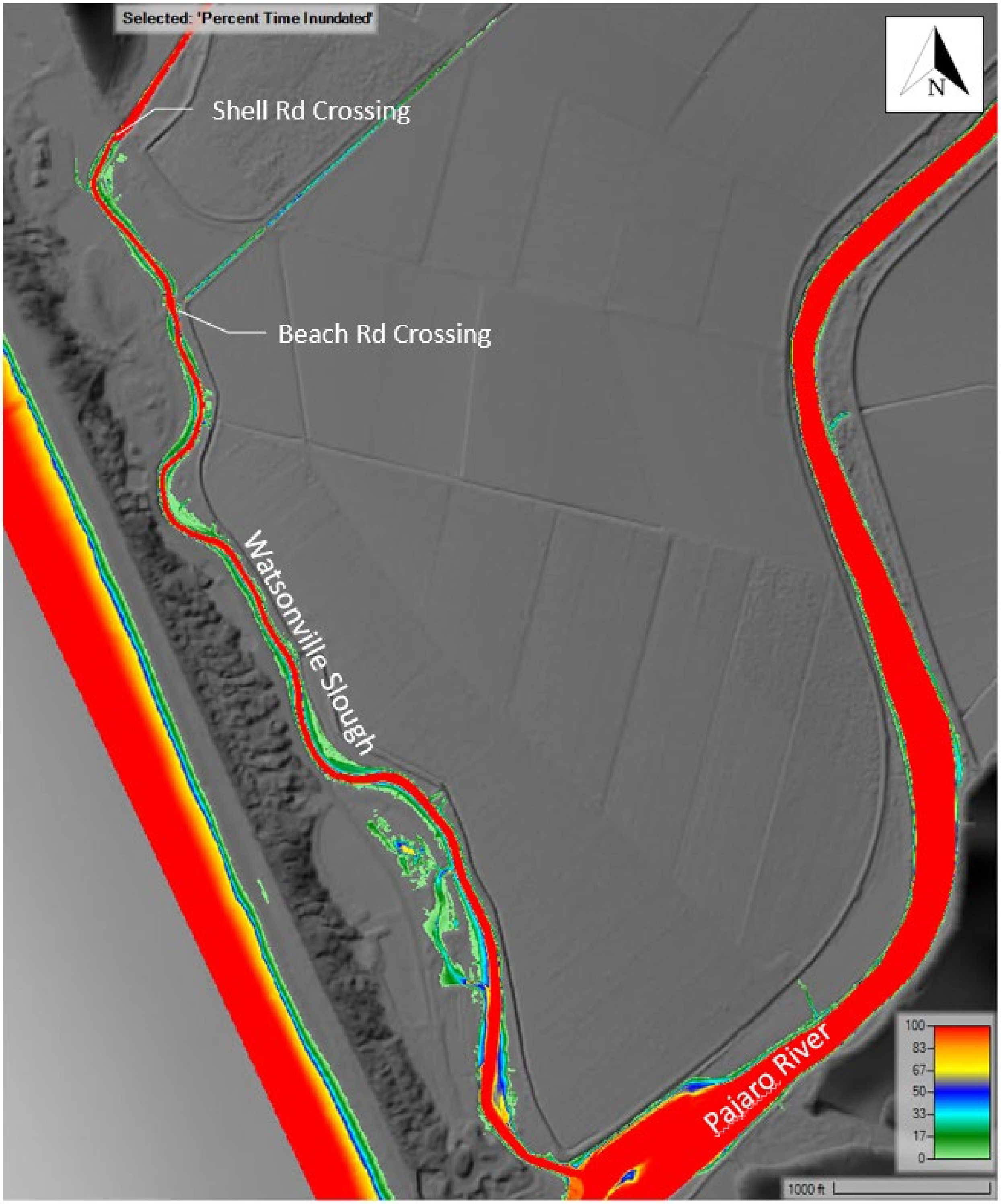


Figure 25: Percent Time Inundated HEC-RAS results for model scenario: No Action, Project Year 0, Open Lagoon, Dry Season.

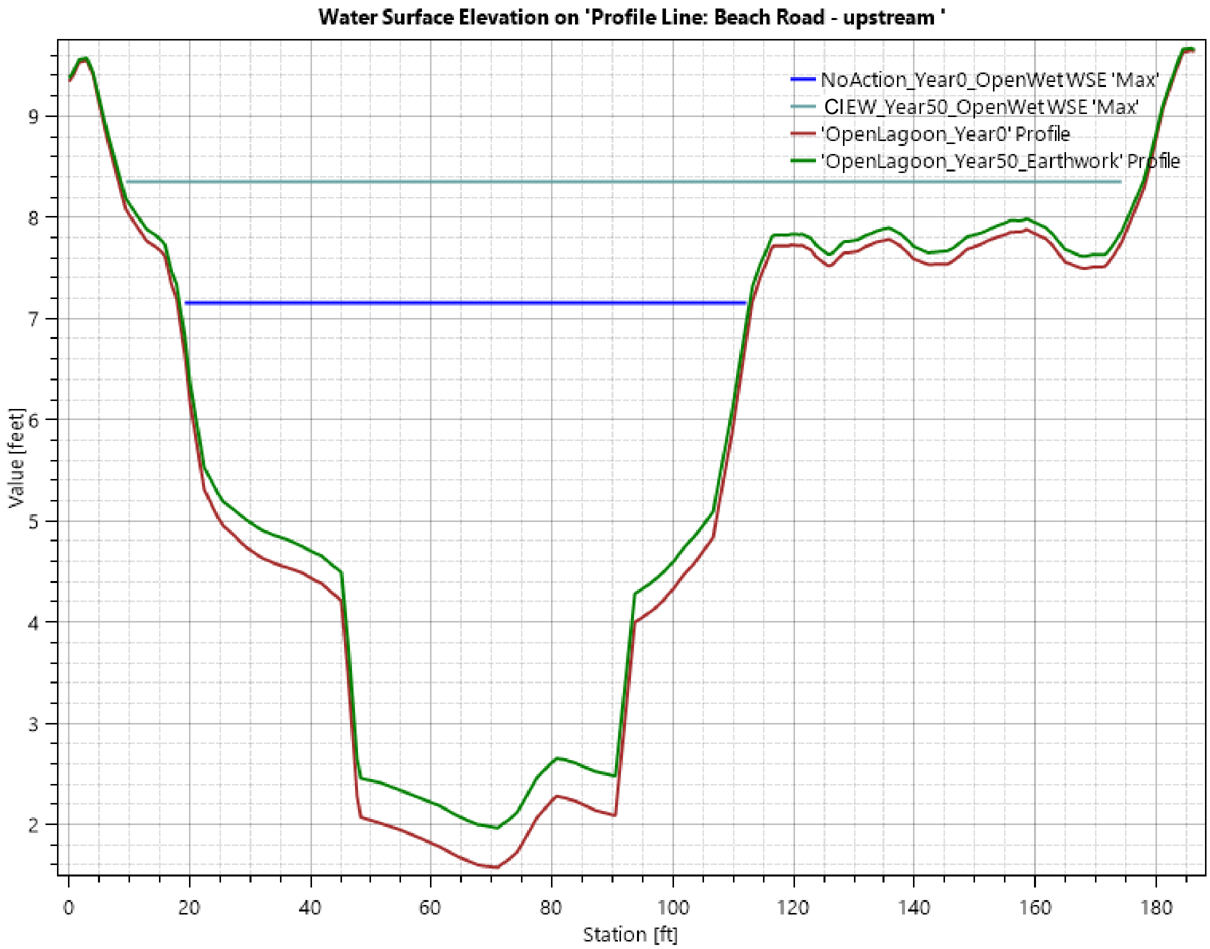


Figure 26: Cross section of terrain and maximum computed WSE immediately upstream of the Beach Road crossing for Simulation 2 (No Action, Year 0, Open Lagoon, Wet Season) and Simulation 46 (Crossing Improvements + Earthwork, Year 50, Open Lagoon, Wet Season).

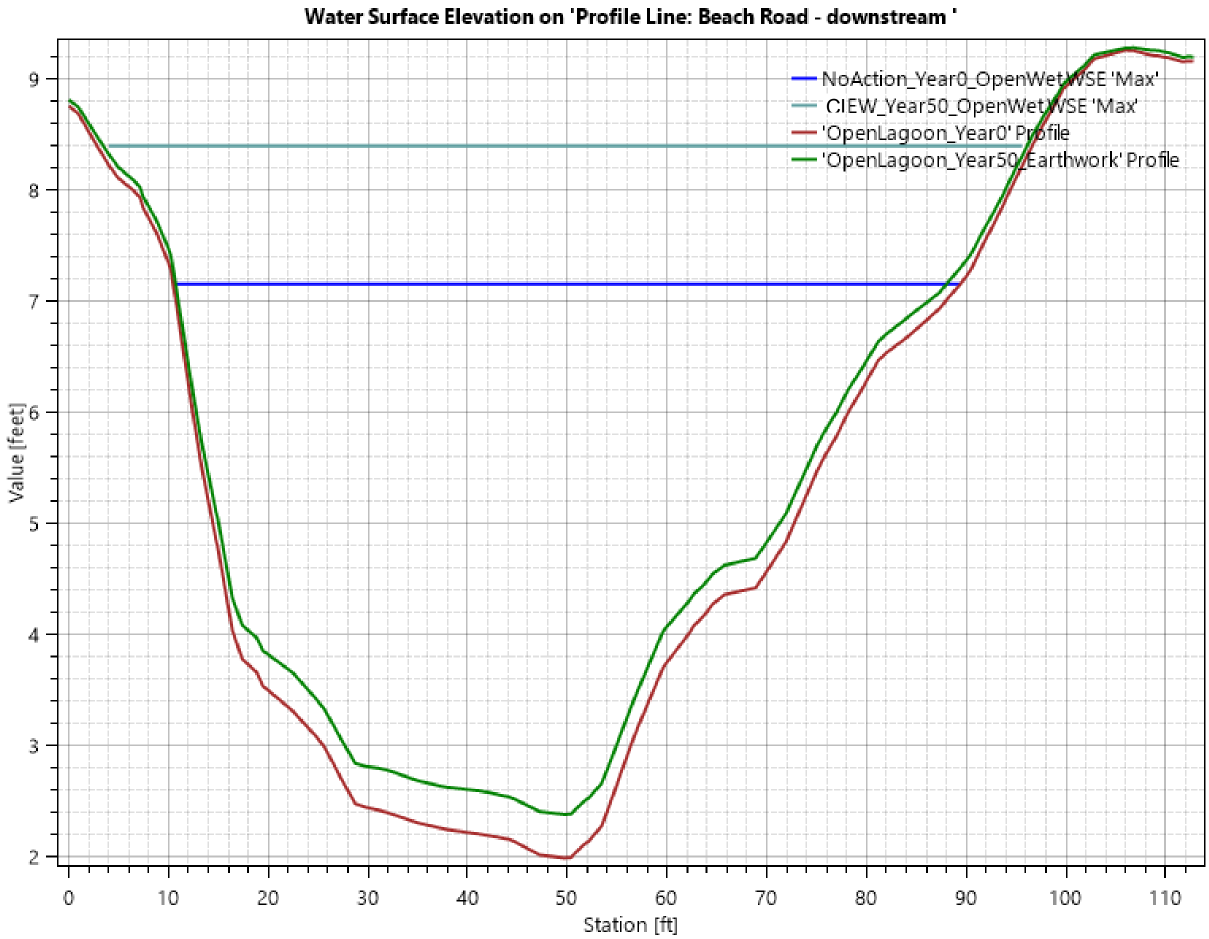


Figure 27: Cross section of terrain and maximum computed WSE immediately downstream of the Beach Road crossing for Simulation 2 (No Action; Year 0; Open Lagoon, Wet Season) and Simulation 46 (Crossing Improvements + Earthwork; Year 50; Open Lagoon, Wet Season).

4.5. Extreme Event Hydraulics

In order to evaluate potential for exacerbated flooding due to the proposed project scenarios, several extreme event flood flows were tested in the HEC-RAS model. For the 10% AEP flow published in the FEMA FIS in Watsonville Slough and the Pajaro River coincident to a steady state downstream boundary condition of MHHW (5.48 feet NAVD88), the entire project area is submerged by at least 3 feet of water. Given this degree of flooding in the existing conditions, the minor changes to infrastructure and/or topography proposed as part of the project scenarios will have no measurable effect on flood conditions during extreme flood events.

4.6. Post-Processing of Hydraulic Model Results

As described in Section 4.4, HEC-RAS was used to model the response of the slough system under four distinct hydrologic regimes and lagoon mouth states across different time horizons throughout the project design life. Percent time inundated was calculated for each scenario, indicating the fraction of time during the HEC-RAS simulation that a given cell is considered wet or dry. The metric used for evaluating ecosystem restoration benefits in the cost-benefit analysis portion of this feasibility study is an *annualized* measure of percent time inundated. Therefore, the results from the individual HEC-RAS simulations were combined into annualized results using a weighted average approach. This feasibility study employed a tool called Lagoon QCM to determine the appropriate weightings to apply to the individual HEC-RAS simulations.

4.6.1. Lagoon State Modeling with Lagoon QCM

There are no existing tools within USACE which address lagoon hydrology. The Sponsor's consultant has developed the Lagoon QCM tool to simulate lagoon water levels, inlet morphology processes (e.g. seepage, wave overtopping, beach berm build-up), and predict the lagoon mouth state (Behrens, 2015). The model has been applied and successfully calibrated to small, sandy coastal California lagoons similar to the study area. Thus, the PDT worked with the Sponsor's consultant to use Lagoon QCM to generate weightings for each regime under existing and future conditions: open-dry, open-wet, closed-dry, closed-wet. As Lagoon QCM is not a Corps-approved model, the PDT pursued and received approval for a single-use waiver for model use in Fall 2022.

The PDT and Sponsor's consultant coordinated closely to ensure that assumptions related to existing conditions and future with-project conditions were consistent (e.g., projected sea level change, the County's breach thresholds, beach seepage, etc.). The Sponsor's consultant evaluated the proportion of time during a representative year for the four states (open-dry, open-wet, closed-dry, closed-wet) under a range of sea level change amounts in +0.5 ft increments and for scenarios where the marsh sedimentation rates are assumed to be able to keep pace with sea level change.

Based on the Lagoon QCM output, the following table of weightings was generated for the scenarios and time horizons:

Table 4: Annual weightings for the four hydrologic regimes under different project alternative and time horizon combinations, as derived from Lagoon QCM results.

	Annual Weightings by Modeling Scenario					
	No Action/ Earthwork - Year0	**No Action/ Earthwork Year25**	**No Action/ Earthwork Year50**	**Crossing Improvements/ CIEW Year0**	**Crossing Improvements/ CIEW Year25**	**Crossing Improvements/ CIEW Year50**
Open-Dry	0.145	0.158	0.151	0.145	0.138	0.154
Open-Wet	0.534	0.543	0.551	0.514	0.512	0.514
Closed-Dry	0.193	0.179	0.187	0.192	0.199	0.183
Closed-Wet	0.128	0.120	0.111	0.149	0.150	0.148

4.6.2. Developing Annualized Inundation Rasters

Annualized PTI maps were developed by weighting the individual PTI values for each respective scenario across all scenarios and project years, using the weightings derived from Lagoon QCM. These calculations were performed using the ArcGIS Pro Modelbuilder tool. The final map results for each alternative, parcel, and simulation year are presented in Attachment C. An example of one of the annual PTI maps for the No Action project alternative is provided in Figure 28.

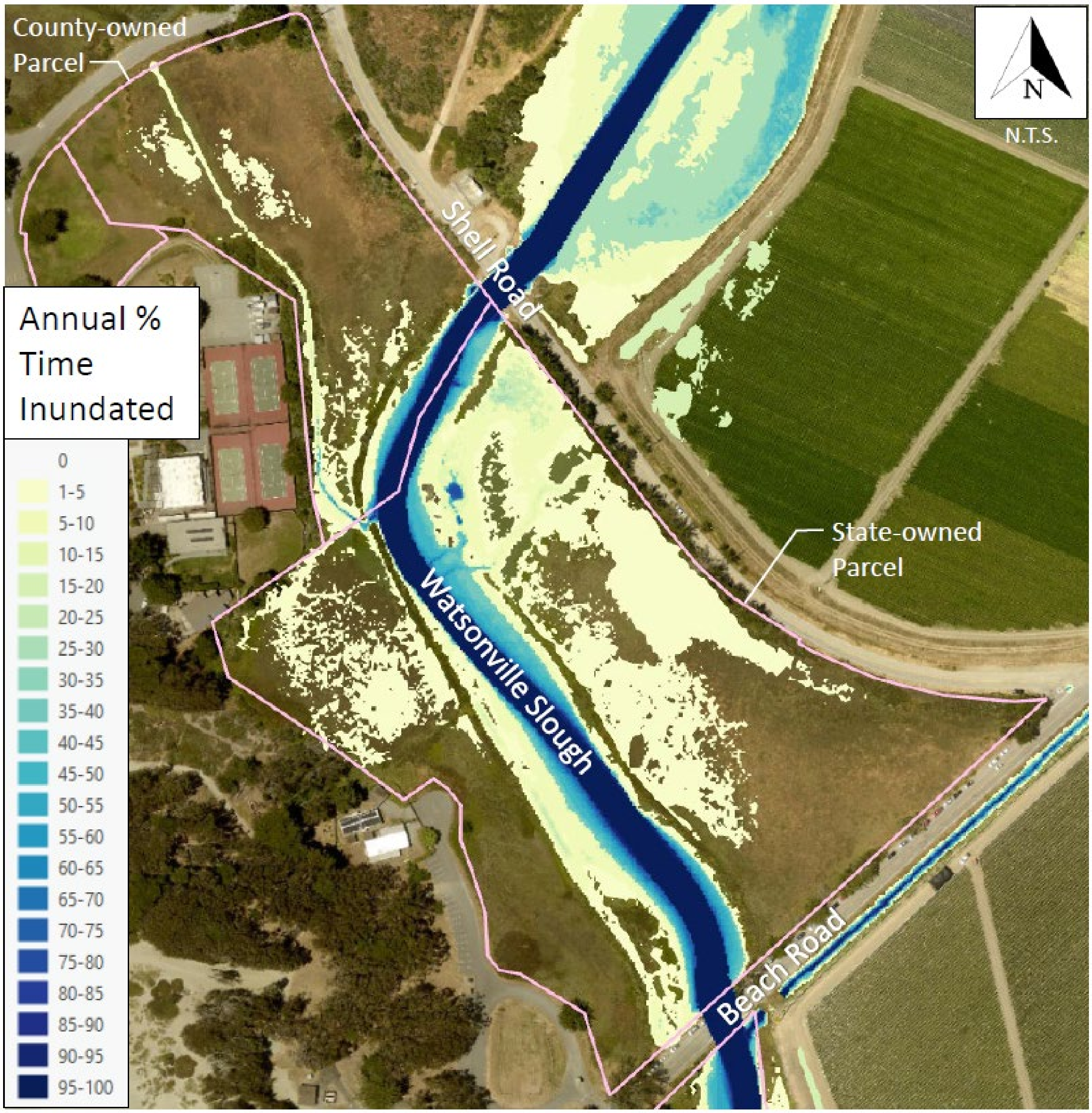


Figure 28: Annual percent time inundated for No Action, Project Year 0.

4.7. Hydraulic Model Results

As previously stated, the analysis results are presented in Attachments B and C. Attachment B presents the intermediate results that were based on the HEC-RAS model results. The intermediate results are maps of the percent time inundated for various project scenarios, time horizons, and hydrologic regimes (refer to Table 2 for details). Note that Attachment B does not include the 12 rasters for the Closed Lagoon, Dry Season scenarios, because these rasters were generated using assumed static water levels in ArcGIS, and not with a HEC-RAS simulation.

Final analysis results are presented in Attachment C. These results are based on the intermediate results from Attachment B. As previously mentioned, the intermediate analysis results were post-processed using the Lagoon QCM findings and GIS.

The final analysis results are maps showing annual percent time inundation. The maps are grouped by project subarea. The subareas, in order of upstream to downstream, are as follows: (1) State and County-owned Parcels, which is the area between the Shell Road crossing and Beach Road crossing; (2) Lower Mile, Upstream Parcel, which is about 0.25 miles long, immediately downstream of Beach Road; and (3) Lower Mile, Downstream Parcel, which is about 0.25 miles long and immediately upstream of the Watsonville Slough and Pajaro River confluence.

5. Climate Assessment

Chapter 5 of the HH&C Appendix includes the climate assessment, which was prepared in accordance with USACE guidance relevant to inland hydrology and sea level change climate assessments (Table 5).

Table 5. USACE guidance relevant to climate assessments

Guidance Document	Description	Date
ECB 2018-14	*Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies*	19 Aug 2024 (Rev 3)
ER 1100-2-8162	*Incorporating Sea Level Change in Civil Works Programs*	15 June 2019
EP 1100-2-1	*Procedures to Evaluate Sea Level Change: Impacts, Responses, and Adaptation*	30 June 2019

According to ECB 2018-14 (Rev 3), sea level change analysis consistent with ER 1100-2-8162 must be conducted prior to the TSP milestone if the elevation of the project area is ≤ 50 ft NAVD 88 and sea level change is likely to affect the project hydrology. For project areas at elevations ≤ 50 ft NAVD88, a determination should be made as to whether sea level change will affect the river stage by increasing (or decreasing) water surface elevation downstream of the project area.

Elevations in the Watsonville Slough watershed range from sea level to approximately 500 ft NAVD 88. Elevations in the Watsonville Slough project area range from approximately sea level to 20 ft NAVD 88. For the Watsonville Slough project site, the sea level controls the downstream boundary condition, and therefore sea level change analysis is included in this climate assessment.

5.1 Existing Conditions Climate

The Watsonville Slough watershed is situated in mid-latitudes between the 36th and 37th north parallels and has a Mediterranean climate. The most distinct feature of Mediterranean climates is a single rainy season each winter and drought each summer. A high pressure system, the Pacific High, blocks storms from reaching the region in summer months. During winter months, the system moves south and allows storm systems to move in. Mid-latitude storms that impact the region generally originate either from narrow bands of subtropical moisture (atmospheric rivers) or cyclones along the northern polar front.

The watershed consists entirely of low elevation coastal terraces and valley bottomlands, thereby limiting orographic effects on precipitation, and resulting in lower precipitation totals than other parts of Santa Cruz County (Balance Hydrologics, 2014). The mean annual precipitation for the 30-year period from WY1981 to WY2010 recorded at the Watsonville Waterworks gage (approximately 5 miles north of the project area) is 23.3 inches.

While the Watsonville Slough watershed is located entirely within Santa Cruz County, it's downstream limit is the Pajaro River, which forms the border between Santa Cruz and Monterey Counties. Cumulative annual precipitation amounts vary widely by water year in Santa Cruz and Monterey Counties (Figure 29). This high interannual variability can be impacted by the El Niño Southern Oscillation (ENSO). Some of the water years with the highest precipitation totals (e.g., 1982-1983, 1997-1998) have coincided with warm (El Niño) episodes of ENSO.

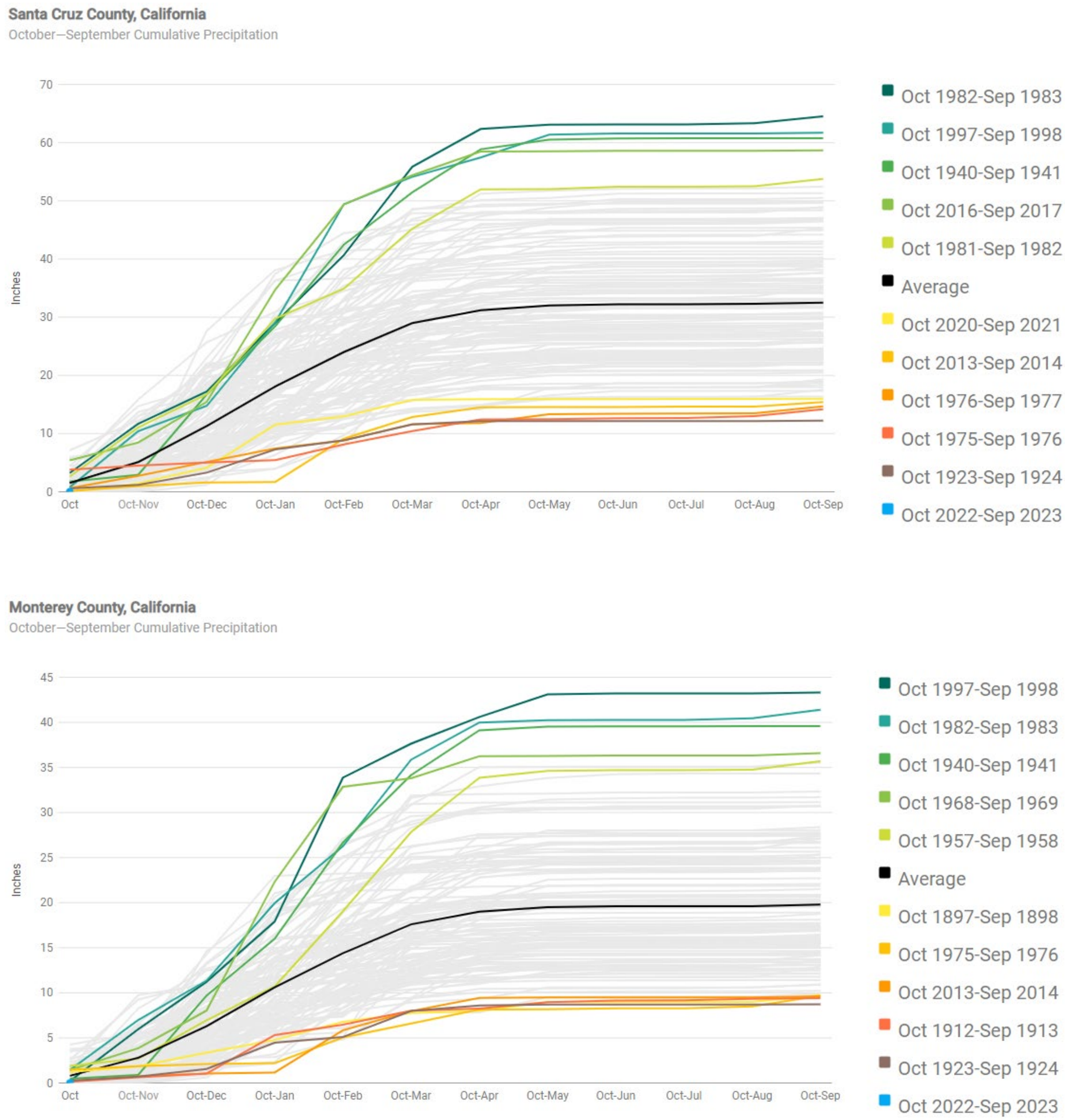


Figure 29: Cumulative precipitation totals by water year for the County of Santa Cruz (top) and Monterey (bottom) for the recent historical record (1895-present). The five highest (green), lowest (orange), and current year-to-date (blue) water year totals are highlighted. While Watsonville Slough is within Santa Cruz County, it is very near the border with Monterey County. Haywood plots downloaded December 6, 2022 from https://www.ncdc.noaa.gov/cag/county/haywood/CA-087/pcp/9 and https://www.ncdc.noaa.gov/cag/county/haywood/CA-053/pcp/9.

5.2 Inland Hydrology Trends

A literature review was conducted to investigate trends in temperature, precipitation, flooding, and drought in the project area. The studies that were consulted are: (1) the Fourth National Climate Assessment (NCA), which provides historic and projected climate trends for the United States as a whole and for the Southwest Region, and (2) the Central Coast Region Summary Report from California's Fourth Climate Change Assessment, which provides climate information for the Central Coast Region, broken down by county.

The USACE Climate Hydrology Assessment Tool (CHAT) (Nguyen et al 2020)[1] was used to investigate trends in simulated historical and projected future precipitation, temperature, and streamflow for HUC 18060002 (Central California Coastal - Pajaro). The Watsonville Slough project is located in HUC 18060002, which includes the Watsonville Slough and Pajaro River watersheds. CHAT results have been spatially aggregated to HUC-8 regions, and provide projected future results for Representative Concentration Pathway (RCP) scenario 4.5 (low emissions) and RCP scenario 8.5 (high emissions).

The findings from the literature review are presented alongside the CHAT results for key inland hydrology climate variables below.

5.2.1 Temperature

United States and Southwest Region

The annual average temperature of the contiguous United States has risen by approximately 1.2°F to 1.8°F since the start of the twentieth century (Vose et al 2017). The NCA's Southwest Region experienced an increase of 1.61°F in annual average, annual average minimum, and annual average maximum temperatures between the present-day measurement period (1986-2016) and the first half of the last century measurement period (1901-1960) (Vose et al 2017). Figure 30 shows the spatial variation of temperature increases across the Southwest Region. Higher air temperatures are associated with an increase in the intensity of extreme precipitation events (Easterling et al 2017).

[1] CHAT version 2.2 (February 2022)

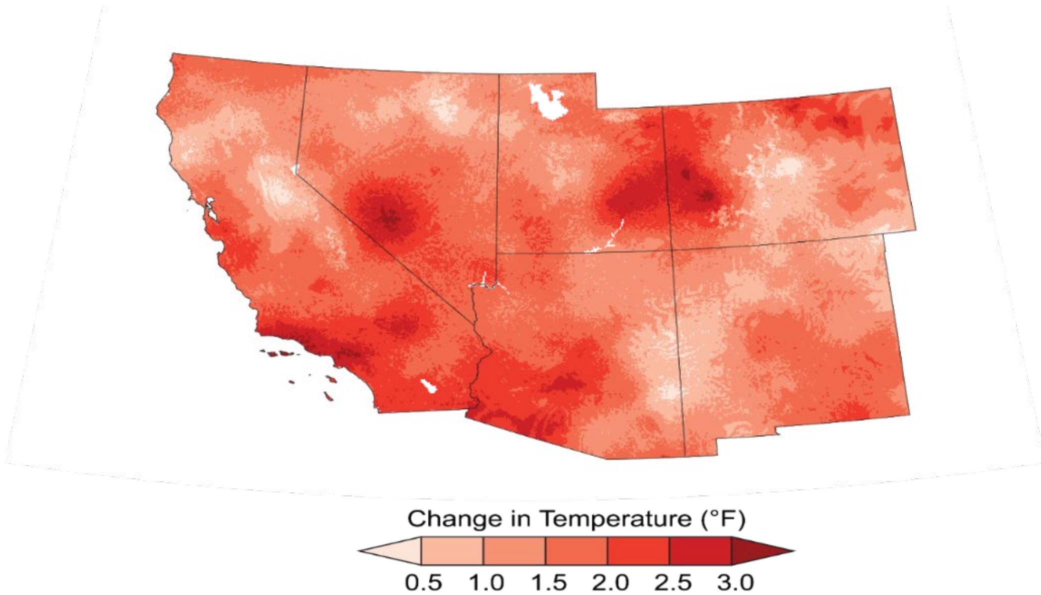


Figure 30: Difference between 1986–2016 average temperature and 1901–1960 average temperature for the Southwest Region (Gonzalez et al 2018).

Temperatures are expected to increase throughout the United States under both the low and high emissions scenarios (Figure 31). In general, northern latitudes and inland areas will experience greater increases in temperatures than coastal areas. Daily extreme temperatures (i.e., coldest and warmest daily temperatures) are also expected to increase in most areas by mid-century (Vose et al 2017).

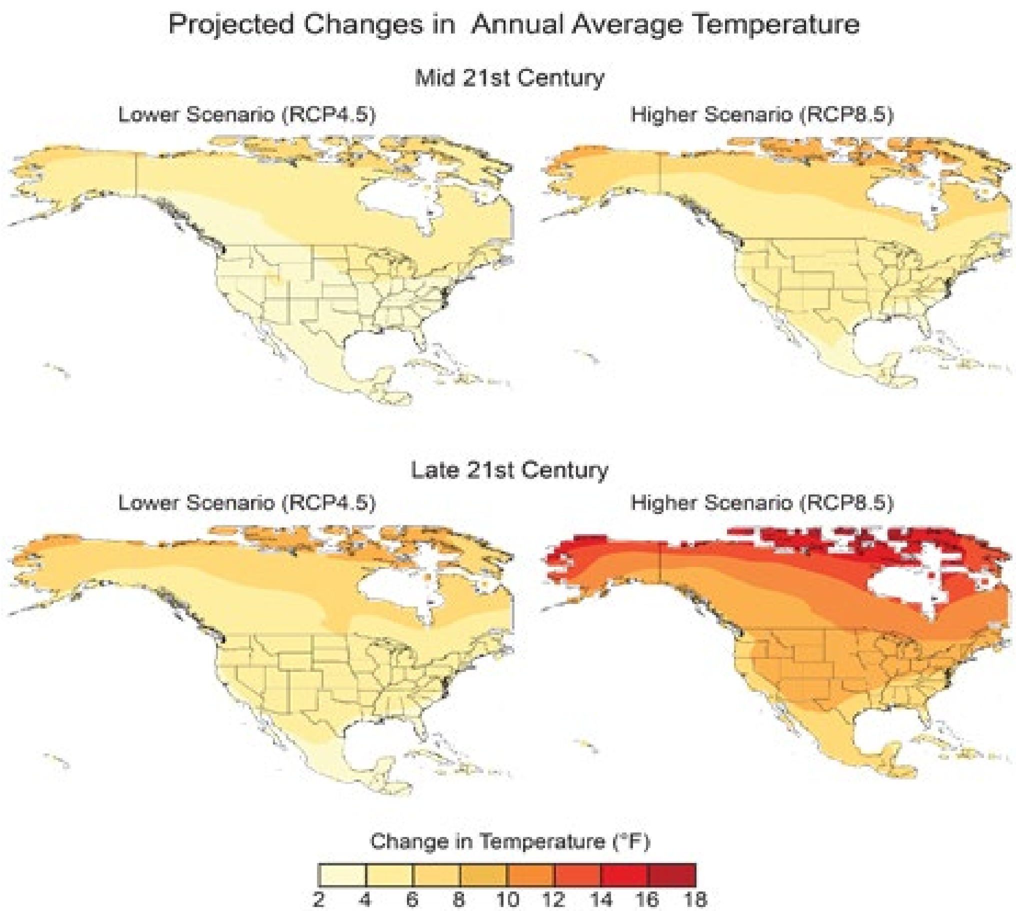


Figure 31: Projected changes in annual average temperatures (°F) for mid and late 21st century under low and high Representative Concentration Pathways (RCP) scenarios. Changes are the difference between the average for mid-century (2036–2065; top) or late-century (2070-2099, bottom) and the average for near-present (1976–2005) (Vose et al 2017).

California Central Coast Region

California's Fourth Climate Change Assessment (CCA) downscales results from several global climate models to project changes in temperature for the Central Coast Region, which consists of the counties of Santa Cruz, Monterey, San Benito, San Luis Obispo, and Santa Barbara. The CCA projects changes in annual average temperature, annual average maximum temperature, and annual average minimum temperature for multiple future time periods and for RCP4.5 and RCP8.5. The results of these projections for annual average maximum temperature are presented in Figure 32.

Future temperature projections are also reported by county in the CCA. The two counties of most interest for the Watsonville project area are Santa Cruz and Monterey. In Santa Cruz County, from the historical period of 1961-1990 to the mid 21st century (2040-2069), the annual average maximum temperature is projected to increase by 3.4 degrees F under RCP4.5 and by 4.3 degrees F under RCP8.5. In Monterey County, for the same projection timeline, the annual average maximum temperature is projected to increase by 3.7 degrees F under RCP4.5 and by 4.9 degrees F under RCP8.5 (Langridge 2018).

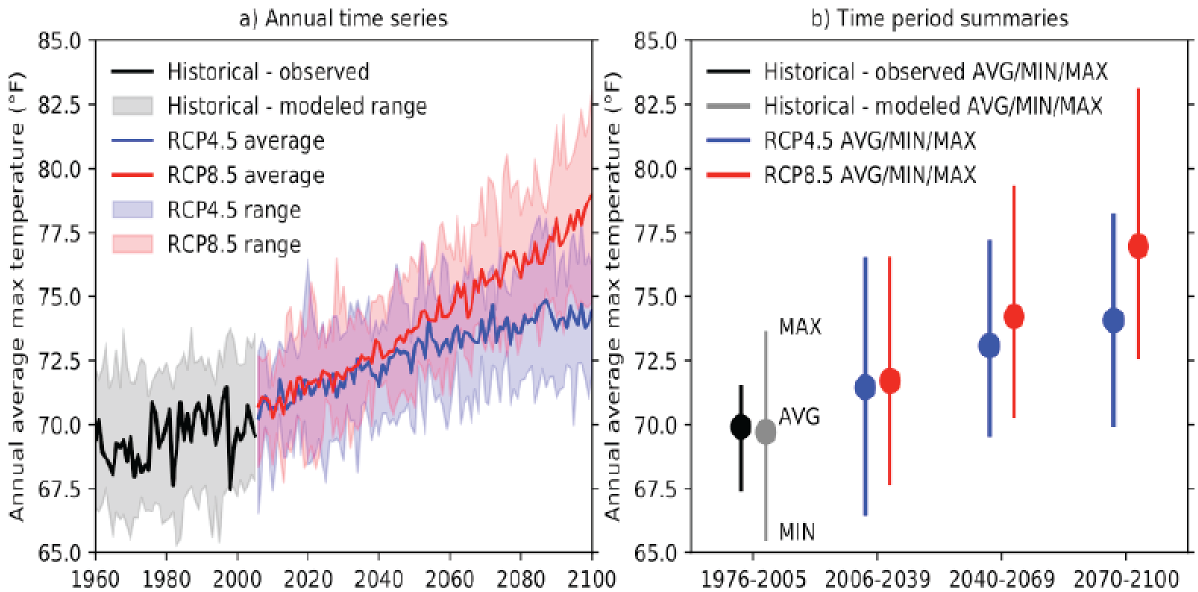


Figure 32: Annual average maximum temperature, historic and projected, for the Central Coast Region of California (Langridge 2018).

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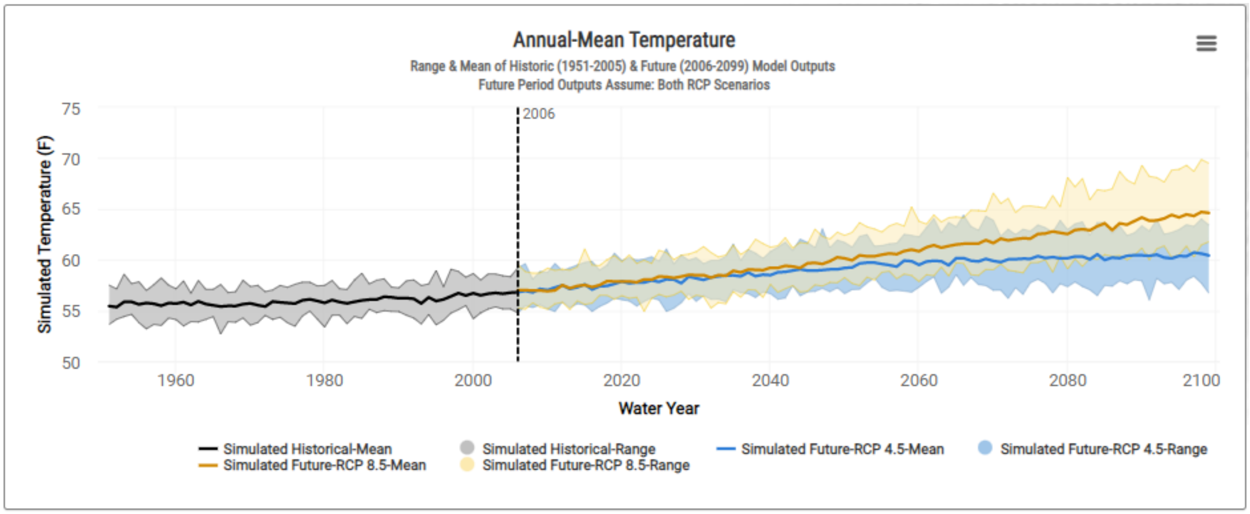
CHAT results for daily average temperature (annual average) and daily maximum temperature (annual maximum) are shown in Figure 33 - Figure 34.

For daily average temperature, the linear trend equates to an increase of 3.8 degrees F over the 93 year projection period (low emissions scenario) and an increase of 7.9 degrees F over the 93 year projection period (high emissions scenario).

For daily maximum temperature, the linear trend equates to an increase of 4.3 degrees F over the 93 year projection period (low emissions scenario) and an increase of 8.3 degrees F over the 93 year projection period (high emissions scenario).



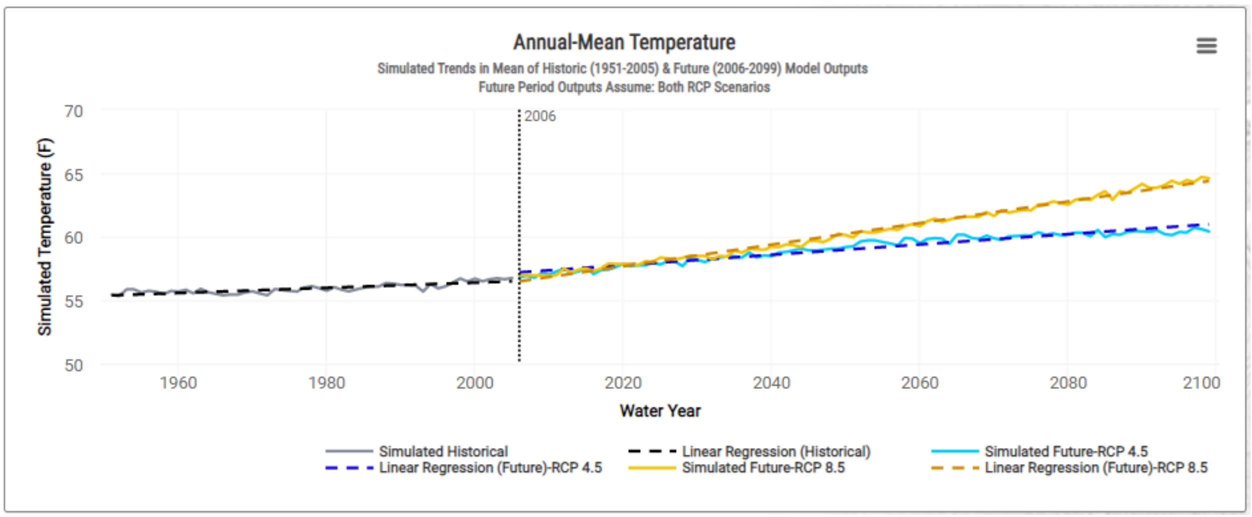
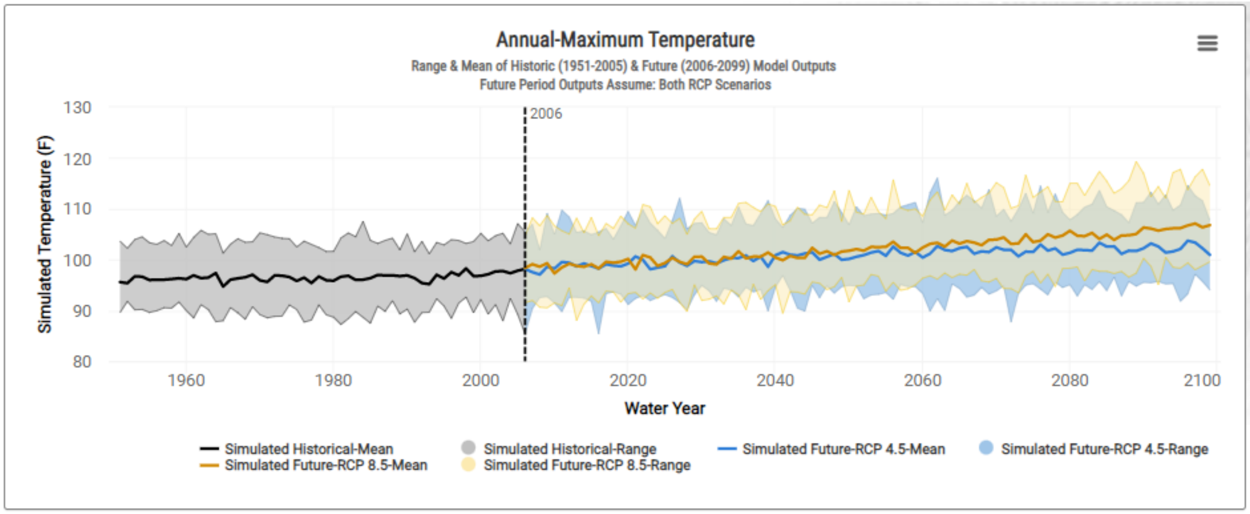


Figure 33: Annual Average of Daily Average Temperature. Range and mean (top) and trends (bottom) for RCP4.5 and RCP8.5. Statistically significant trends were detected for simulated historical and projected future temperatures under both RCP scenarios.



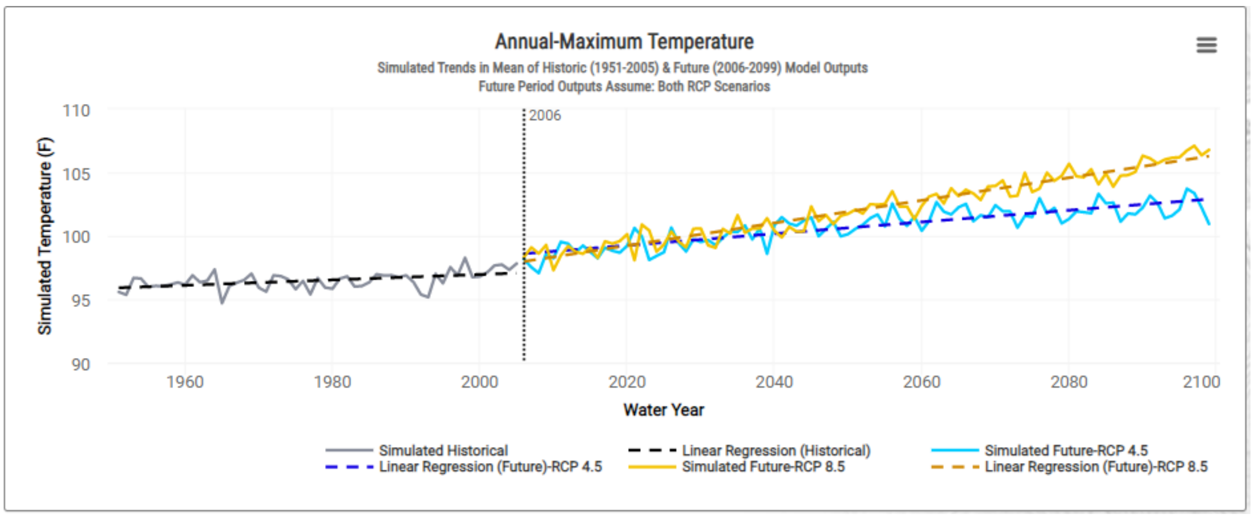


Figure 34: Annual Maximum of Daily Maximum Temperature. Range and mean (top) and trends (bottom) for RCP4.5 and RCP8.5. Statistically significant trends were detected for simulated historical and projected future temperatures under both RCP scenarios.

5.2.2 Precipitation

United States and Southwest Region

Annual and seasonal precipitation have changed throughout the United States from the first half of the last century (1901-1960) to the present (1986-2015). Average annual precipitation for the entire country has increased by approximately 4%, but the observed changes in magnitude vary by season and by region (Easterling et al 2017; Figure 35).

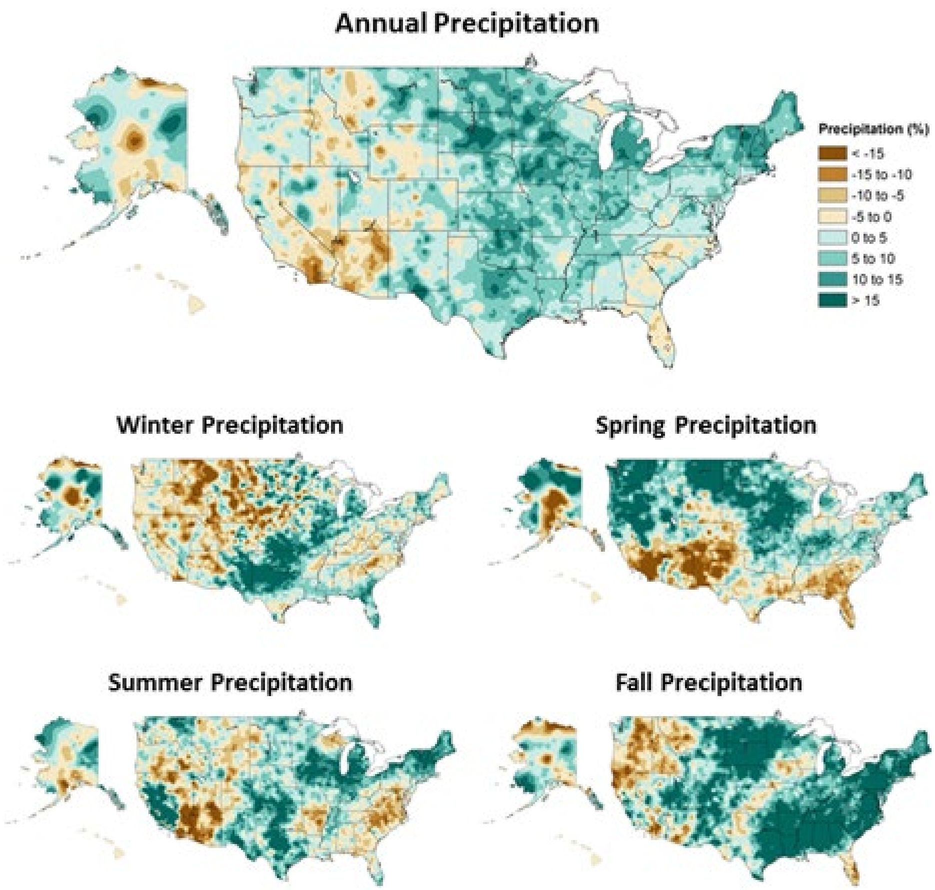


Figure 35: Annual and seasonal changes in average precipitation in the United States. Changes are the average for present-day (1986–2015) minus the average for the first half of the last century (1901–1960 for the contiguous United States, 1925–1960 for Alaska and Hawai'i) divided by the average for the first half of the century. (Easterling et al 2017).

Extreme precipitation indices have also shown increases (Easterling et al 2017). *Figure 36* shows a general increasing trend for most of the country in daily 20-year return level precipitation by season over the period 1948-2015.

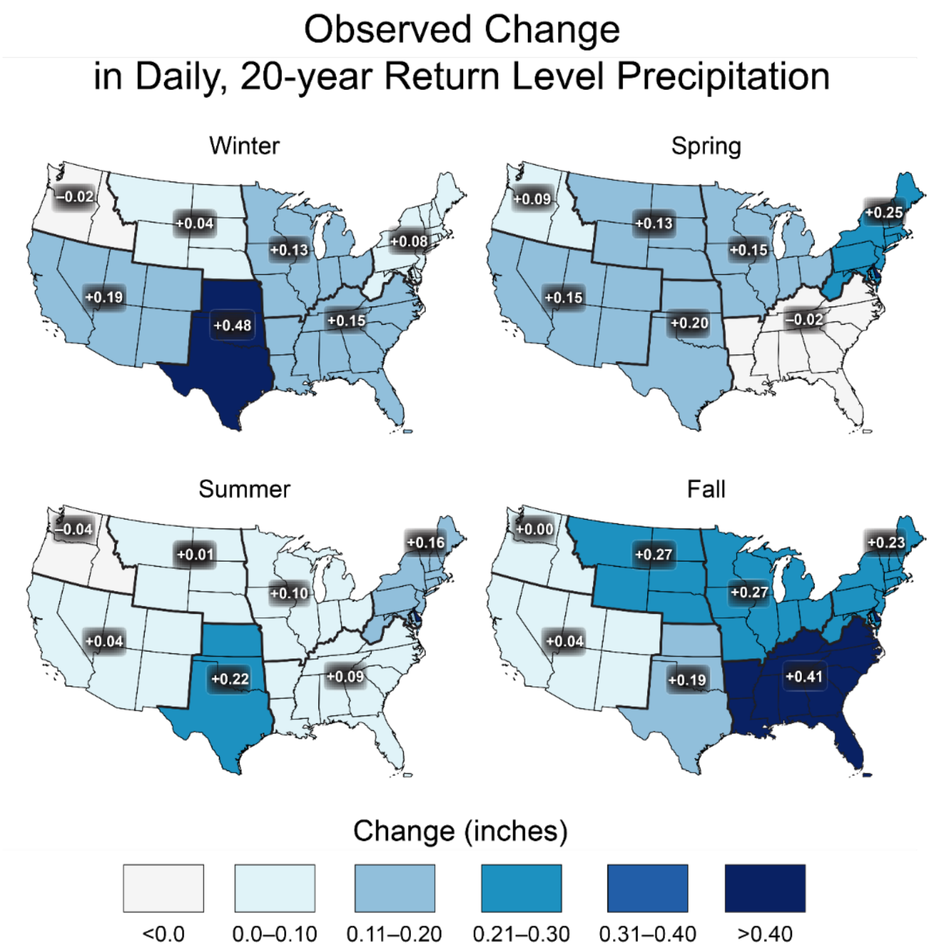


Figure 36: Observed change in the 20-year return value of the seasonal daily precipitation totals over the period 1948 to 2015 (Easterling et al 2017).

Changes in seasonal mean precipitation is projected to vary by region across the country (Easterling 2017). Extreme precipitation is expected to increase throughout all NCA regions (Easterling 2017; *Figure 37*). The increases in extreme precipitation tend to increase with return level, such that increases for the 100-year return level are about 30% by the end of the century under a higher (RCP8.5) scenario (Easterling 2017).

Along the West Coast, atmospheric rivers are responsible for a significant portion of annual precipitation and have historically been connected to flood events (Kossin et al 2017). Climate projections indicate a greater frequency of atmospheric rivers in the future (Wehner et al 2017) and an increase in atmospheric river water vapor transport by the end of the 21st century (Easterling 2017).

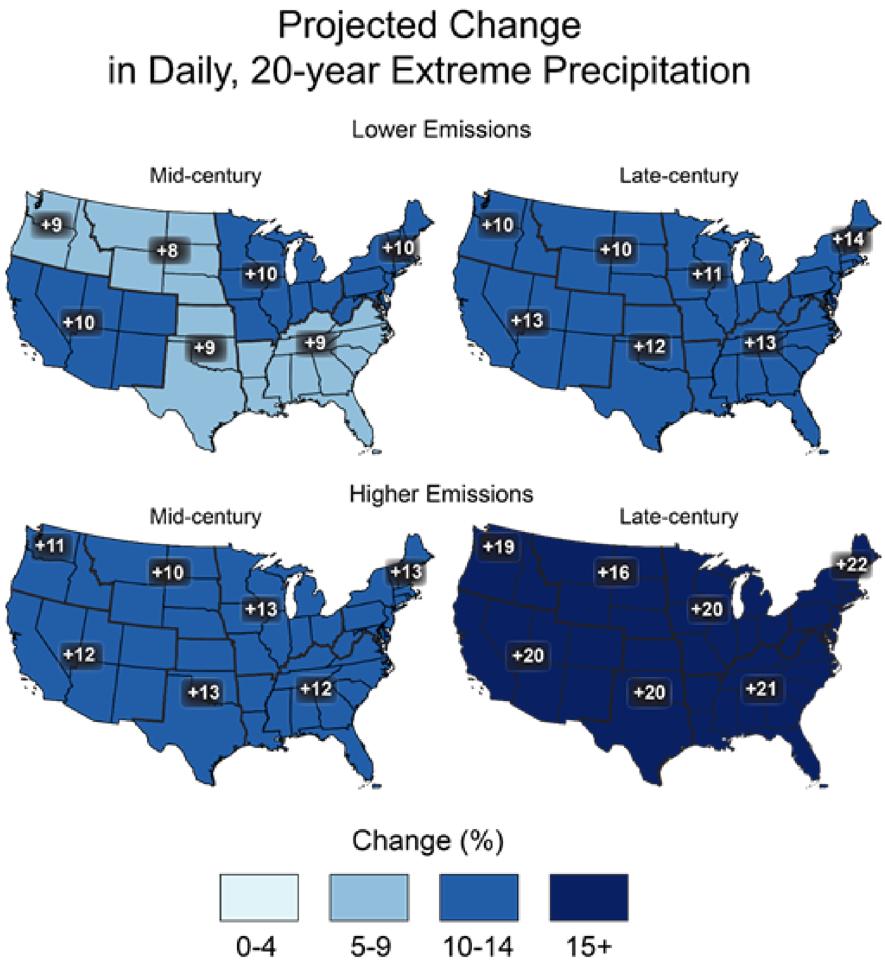


Figure 37: Projected change in the 20-year return period amount for daily precipitation for mid- (left) and late- (right) 21st century. Results are shown for a lower scenario (top; RCP4.5) and for a higher scenario (bottom; RCP8.5) (Easterling et al 2017).

California Central Coast Region

The CCA reports projected changes in precipitation for Santa Cruz and Monterey counties for multiple future time periods and for both RCP4.5 and RCP8.5. In Santa Cruz County, from the historical period of 1961-1990 to the mid 21st century (2040-2069), the annual average precipitation is projected to increase by 3.4 inches (9%) under RCP4.5 and by 4.3 inches (12%) under RCP8.5. In Monterey County, for the same projection timeline, the annual average precipitation is projected to increase by 1.8 inches (9%) under RCP4.5 and by 2.1 inches (11%) under RCP8.5 (Langridge 2018). *Figure 38* presents the precipitation projections for the whole Central Coast Region.

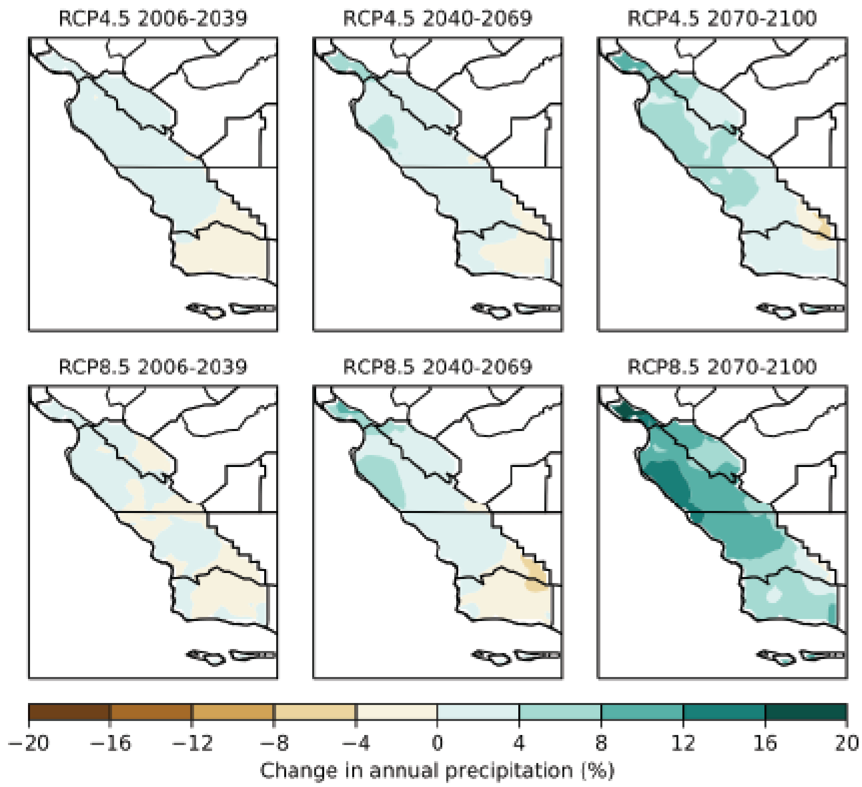


Figure 38: Projected change in annual precipitation from historic baseline of 1961-1990 in California Central Coast Region (Langridge 2018).

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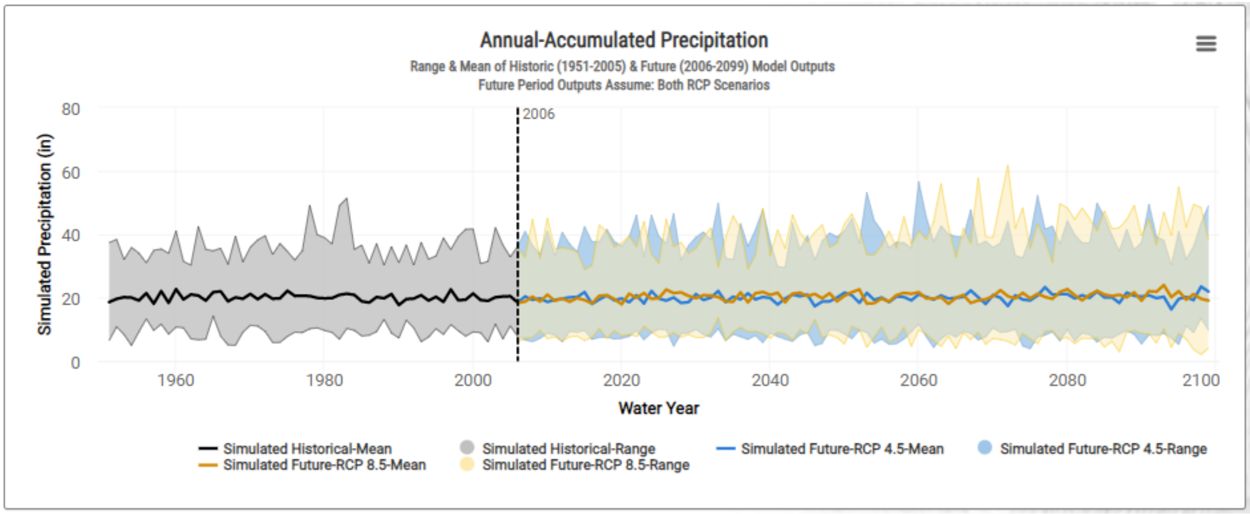
CHAT results for daily accumulated precipitation (annual sum) and 3-day sum of accumulated precipitation (annual maximum) are shown in *Figure 39* -*Figure 40*.

For daily accumulated precipitation, the linear trend equates to an increase of 0.9 inches (5%) over the 93-year projection period (low emissions scenario) and an increase of 1.1 inches (6%) over the 93-year projection period (high emissions scenario).

For the 3-day sum of accumulated precipitation, the linear trend equates to an increase of 0.3 inches (11%) over the 93-year projection period (low emissions scenario) and an increase of 0.5 inches (17%) over the 93-year projection period (high emissions scenario).



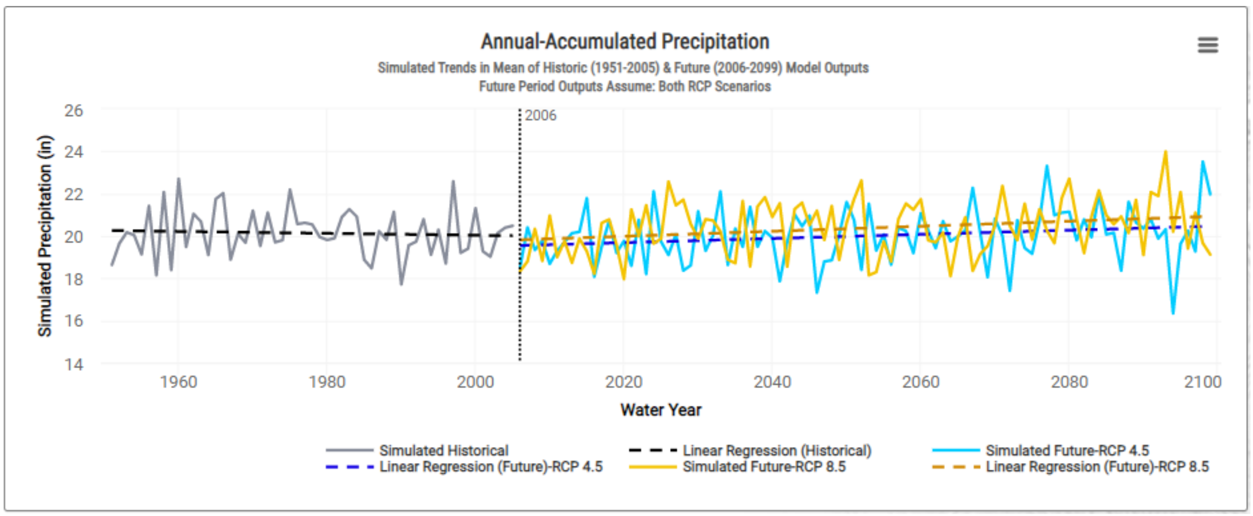
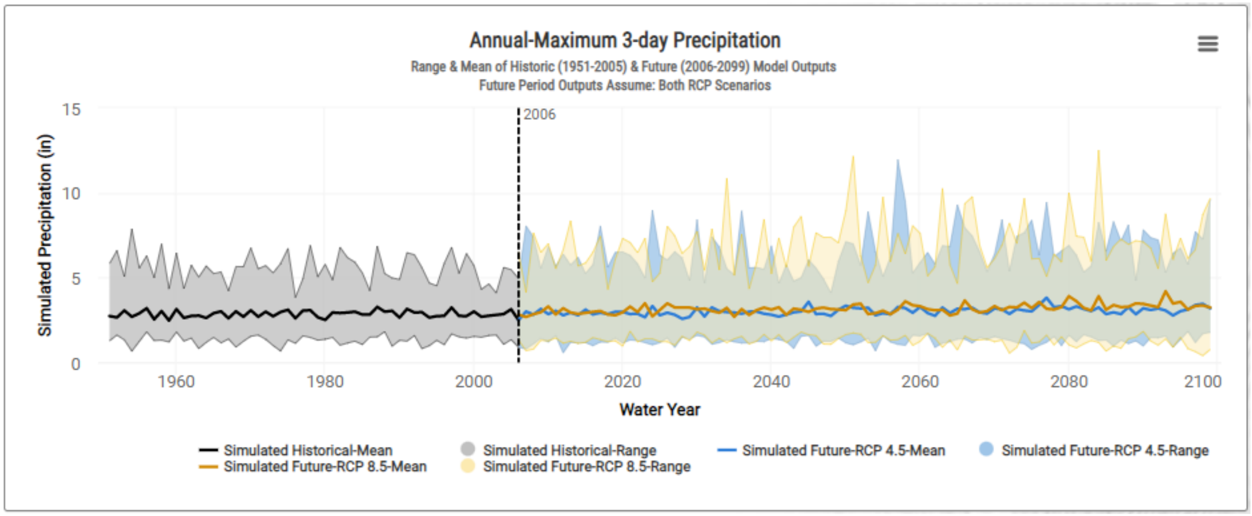


Figure 39. Annual Sum of Daily Accumulated Precipitation. Range and mean (top) and trends (bottom) for RCP4.5 and RCP8.5. Statistically significant trends were detected for projected future precipitation under both scenarios. Statistically significant trend was not detected for simulated historical precipitation.



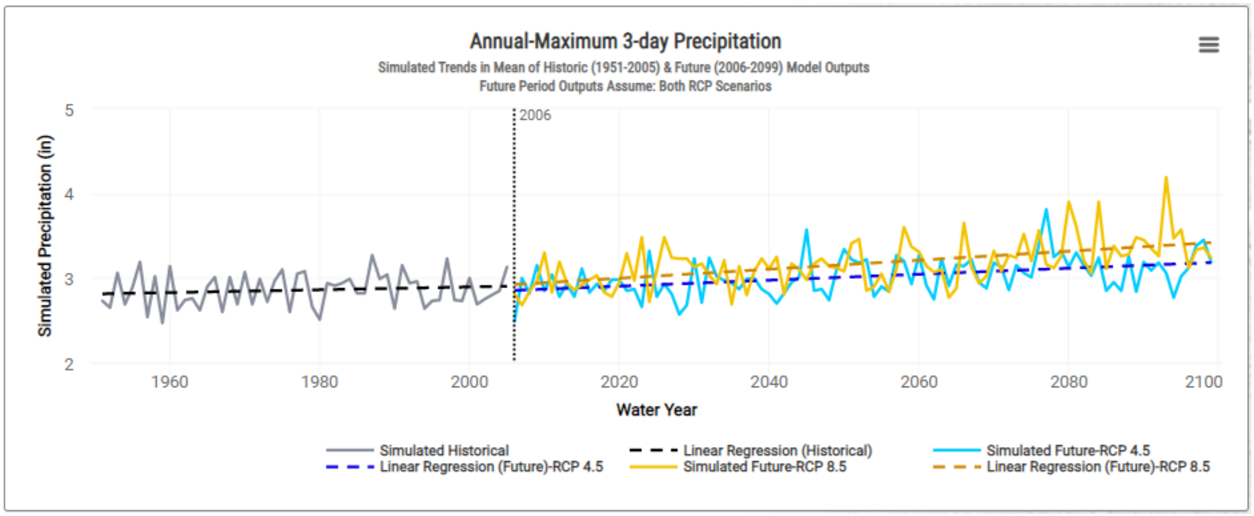


Figure 40. Annual Maximum of 3-day Sum of Daily Accumulated Precipitation. Range and mean (top) and trends (bottom) for RCP4.5 and RCP8.5. Statistically significant trends were detected for projected future precipitation under both scenarios. Statistically significant trend was not detected for simulated historical precipitation.

Precipitation Gage in City of Watsonville

There is a long-term precipitation record from a gage maintained by the City of Watsonville (Gage ID: WTW) located approximately 5 miles northeast of the project area. There are annual precipitation data available from 1880 to 2021 at this gage. The annual mean precipitation from this record is 21.9 inches with a standard deviation of 7.84 inches. Figure 41 shows the monthly distribution of precipitation across the historic record. There is very little precipitation during the months of June through September, which agrees with the temporal distribution of precipitation presented in the Hayward plots in Figure 29.

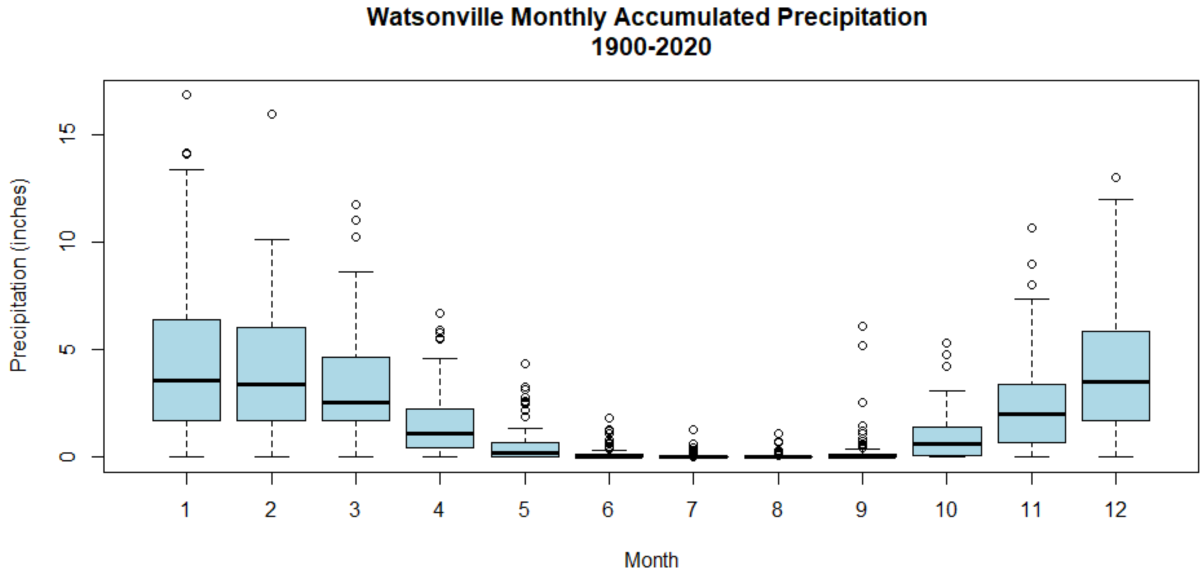


Figure 41: Box and whisker plot of monthly precipitation at Watsonville Waterworks (WTW) rain gage.

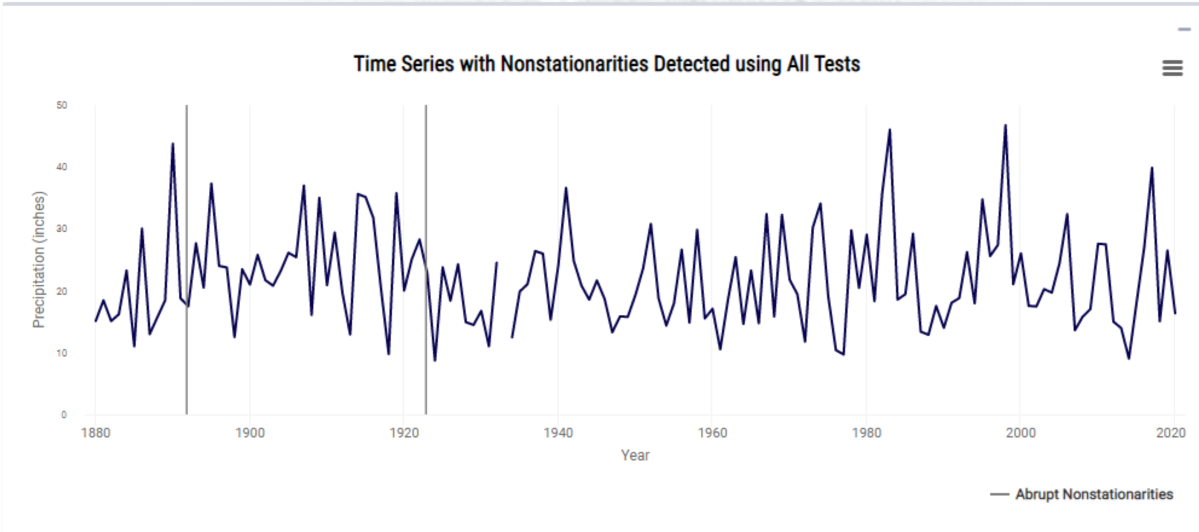
Nonstationarity Detection Tool

Given the length of historic record, the PDT decided to test the precipitation data for nonstationarity using the USACE Nonstationarity Detection (NSD) tool (Friedman et al. 2018)[2]. This tool is a web-based tool, developed in conjunction with USACE Engineering Technical Letter (ETL) 1100-2-3, to detect nonstationarities in maximum annual flow time series. While the precipitation data set in question is not a maximum annual flow time series, the statistical methods employed by the tool are still applicable.

As shown in *Figure 42*, the NSD tool detected no strong nonstationarities in this record. The Kolmogorov-Smirnov test identified two abrupt nonstationarities (one in 1892 and one in 1923), but without consensus or robustness from other tests, there is insufficient evidence to reject the null hypothesis of statistical stationarity at this site. Additionally, no monotonic trends are detected in the annual precipitation dataset between 1880 and 2021 using the t-Test, Mann-Kendall Test, and Spearman Rank Order Test applied using a 0.05 level of significance.

[2] NSD tool version as of 22 July 2022

AnnualPrecip_WTW.csv



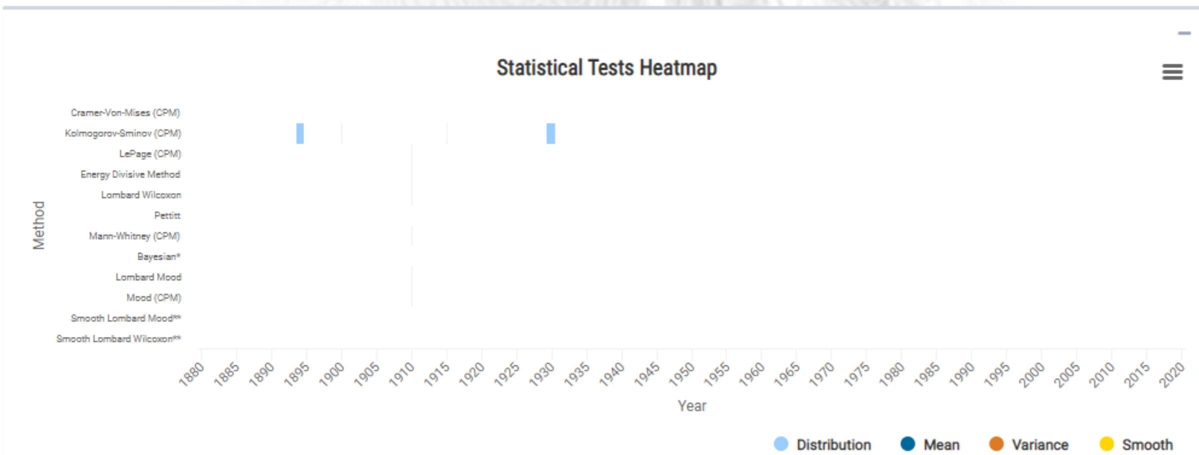


Figure 42: Nonstationarity detection results for annual precipitation at Watsonville Waterworks (WTW). Two nonstationarities were detected in 1890 and 1923 (in distribution). No consensus or robustness were detected for these nonstationarities.

5.2.3 Streamflow

Climate Hydrology Assessment Tool

The CHAT can be used to assess projected, future changes to streamflow in the watershed. Projections are at the spatial scale of a HUC-8 watershed, with flows generated using the U.S. Bureau of Reclamation (USBR) Variable Infiltration Capacity (VIC) model from temperature and precipitation data downscaled from GCMs. The USBR VIC model is setup to simulate unregulated basin conditions. *Figure 43* shows the range of output presented in the CHAT using 64 combinations of GCMs and representative concentration pathways (RCPs) applied to generate non-stationary hydrology using the USBR VIC model. The range of data is indicative of the uncertainty associated with projected, non-stationary hydrology. Simulated streamflow values represent only the single largest stream in the HUC-8 basin.

For HUC 18060002, there is no statistically significant trend in the annual maximum of average monthly streamflow for the hindcast/historic (pre-2006) period. There is a statistically significant positive trend in the projection period with a linear trend equating to an increase of 420 cfs (25%) over the 93-year projection period. Projected future streamflow reflects the combined RCP 4.5 and 8.5 scenarios. (*Figure 44*)

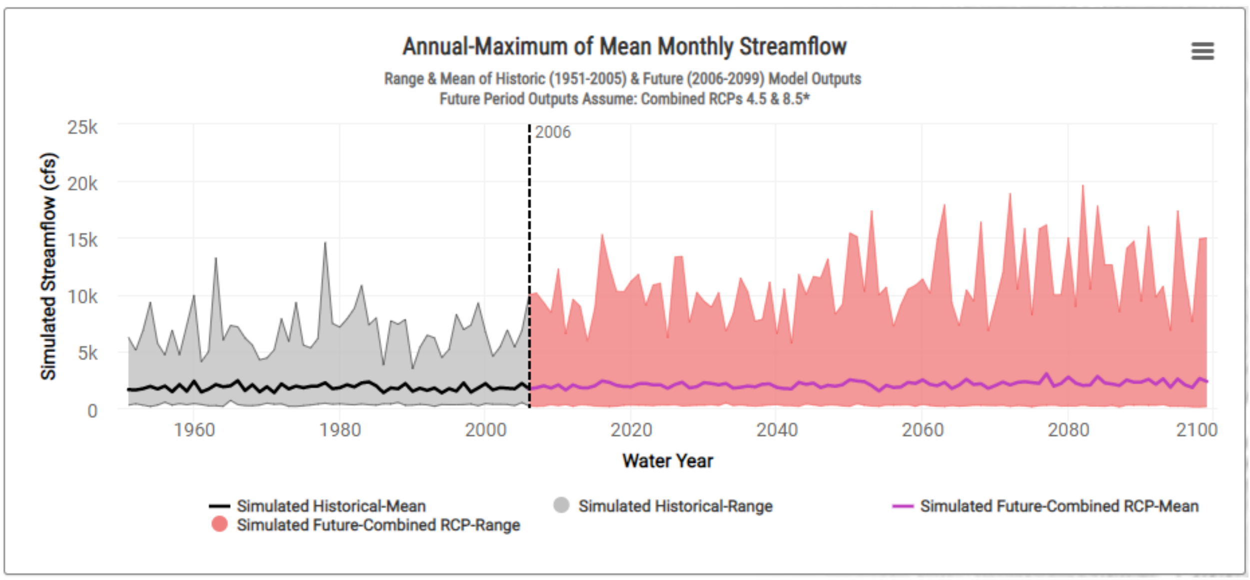


Figure 43. Range and mean of Annual Maximum of Average Monthly Streamflow for HUC 18060002. Spatially-downscaled, hydrologically-simulated and routed, and statistically-aggregated CMIP5 GCM output for the stream segment with the largest flow in the HUC 8 region. Streamflow is representative of cumulative flow from all upstream segments as well as the local runoff contributions to the aligned stream segment. Simulated flows are unregulated.

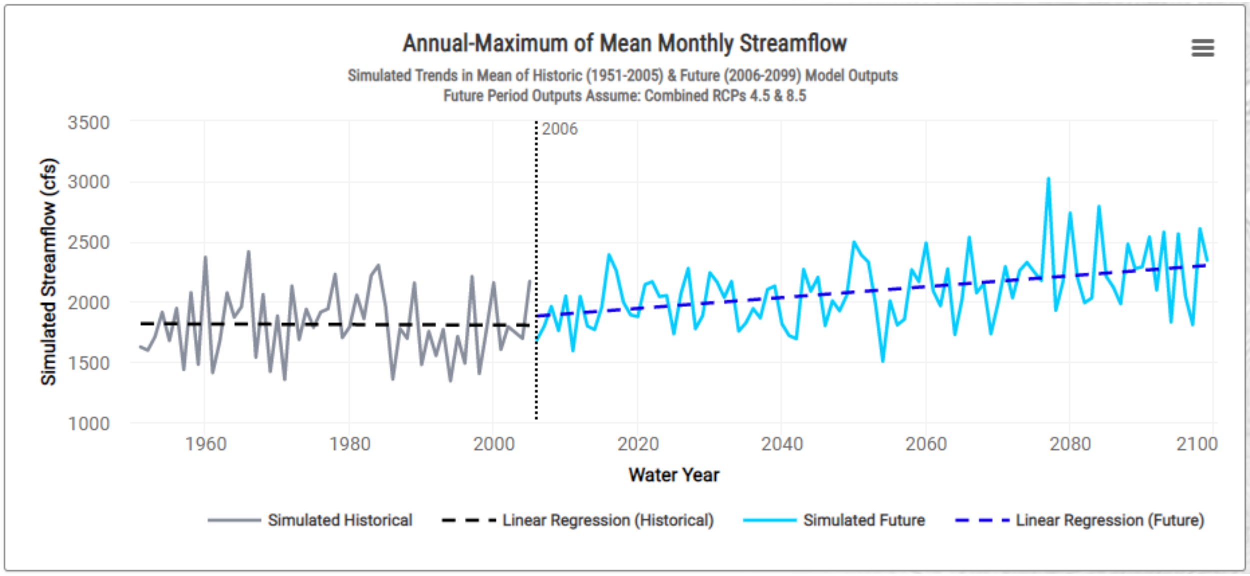


Figure 44. Trend in Annual Maximum of Average Monthly Streamflow. A statistically significant trend was detected for projected streamflow. A statistically significant trend was not detected for simulated historical streamflow.

Nonstationarity Detection Tool

For this project, the USACE NSD tool was also applied to the annual peak streamflow data and annual maximum stage data from the USGS gage on the Pajaro River at Chittenden (Gage ID: 11159000). This gage captures 1,186 square miles of drainage area and is located approximately 19 miles upstream of the project area at the confluence with Watsonville Slough. It has a continuous period of record from 1940 to 2021. This is the nearest gage upstream of the project with a sufficiently long record for nonstationarity analysis. There is a USGS gage nearer the project site on the Pajaro River in Watsonville (Gage ID: 11159500) and a Pajaro Valley Water-operated gage on Watsonville Slough, however those gages have only 3 years and 7 years of record, respectively, and therefore are not suitable for nonstationarity or trend analyses.

As shown in *Figure 45* - *Figure 46*, no nonstationarities were detected. Additionally, no monotonic trends were detected in the peak streamflow dataset between 1940 and 2021 using the Mann-Kendall (p-value = 0.39>0.05) and Spearman Rank-Order (p-value = 0.38>0.05) tests applied using a 0.05 level of significance.

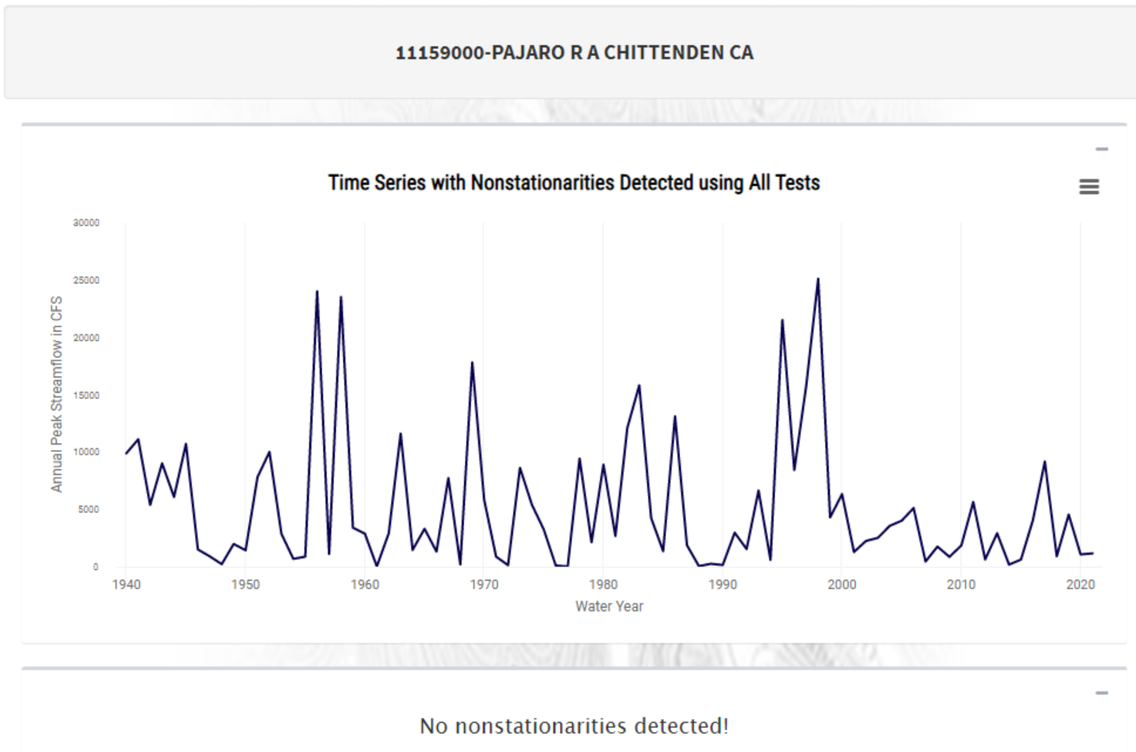


Figure 45. Nonstationarity detection results for annual peak streamflow for Pajaro River at Chittenden (11159000). No nonstationarities were detected.

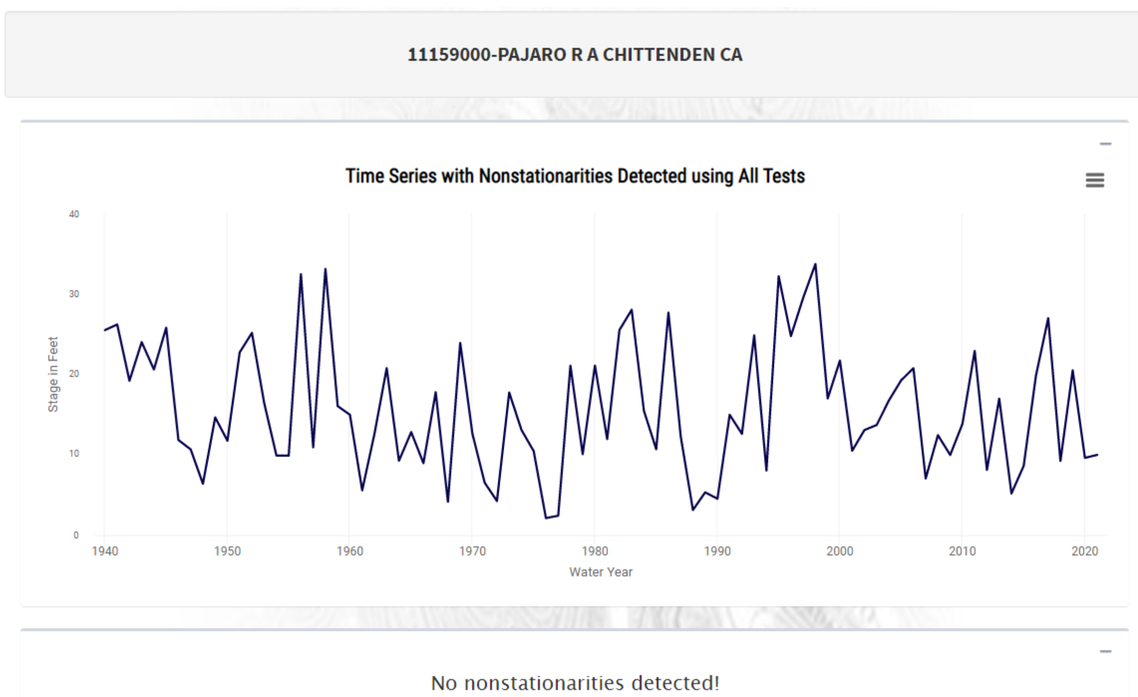


Figure 46. Nonstationarity detection results for annual peak stage for Pajaro River at Chittenden (11159000). No nonstationarities were detected.

5.2.4 Drought

Climate Hydrology Assessment Tool

CHAT results for number of consecutive dry days (annual maximum) are shown in *Figure 47*.

Under the RCP 8.5 scenario (the scenario for which trend is significant), the linear trend equates to an increase of 5.3 days per water year (6%) over the 93-year projection period.

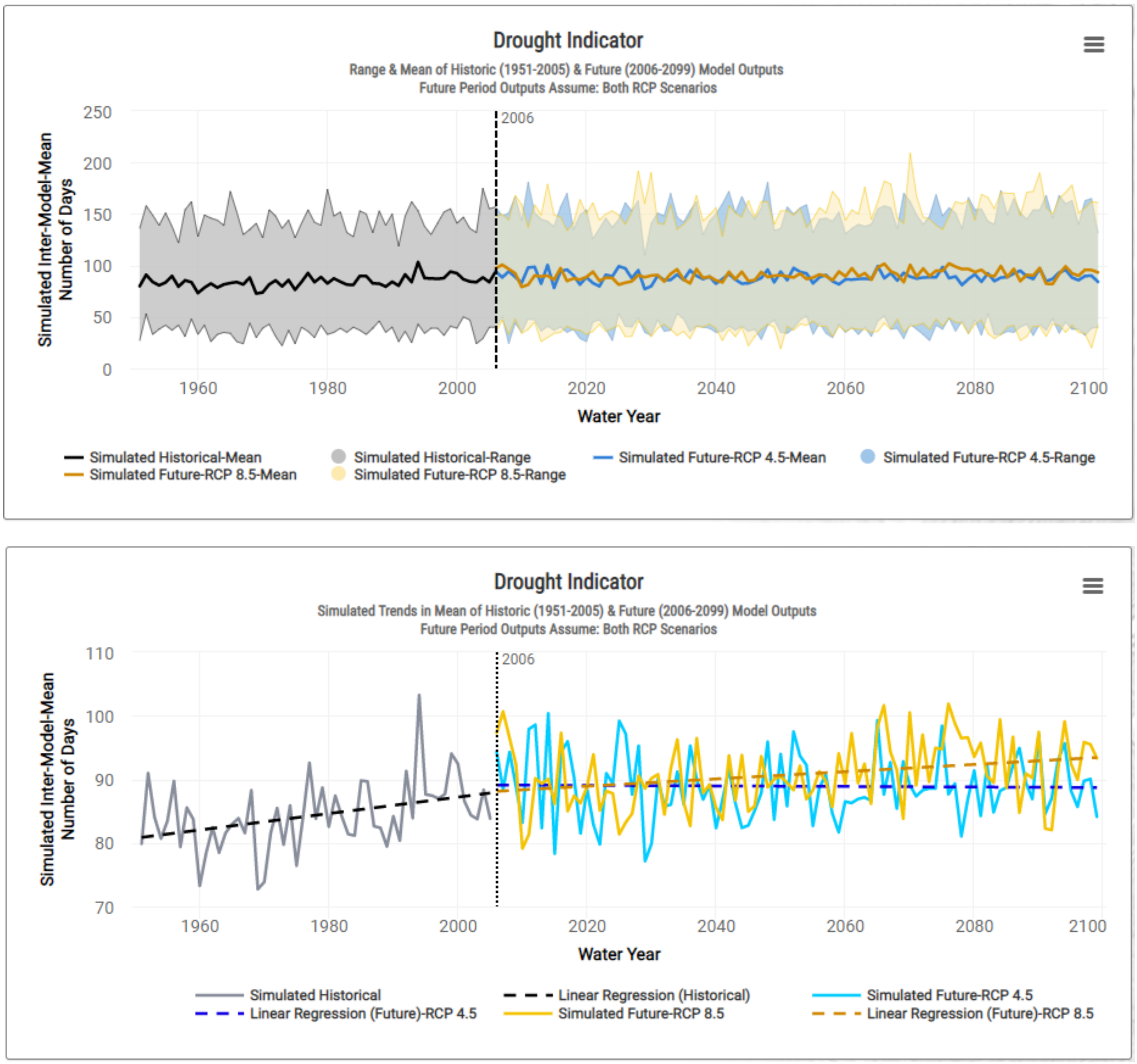


Figure 47. Annual Maximum of Number of Consecutive Dry Days. Range and mean (top) and trends (bottom) for RCP4.5 and RCP8.5. Statistically significant trends were detected for simulated historical precipitation and projected future precipitation under RCP8.5. A statistically significant trend was not detected for RCP4.5.

5.2.5 Summary

The results of the CHAT analysis for HUC 18060002 are in general agreement with the trends and projections reported in the Fourth National Climate Assessment and the Fourth California Climate Assessment. All sources project increases in temperature, precipitation, and climatic extremes, though the magnitudes of those increases vary by source. Results of the CHAT tool trends and significance tests are summarized in *Table 6*.

Table 6. Summary of Trends and Significance for Climate Parameters in HUC 18060002

Parameter		Simulated Historical	Projected Future (RCP4.5)	Projected Future (RCP8.5)	Interpretation
		p-value (5% significance level)			
Daily Average Temperature	**Annual Average**	Significant	Significant	Significant	The directionality and magnitude of trends suggest that increases in temperature are already materializing in the region, and can be anticipated to persist and accelerate into the future.
Daily Maximum Temperature	**Annual Maximum**	Significant	Significant	Significant	
Daily Accumulated Precipitation	**Annual Sum**	Not significant	Significant	Significant	There is not enough evidence to suggest a trend in the simulated historical precipitation data, but the statistically significant change in projected, future precipitation suggests changes in the future without project condition.
Daily Accumulated Precipitation	**Annual Maximum of 3-day Sum**	Not significant	Significant	Significant	
Number of Consecutive Dry Days	**Annual Maximum**	Significant	Not significant	Significant	Implications vary depending on future RCP scenario.
Average Monthly Streamflow	**Annual Maximum**	Not significant	Significant (Note: Streamflow trend analysis combines RCP 4.5 and 8.5 scenarios)		There is not enough evidence to suggest a trend in the simulated historical streamflow data, but the statistically significant change in projected future streamflows suggests changes in the future without project condition.

5.3 Sea Level Change

5.3.1 Anticipated Sea Level Change and Selection of Curve

Sea level change is an uncertainty, potentially increasing the frequency of extreme water levels. USACE Engineering Regulation (ER), USACE ER 1100-2-8162 (USACE 2019), incorporates new information, including projections by the Intergovernmental Panel on Climate Change and National Research Council (IPCC 2007, NRC 2012). Planning studies and engineering designs are to evaluate the entire range of possible future rates of sea-level change (SLC), represented by three scenarios of “low”, “intermediate”, and “high” sea-level change. The general approach to evaluating sea level change at the project site and selecting an appropriate curve for use in project planning is as follows:

1. Identify the appropriate tide station
2. Specify the project base year, 50-yr economic period of analysis, and 100-yr planning, lifecycle, and adaptation period
3. Determine the range of sea level change projections
4. Assess the sensitivity of the project

The NOAA Monterey station (#9413450) is the closest tide gauge to the project area (approx. 17.5 miles SSW), with an observed water level record from 1974 to present-day. As the Monterey tide station record spans nearly 50 years, which complies with the minimum data record length recommended by ER 1100-2-8162, and has few data gaps, this station was selected as the tide data source for the project. *Figure 48* shows the tidal datums at the NOAA Monterey station, with respect to the land datum North American Vertical Datum of 1988 (NAVD88).

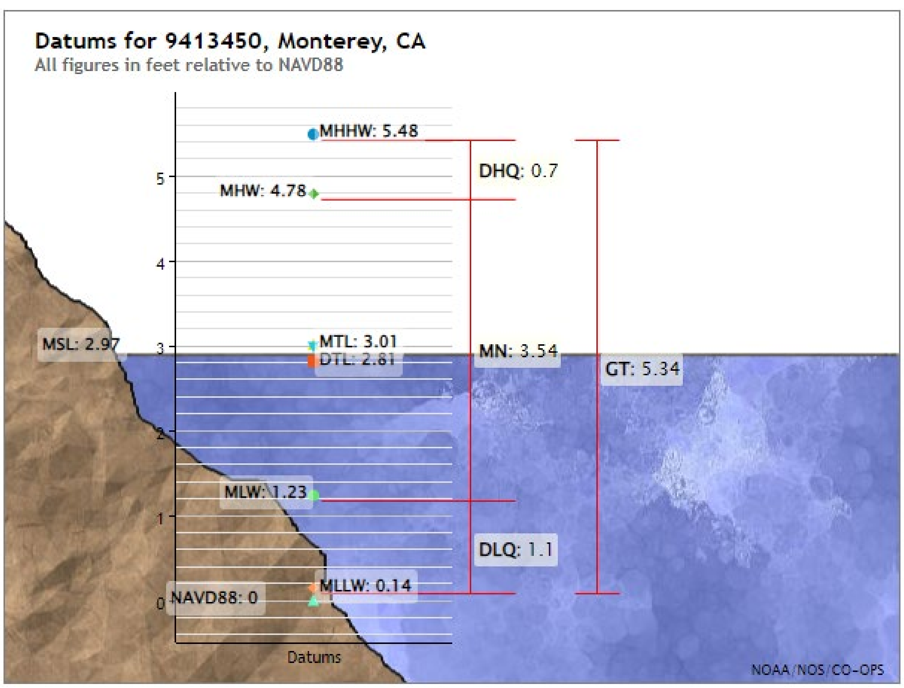


Figure 48: Tidal datums for NOAA Monterey tide station (#9413450).

The project base year is assumed to be 2025. Thus, the economic period of analysis for the scenarios extends until 2075 and the 100-yr planning, lifecycle and adaptation period at 2125. The PDT gathered observed sea level change trend information from this location and compared the data against future USACE sea level change projections to select a sea level change curve for use in the planning scenarios.

NOAA generates a relative sea level trend estimate for the tide station location, based on the available data record. The observed mean sea level is rising at a rate of +1.67 mm/yr (0.005479 ft/yr), which over 100 years would equal approximately 0.55 feet of rise.

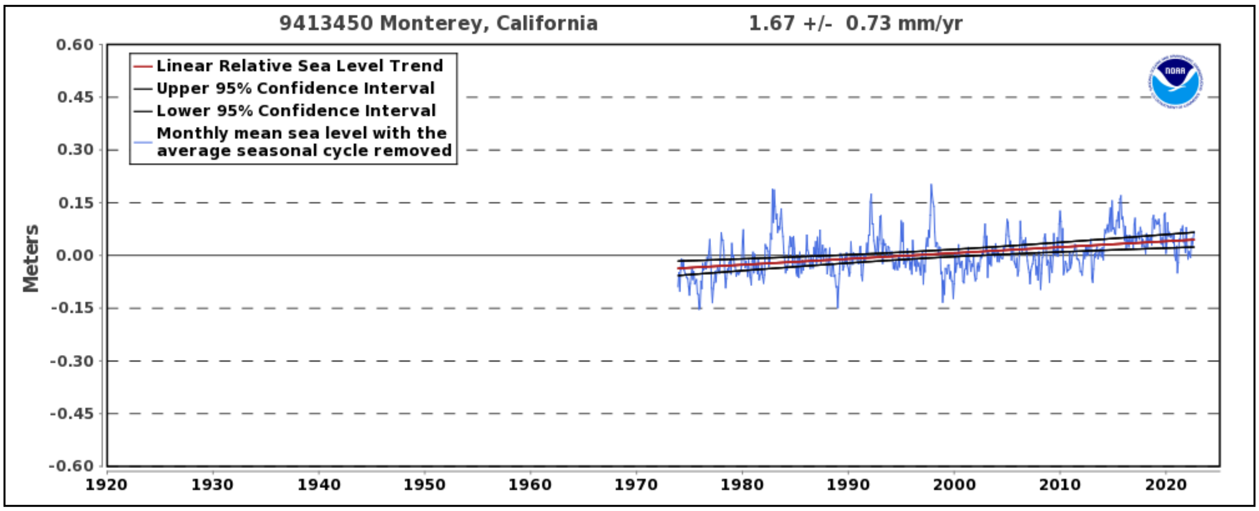


Figure 49: Relative sea level trend for NOAA Monterey station (#9413450), based on mean sea level data from 1973 to 2021. The relative sea level change trend is +1.67 mm/year (0.005479 ft/yr) with a 95% confidence interval of +/- 0.73 mm/yr (0.002395 ft/yr). This translates to 0.55 feet over 100 years.

The historical (observed) sea level change trend was compared against the existing USACE sea level change rates, using the USACE Sea Level Tracker, which computes moving averages over the duration of a tidal epoch (19 years) and a shorter window of 5 years.

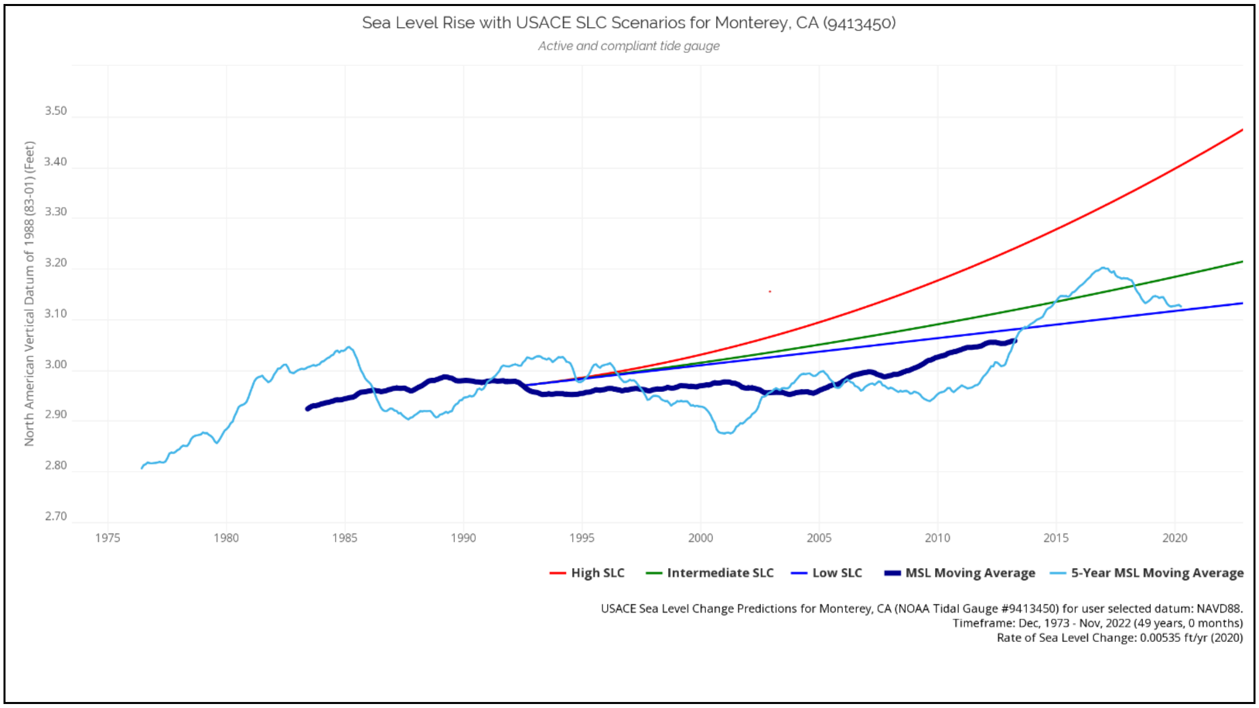


Figure 50: Historical and projected sea level change at Monterey, CA from the USACE Sea Level Tracker, based on the observed mean sea level (MSL) record. The light blue line represents the 5-year MSL moving average and the dark blue line the 19-year moving average.

Projected estimates of relative sea level change from 1992 to 2125 were evaluated for the USACE Low, Intermediate and High curves from the USACE Sea-Level Change Curve Calculator (Version 2022.72)[3]. The observed relative sea level trend of +1.67 mm/yr (entered as 0.005479 ft/yr) was used.

Table 7: Sea level change projections from 1992 to 2125, Monterey, CA, NOAA Station #9413450.

Estimated Relative Sea Level Change
from 1992 To 2125 Watsonville Slough CAP 1135
9413450, Monterey, CA
User Defined Rate: 0.00548 feet/yr
All values are expressed in feet

Gauge Status: Compliant

Year	USACE Low	USACE Int	USACE High
1992	0.00	0.00	0.00
1995	0.02	0.02	0.02
2000	0.04	0.05	0.07

[3] The USACE Sea-Level Change Curve Calculator (Version 2022.72) is accessible at: https://cwbi-app.sec.usace.army.mil/rccslc/slcc_calc.html

Year	USACE Low	USACE Int	USACE High
2005	0.07	0.09	0.13
2010	0.10	0.13	0.22
2015	0.13	0.17	0.32
2020	0.15	0.22	0.44
2025	0.18	0.28	0.58
2030	0.21	0.34	0.74
2035	0.24	0.40	0.92
2040	0.26	0.47	1.12
2045	0.29	0.54	1.33
2050	0.32	0.62	1.56
2055	0.35	0.70	1.82
2060	0.37	0.78	2.09
2065	0.40	0.87	2.38
2070	0.43	0.97	2.68
2075	0.45	1.07	3.01
2080	0.48	1.17	3.35
2085	0.51	1.28	3.72
2090	0.54	1.39	4.10
2095	0.56	1.51	4.50
2100	0.59	1.63	4.92
2105	0.62	1.75	5.35
2110	0.65	1.88	5.81
2115	0.67	2.02	6.28
2120	0.70	2.16	6.78
2125	0.73	2.30	7.29

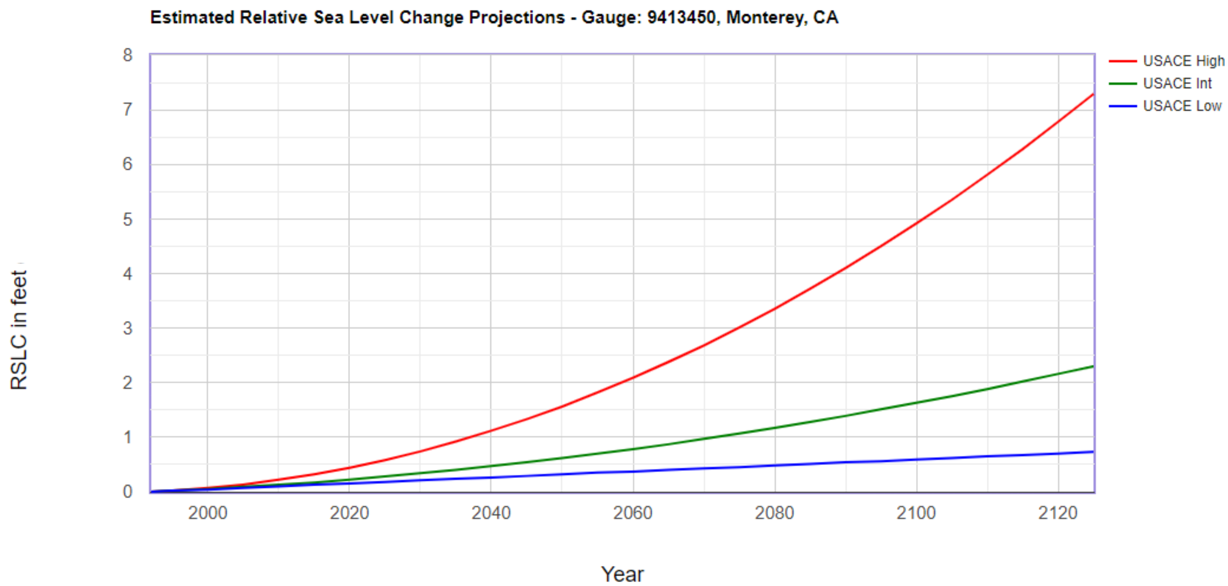


Figure 51: Relative sea level change projections from 1992 to 2125, Monterey, CA, NOAA Station #9413450.

The PDT reviewed sea-level rise estimates from other federal and state agencies for the study area, which provided projections relative to mean sea levels at base year 2000. The OPC (2018) report estimates +0.5 to +1.1 ft rise in sea level by 2050 for the Monterey area, under the 'Likely Range, High Emissions' scenario. Similarly, NOAA (2022) predicts approximately +0.5 to +1.0 ft of sea level change by 2050 along the West Coast. The USACE Intermediate values for 2050 and 2075, +0.57 ft and +1.02 ft respectively, track closely with these projections.

The PDT evaluated the sensitivity of the project and sensitivity of risks to the USACE Low, Intermediate and High SLC estimates, in order to select a single scenario for planning. The Low SLC curve, which is based off of the historic RSLC trend for the Monterey region, predicts +0.45 ft of SLR by 2075 and +0.73 ft by 2125. The existing marsh plain in the study area is perched and future tidal elevations (assuming the Low curve) would not be high enough to flood the marsh plain. Thus, the project would show little to no ecological benefit with SLR estimates from the USACE Low curve in either the project lifecycle (50 years) or planning horizon (100 years). Additionally, it is likely that the Low curve would underestimate the future tidal range.

The High SLC curve predicts approximately 3 ft of sea level change by 2075 and over 7 ft by 2125. Sea level change mapping for the Pajaro River/Watsonville Slough area show extensive flooding of low-lying agricultural land adjacent to the study area beginning with 2 to 3 feet of sea level change. The predicted permanent flooding of lower Watsonville by future tidal action would trigger shifts in system hydrology, adjacent land use and access to the site and would likely preclude any project benefits.

Based on the considerations above, the PDT used sea-level change estimates corresponding to the USACE Intermediate SLC curve to develop a suite of scenarios. The preferred alternative under the Intermediate scenario will be evaluated against the Low and High SLC estimates after the Tentatively Selected Plan milestone.

5.3.2 Lagoon Mouth Response

Lagoon closure frequency is an important element of the hydrologic conditions in the Watsonville Slough project area, and it is expected that it will be affected by future climate. However, lagoon closure is dependent on multiple factors, making it difficult to predict future changes to mouth closure state. For example, projected intensification of storms could have conflicting effects on closure frequency: increased wave energy could result in more frequent closures, while increased streamflow from intense rainfall could result in more frequent openings (Thorne et al., 2021).

Generally, during dry years, the lagoon mouth experiences more frequent and longer closures, sometimes on the order of months. During closures events in dry years, the relative magnitudes of water level sinks (e.g. beach seepage and evaporative losses) versus sources (e.g. streamflow, wave overtopping) control the lagoon water level. During wetter years, high winter streamflows scour a deeper channel at the mouth, which allow the lagoon to remain open to tides for longer periods of time. Powerful winter waves, such as during the El Niño winter of 2015-2016, can partially block outflows from the lagoon and contribute to high water levels in the open lagoon.

The non-federal sponsor's consultant (Environmental Science Associates) modeled the lagoon response to incremental changes in sea level change (SLC) and with/without sedimentation, using the Lagoon Quantified Conceptual Model (Lagoon QCM; Behrens et al., 2015)[4]. The Lagoon QCM is a parametric water balance model which predicts the lagoon morphology, hypsometry and open/closed inlet state as a function of waves, streamflow and sediment processes that contribute to beach berm build-up.

The QCM was calibrated and run to simulate baseline conditions from 2008 to 2021 (based on availability of data for the beach and lagoon mouth and lagoon hydrology). Subsequently, the model was run for future conditions with SLC from 0 to +3 ft, in increments of +0.5 ft and with/without sedimentation (see following section). The technical memorandum describing the full model background, development and results is included as an attachment to this Attachment D.

The QCM modeling showed that the Pajaro River lagoon mouth would continue to seasonally close with decreasing frequency with increasing increments of sea level change. Assuming zero sedimentation within the estuary, at 0 ft of SLC, the % time of mouth closure was predicted to be 32%; at +1 ft of SLR, which corresponds to the amount of SLC at the end of project life for the USACE Intermediate Curve, this value falls to 26%. At +2 ft of SLC, the lagoon mouth is predicted to close less than 10% of the time. The lagoon mouth and hydrology become permanently open to oceanic influence with higher levels of SLC (<5% of time, +3 ft SLR). These overall trends were true assuming zero sedimentation and with sedimentation in the estuary.

The PDT evaluated the number of anticipated breach events for the different increments of SLC (0 to 3 ft) assuming the existing and increased breach threshold (with Crossing Improvements). Increasing the County's breach threshold to +9.2 ft NAVD effectively allows the lagoon mouth to

[4] The Lagoon QCM is a proprietary lagoon hydrology model developed by Environmental Science Associates and is not a Corps-approved model. The PDT followed all applicable guidance related to conducting agency review on the model and acquired a single-use waiver for use of Lagoon QCM as part of the project analyses and scenariosevaluation in February 2023.

remain an intermittently/seasonally closed estuary longer into the future and over the project lifetime, which would result in ecosystem benefits to the lower Watsonville Slough marsh plain. Maintaining the County's existing breach threshold would mean an increased frequency of manual breaching as sea levels rise (nearly double the frequency for with-project conditions for up to +1 ft SLC), which represents a larger cost burden and environmental impact on the lagoon and beach habitat.

5.3.3 Marsh Accretion

The rate of marsh accretion within intermittently-closed estuaries is influenced by the frequency of lagoon mouth closure patterns and suspended sediment concentration within the estuary. Thorne et al (2021) shows that marshes in intermittently-closed estuaries have higher initial elevation capital compared to open-estuary marshes and exhibit higher accretion rates due to closure events. The authors modeled marsh elevation change in response to SLC until 2100 for a range of California-based perennially open and intermittently-open estuaries. \

For systems with annual mouth closure, accretion kept pace with sea level change for SLC rates up to 10 mm/year (0.0328 ft/year). The relative SLC trend assumed for the study area, based on historic water level observations from the NOAA Monterey tide gauge, is 0.005479 ft/year. The rates of SLC during the project lifetime (2025 thru 2075) range between 0.012 ft/year to 0.020 ft/year, assuming the USACE Intermediate Curve. Under the USACE High Curve, the sea level change rate exceeds 0.0328 ft/year by 2035 and ranges between 0.028 ft/year to 0.066 ft/year over the 50-year lifetime. It is predicted that the Slough marsh plain sedimentation rate would be able to keep pace with SLC under the Intermediate Curve, but would be overtaken by SLC under the High Curve.

Based on the literature and comparison with existing information at the site, this study assumes a conservative marsh accretion magnitude equal to 50% of the magnitude of sea level change. I.e., in year 50 of the project design life, when sea level change is estimated to be +0.79 feet over project year 0 (assuming the USACE Intermediate SLC curve), marsh accretion is estimated to be +0.395 feet.

5.3.4 Interannual Oscillations

The El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) are interannual, recurring climate patterns that encompass shifts in winds, water temperature and currents across the equatorial and mid-latitude Pacific, respectively. ENSO cycles last 2 to 7 years and typically include three phases: El Nino, La Nina and neutral years, while PDO cycles recur on a longer time scale of 5 to 20 years. In particular, El Nino years are characterized by warm water and atmospheric convection moving eastwards, resulting in elevated water levels along the West Coast. This signature is observable in the monthly mean sea level, when the average seasonal cycle and linear sea level change trend is removed. Historic El Nino years that are captured within the NOAA Monterey station record include the 1982/1983, 1997/1998 and 2015/2016 events. As the length of the record is nearly 50 years, warm and cool phases of historic PDO cycles are also captured in the signal.

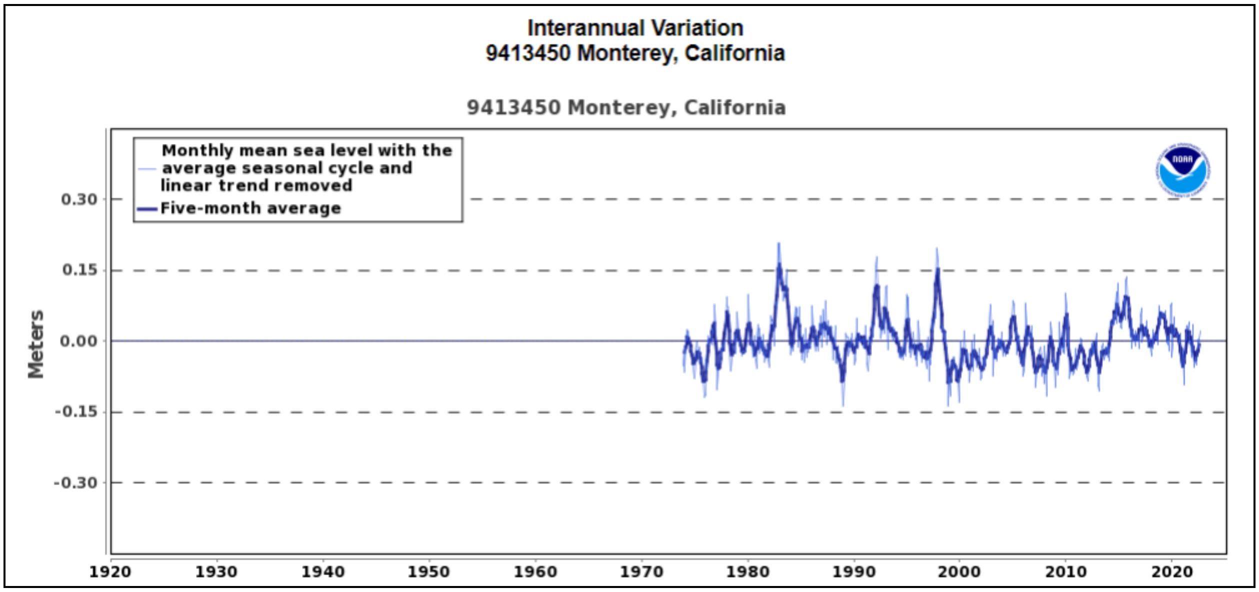


Figure 52: Interannual variation at the NOAA Monterey tide gage (Station #9413450).

Changes in the global climate are anticipated to intensify ENSO patterns in the future. The scientific literature suggests that extreme El Nino occurrences could potentially double in the future (McPhaden et al., 2020; Ying et al., 2022). The upper bound of increase in water level due to interannual oscillations (five-month average) is approximately +0.5 ft. Given the current science, the PDT selected this value to represent the contribution of regional climate variations to local water levels; this was added into the total water level stage hydrograph used as the downstream boundary condition in the project H&H modeling.

5.4 Vulnerability Assessment

The USACE Watershed Climate Vulnerability Assessment (VA) Tool facilitates a screening-level, comparative assessment of the vulnerability of a given business line and HUC-4 watershed to the impacts of climate and extreme weather, relative to the other HUC-4 watersheds within the continental United States (CONUS). It uses the Coupled Model Intercomparison Project (CMIP5) dataset to define projected hydrometeorological inputs, combined with other data types, to define a series of indicator variables to define a vulnerability score.

Vulnerabilities are represented by a weighted-order, weighted-average (WOWA) score generated for two subsets of simulations (wet—top 50% of cumulative runoff projections; and dry—bottom 50% cumulative runoff projections). Data are available for three epochs. The epochs include the current time period (“Base”) and two 30-year, future epochs (centered on 2050 and 2085). The Base epoch is not based on projections and so it is not split into different scenarios. For this application, the tool was applied using its default, National Standards Settings. In the context of the VA Tool, there is some uncertainty in all of the inputs to the vulnerability assessments. Some of this uncertainty is already accounted for in that the tool presents separate results for each of the scenario-epoch combinations rather than presenting a single aggregate result. Under the National Standard settings, the vulnerability threshold for each business line is typically 20% (i.e., 20% of HUC-4 watersheds throughout the country are classified as vulnerable).

The Watsonville Slough project is in HUC 1806 (Central California Coastal) and classified under the Ecosystem Restoration business line. Potential project scenarios have features that can also be classified under the Flood Risk Reduction business line. *Table 8* shows that both business lines in HUC 1806 are vulnerable to climate and extreme weather under all scenario/epoch combinations. *Table 9* shows the three indicators exhibiting the highest contribution to extreme weather vulnerability for each scenario/epoch combination. *Figure 53* and *Figure 54* show the relative vulnerability of watersheds throughout the country and summarize the vulnerability assessment results for HUC 1806.

Table 8. HUC-1806 Climate Vulnerability by Epoch/Scenario Combination

Business Line	**Epoch**	**Dry Subset of Scenarios**	**Wet Subset of Scenarios**
Ecosystem Restoration	2050	Vulnerable	Most Vulnerable
	2085	Vulnerable	Most Vulnerable
Flood Risk Reduction	2050	Vulnerable	Most Vulnerable
	2085	Vulnerable	Most Vulnerable

Table 9. Top three indicators exhibiting the highest contribution to climate and extreme weather vulnerability for each epoch/scenario

<table>
<tr><th>Business Line</th><th>Epoch</th><th>Dry Subset of Scenarios</th><th>Wet Subset of Scenarios</th></tr>
<tr><td rowspan="1">Ecosystem Restoration</td><td>2050/2085</td><td colspan="2">(1) Percentage of wetland and riparian plan communities that are at risk of extinction, based on remaining number and condition, remaining acreage, threat severity, etc. (8)
(2) Short-term variability in the region’s hydrology (221C)
(3) Percent change in runoff divided by percent change in precipitation (elasticity between precipitation and streamflow) (277)</td></tr>
<tr><td rowspan="2">Flood Risk Reduction</td><td>2050</td><td rowspan="2">(1) Acres of urban area within the 500-yr floodplain (590)
(2) Long-term variability in hydrology (175C)
(3) Flood magnification - cumulative runoff (568C)</td><td>(1) Flood magnification – cumulative runoff (568C)
(2) Acres of urban area within the 500-yr floodplain (590)
(3) Flood magnification – local runoff (568L)</td></tr>
<tr><td>2085</td><td>(1) Flood magnification – cumulative runoff (568C)
(2) Flood magnification – local runoff (568L)
(3) Acres of urban area within the 500-yr floodplain (590)</td></tr>
</table>

Note: The flood magnification indicators represent change in flood runoff (monthly runoff exceeded 10% of the time) from the base period.

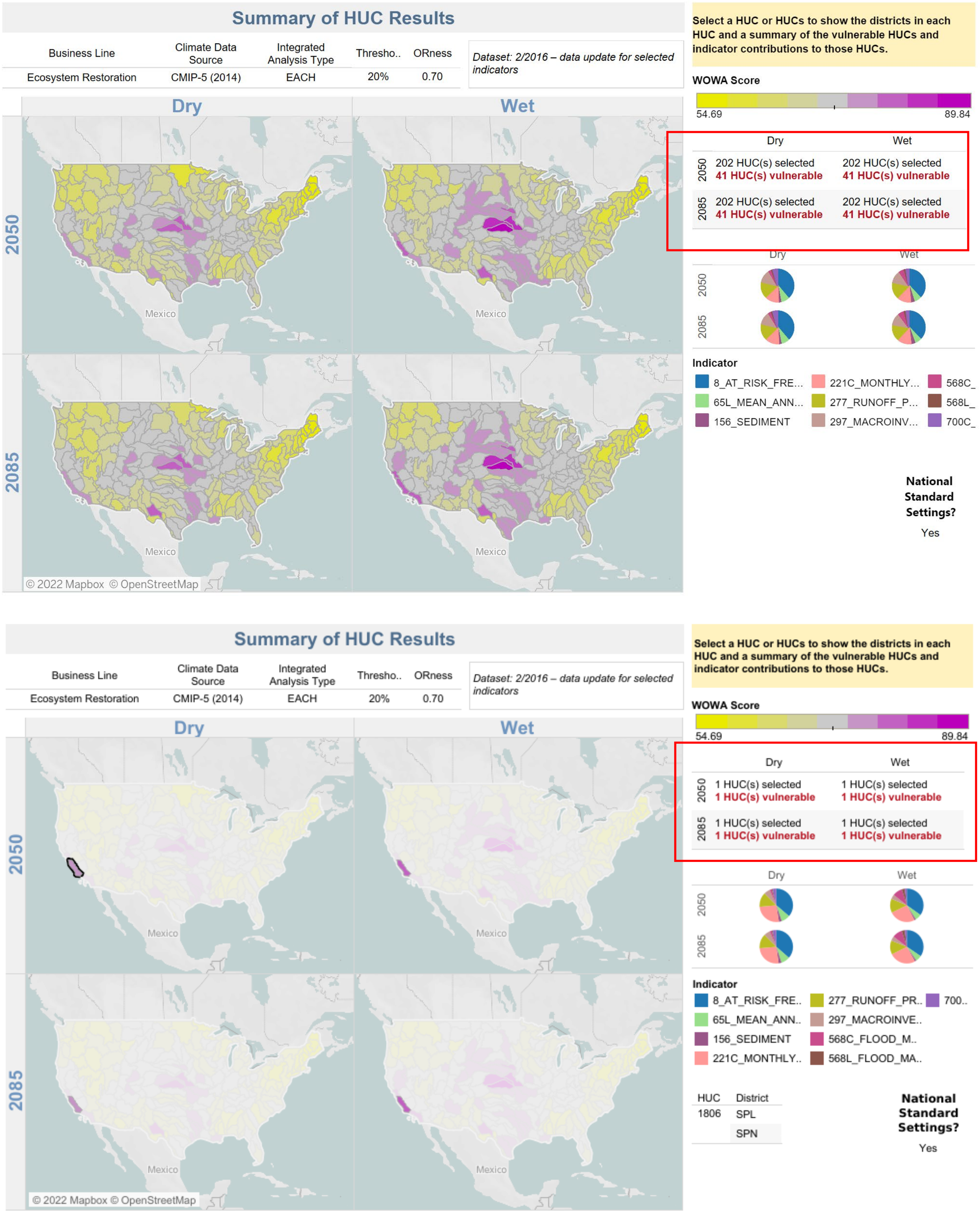
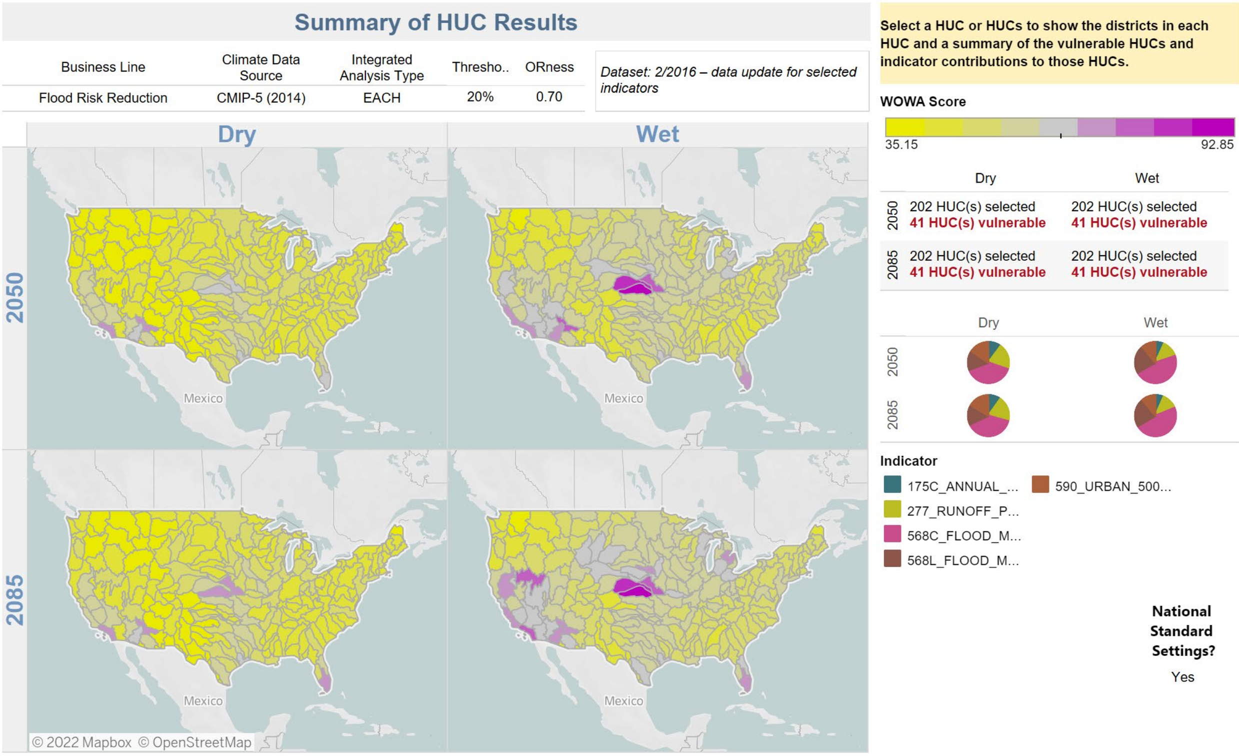


Figure 53. Top: For the Ecosystem Restoration Line of Business, approximately 20% of included HUC-4 watersheds (41 of 202) are considered most vulnerable nationwide. Bottom: HUC 1806 (Central California Coastal) is considered vulnerable under all epoch/scenario combinations.



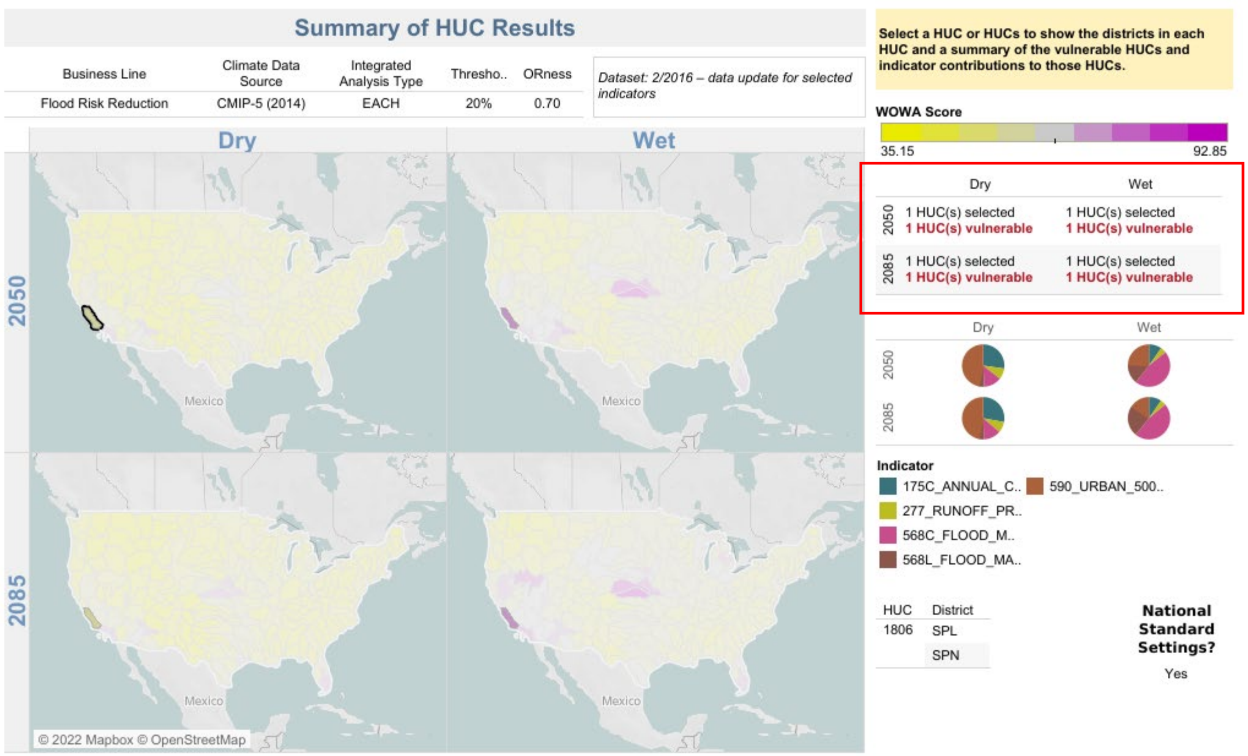


Figure 54. Top: For the Flood Risk Reduction Line of Business, approximately 20% of included HUC-4 watersheds (41 of 202) are considered most vulnerable nationwide. Bottom: HUC 1806 (Central California Coastal) is considered vulnerable under all epoch/scenario combinations.

5.5 Summary of Climate Risks

Per guidance in ECB 2018-14, *Table 10* identifies the risks resulting from changed climate conditions in the future. The table shows the major project feature affected, the triggers (the climate variables that cause the risk), the hazard to the project feature, the potential harm to the project feature, and a qualitative assessment of the likelihood of this harm.

Table 10. Climate Residual Risks Table

Project Feature or Measure	Trigger (Climate Variable)	Impact or Hazard to Project Feature or Measure	Harm	Qualitative Likelihood	Justification for Rating
Restoration earthwork (tidal channels and berm breaches) only	Increased temperatures	Increased evapotranspiration; increased water temperatures.	Increased evapotranspiration may result in decreased inundation frequency / hydroperiod in marsh restoration areas, reducing project benefits. Increased water temperatures could lead to water quality concerns.	Moderate	CHAT tool indicates changes in the future without project condition
	Increased frequency of drought conditions	Reduced flows in dry season. Increased length of dry season.	Decreased flows during closed lagoon conditions may result in reduced hydroperiod in marsh restoration areas, reducing project benefits.	Moderate	CHAT tool indicates changes in the future without project condition under the RCP 8.5 scenario, but not RCP 4.5.
	Increased variability and intensity of precipitation events	Greater upstream inflows to slough system during storm events.	High streamflow resulting from more intense precipitation events could result in greater flooding during both closed lagoon and open lagoon conditions. Flooding of the marsh plain is beneficial for the project objective of increasing hydroperiod; however, flooding of adjacent agricultural lands and infrastructure is undesirable. High streamflow events are often responsible for natural breaching of a lagoon closure, so more frequent high streamflow events could result in more frequent lagoon breaches, and therefore, shorter durations of lagoon closure events, and potentially shorter hydroperiod.	Moderate	There is consensus among the literature and CHAT that annual total precipitation will increase, as will the intensity of individual precipitation events.

Project Feature or Measure	Trigger (Climate Variable)	Impact or Hazard to Project Feature or Measure	Harm	Qualitative Likelihood	Justification for Rating
	Relative sea level change (RSLC)	Relative sea level change exceeding 1.5 ft triggers a shift in the lagoon mouth to become permanently tidal and open. Without modification of the lagoon breach threshold, water levels upstream of W. Beach Road are not expected to exceed marsh plain elevation and result in changed hydrology to the affected area, even with the tidal channel features.	Increased sea levels will result in greater saline influence around the project area and up the Slough channel, which may trigger shifts in marsh vegetation as the lagoon mouth and Slough become permanently open to oceanic influence. Increased wave overtopping during closed lagoon conditions could result in more high backwatering events and need to manually breach. This measure only includes tidal channel excavation and would maintain the same breach threshold, which would increase the frequency of manual breaching up to RSLR of 1.5 ft. If marsh sedimentation rates do not keep pace with the rate of SLR, marsh habitat area may be lost due to habitat conversion and the overall project benefits will decrease.	Moderate	Likelihood of RSLC is high. PDT has leveraged Lagoon QCM simulations to carefully evaluate with and without-project conditions and effect of sea level change on project elements.
Crossing improvement at Beach Road (increasing the County's lagoon	Increased temperatures	Increased evapotranspiration; increased water temperatures.	Increased evapotranspiration may result in decreased inundation frequency / hydroperiod in marsh restoration areas, reducing project benefits. Increased water temperatures could lead to water quality concerns.	Moderate	CHAT tool indicates changes in the future without project condition.

Project Feature or Measure	Trigger (Climate Variable)	Impact or Hazard to Project Feature or Measure	Harm	Qualitative Likelihood	Justification for Rating
breach threshold)	Increased frequency of drought conditions	Reduced flows in dry season.	Decreased flows during closed lagoon conditions may result in reduced hydroperiod in marsh restoration areas, reducing project benefits.	Moderate	CHAT tool indicates changes in the future without project condition under the RCP 8.5 scenario, but not RCP 4.5.
	Increased variability and intensity of precipitation events	Greater upstream inflows to slough system during storm events.	High streamflow resulting from more intense precipitation events could result in greater flooding during both closed lagoon and open lagoon conditions. High streamflow events are often responsible for natural breaching of a lagoon closure, so more frequent high streamflow events could result in more frequent lagoon breaches, and therefore, shorter durations of lagoon closure events, and potentially shorter hydroperiod.	Moderate	There is consensus among the literature and CHAT that annual total precipitation will increase, as will the intensity of individual precipitation events.
	Relative sea level change	Relative sea level change exceeding 1.5 ft triggers a shift in the lagoon mouth to become permanently tidal and open. Lagoon QCM modeling with and without the higher breach threshold shows that the higher breach elevation allows the lagoon estuary to	Increased sea levels will result in greater saline influence around the project area and up the Slough channel, which may trigger shifts in marsh vegetation as the lagoon mouth and Slough become permanently open to oceanic influence. This measure slows the rate at which the lagoon system shifts to this permanently tidal regime up to 1.5 ft of RSLC. If rates of RSLC are higher than anticipated, benefits to the marsh plain would be frontloaded during the project lifetime.	Moderate	Likelihood of RSLC is high. PDT has leveraged Lagoon QCM simulations to carefully evaluate with and without-project conditions and effect of sea level change on project elements.

Project Feature or Measure	Trigger (Climate Variable)	Impact or Hazard to Project Feature or Measure	Harm	Qualitative Likelihood	Justification for Rating
		remain intermittently closed longer into the project lifetime.	Increased wave overtopping during closed lagoon conditions could result in more high backwatering events and the need to manually breach. The higher elevation threshold means that there would be less frequent need to manually breach as sea levels rise. If marsh sedimentation rates do not keep pace with the rate of SLC, marsh habitat area may be lost due to habitat conversion and the overall project benefits will decrease.		

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Attachment A. Watsonville CAP 1135 Hydrology Technical Memorandum

MEMORANDUM FOR RECORD (MFR)

SUBJECT: Watsonville Slough CAP Sec 1135 Feasibility Study – Hydrologic Assessment

1. Introduction

The purpose of this MFR is to describe the assessment that was performed to characterize the hydrology of the Watsonville Slough CAP project area, in support of selecting appropriate boundary conditions for hydraulic modeling.

1.1. Project Background

The Watsonville Slough CAP project is an ecosystem restoration project located at the confluence of the Watsonville Slough with the Pajaro River and Lagoon. The project area is bounded by Shell Road at the upstream end, and the Pajaro Lagoon at the downstream end (Figure 1). The hydrologic forcings of this system are streamflow from Watsonville Slough, streamflow from the Pajaro River, and tidal forcing from Monterey Bay. The hydrologic regime in the project area is complicated by the fact that the mouth of the Pajaro Lagoon periodically closes, due to the formation of a barrier beach that is formed by wave-driven sand transport during low river flows (Figure 2).

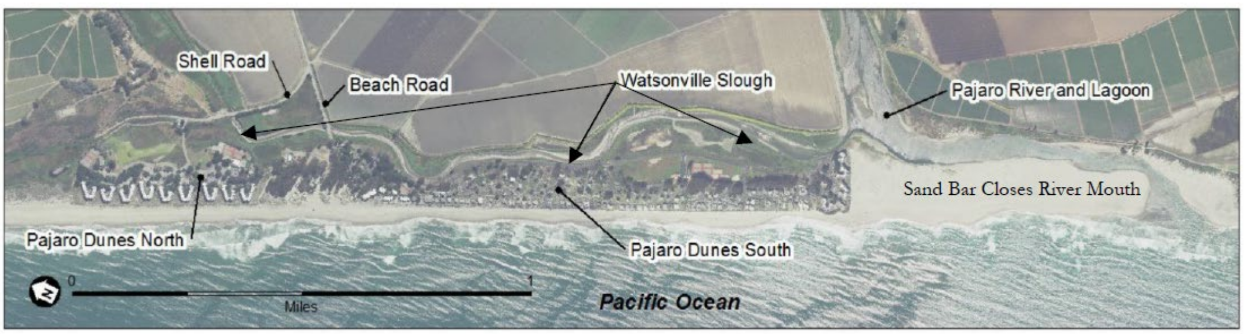


Figure 1: Map of the project area extents, showing the confluence of the Watsonville Slough and the Pajaro River at the Pajaro Lagoon (Source: Technical Memo from ESA, 2018).

When the lagoon is closed, the project area is effectively disconnected from tidal forcing, and water levels in the project area are determined predominantly by streamflow inputs and losses due to evapotranspiration and seepage/infiltration. When the lagoon is open, both streamflow and tide stage play a role, though tidal fluctuations have a more significant impact on water levels in the lagoon.

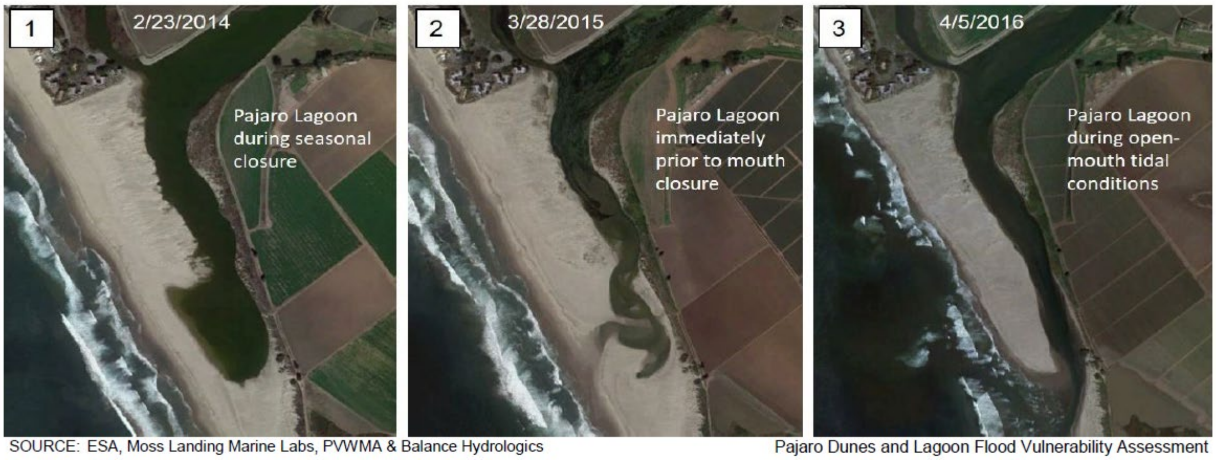


Figure 2: Pajaro Lagoon under open and closed conditions (Source: ESA, 2018).

Given this set of circumstances, to appropriately characterize this hydrologic system, it was determined that three distinct hydrologic regimes should be modeled. Those three regimes are: (1) Open Lagoon, Dry Season; (2) Open Lagoon, Wet Season; and (3) Closed Lagoon. Note, the modeling approach does not distinguish between dry and wet conditions for the closed lagoon case. This is because the barrier of the closed lagoon is typically breached when the system transitions from dry to wet conditions. I.e., either a high streamflow event will generate enough erosive force to naturally breach the lagoon closure, or, as part of its flood control duties, the County of Santa Cruz will use heavy machinery to manually breach the beach barrier in anticipation of a high flow event that could cause flooding if the lagoon is not opened.

1.2. Hydrologic Assessment Approach

There are two components of the hydrologic assessment required for this project: (1) extreme event hydrology to evaluate risk of induced flooding from the project alternatives and (2) characterization of “typical” hydrology for the sake of quantifying ecosystem restoration benefits of the project alternatives.

In the case of extreme event hydrology, the flows published in the FEMA Flood Insurance Study for Santa Cruz County will be used (Study #06087CV001C, Effective Date: 29 September 2017).

In the case of quantifying ecosystem restoration benefits, it is useful to explain the overall quantification methodology to understand how the hydrologic analysis fits in. The methodology for benefit quantification is based on modeling the changes in annual hydroperiod that result from the proposed project alternatives in a typical/representative year. The steps of that annual hydroperiod quantification and subsequent ecosystem benefit quantification are as follows:

1) Run HEC-RAS for a representative simulation period for each of the three hydrologic regimes. The simulation period for the open lagoon model runs is one month, and for the closed lagoon model run, two months.
2) Use RASMapper to generate a Percent Time Inundated raster for each of the three HEC-RAS simulations.
3) Use a parametric lagoon model called Lagoon QCM (Behrens et al., 2015) to determine the fraction of a typical year during which the Pajaro Lagoon is in each of the three

hydrologic regimes. For example, Lagoon QCM may calculate that the Pajaro Lagoon is, on average, in an “open-dry” state for x% of the year, “open-wet” for y% of the year, and “closed” for z% of the year.

4) Use GIS raster processing tools to multiply the lagoon state annual fractions from Step (3) by the Percent Time Inundated rasters from Step (2), and generate an annual weighted average Percent Time Inundated raster. This is the annual hydroperiod output.
5) Use GIS to reclassify the annual hydroperiod raster into relevant ranges of percent time inundated (e.g., 10% to 20% corresponds to habitat A, 20% to 40% corresponds to habitat B, etc.). The acreage of project area that falls into these different ranges are tallied and multiplied by their respective habitat quality score.
6) Calculate the differences in acres of various habitat quality between the various project alternatives.

The hydrologic analyses that are described in this MFR are the derivation of the representative hydrologic conditions that are used as boundary conditions in the HEC-RAS models described in Step (1) above.

It is also important to point out that the overall ecosystem restoration benefits quantification methodology involves performing this same workflow for future conditions, taking into account sea level rise and marsh accretion at multiple future time horizons. However, this MFR only addresses the hydrology for the existing conditions. The future conditions scenarios, and the ways in which climate change, sea level rise, and marsh accretion affect the study area, are addressed elsewhere in project documentation.

The following sections of this MFR will describe in the details of the hydrologic assessment and the resulting sets of hydrologic boundary conditions. The open lagoon, dry season and open lagoon, wet season will be explained together in Section 2. The closed lagoon condition will be explained separately in Section 3. Extreme event hydrology will be addressed in Section 4.

2. Open Lagoon Hydrology

Based on the methodology for translating hydraulic modeling results into ecological benefits, the goal of the modeling was to select boundary conditions that are representative of a typical month in each hydrologic regime. For the open lagoon condition, the boundary conditions consist of coincident streamflow and total water level (TWL) hydrographs.

A simulation duration of one month was selected so that the hydraulic model simulation is long enough to capture a wide range of tidal conditions, but not so long as to cause prohibitively long model runtimes. The selection of a one-month simulation period also allows for a key component of the hydrologic analysis: using monthly precipitation data as a proxy for monthly accumulated flow volumes.

2.1. Streamflow Analysis

2.1.1. Available Data

The relevant data available for this analysis consists of a short-term (WY2016 to WY2021) observed flow record in Watsonville Slough approximately 1.5 miles upstream of the project area at San Andreas Road, a long-term (1908 to present) precipitation gage approximately 5 miles inland from the project area, and a relatively long-term (1973 to present) tide gage in Monterey Bay. There is also a synthetic flow record (WY2003 to WY2018) for Watsonville

Slough that was generated with a combined HEC-HMS and 1D HEC-RAS model. This modeling was performed by Balance Hydrologics for the Santa Cruz Resource Conservation District. Its purpose was to calculate the overall water balance of the broader system of sloughs, and to evaluate the effects on that balance of a potential wetland restoration project and flow diversion project. This modeled flow record was evaluated as a potential data source for use in the current hydrologic assessment. Ultimately, when comparing the modeled flows to the observed flows (Figures 5 and 6), it was determined that the modeled flows significantly underestimate high flows in Watsonville Slough, and therefore should not be used in this analysis.

Table 1 summarizes the data sets that were available. Figure 3 shows a map of the streamflow and precipitation gages in relation to the project area. Figures 4 and 5 visualize the precipitation data and streamflow data. The tide data is visualized and explained in Section 2.2.

Figure 3: Flow and precipitation gage locations with respect to the project area.

Table 1: Data sets of interest for Watsonville Slough.

Type	Period of Record	Time Step	Source
Precipitation	1908 to 2021	Monthly	Gage at Watsonville Waterworks (NOAA gage ID: WTW)
Modeled Flow in Watsonville Slough	WY2003 to WY2018	Hourly	Combined HEC-HMS & HEC-RAS modeling performed by Balance Hydrologics in 2014 and then updated by ESA in 2018
Observed Flow in Watsonville Slough	WY2016 to WY2021	15-minute	Gage operated by PV Water
Observed Flow in Pajaro River	Feb. 2019 to Present	15-minute	USGS gage on Pajaro River in Watsonville (Gage ID: 11159500)
Observed Flow in Pajaro River	WY1939 to Present	Daily	USGS gage on Pajaro River in Chittenden (Gage ID: 11159000)
Tide Stage in Monterey Bay	1973 to Present	Hourly	NOAA gage at Monterey (Gage ID: 9413450)

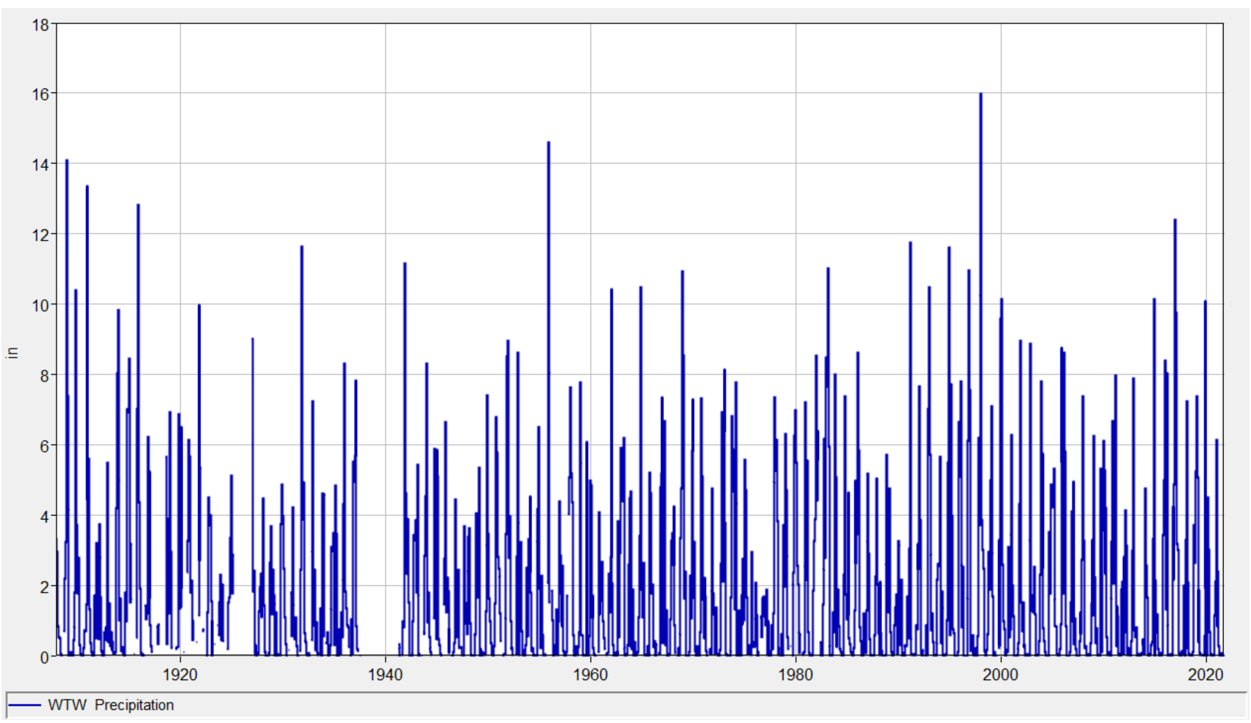


Figure 4: Monthly precipitation depths from 1908 to 2021 at the rain gage at Watsonville Waterworks.

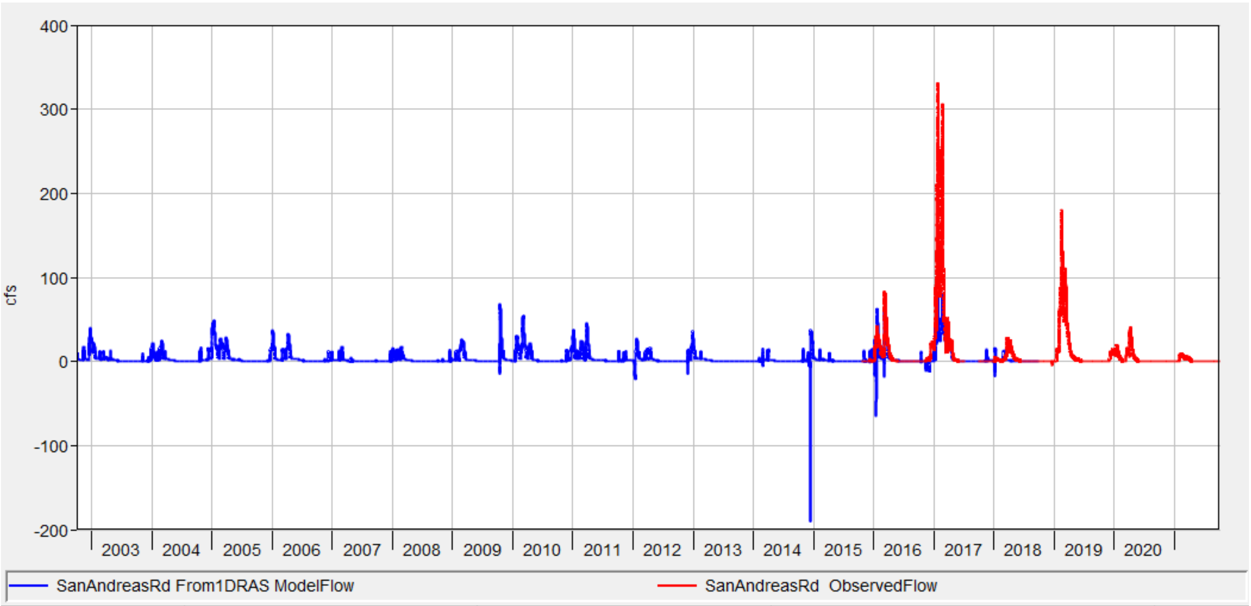


Figure 5: Observed (red) and modeled (blue) streamflow data record in Watsonville Slough at San Andreas Road. Note, negative flow values in the modeled record indicate flow in the upstream direction, due to tidal conditions.

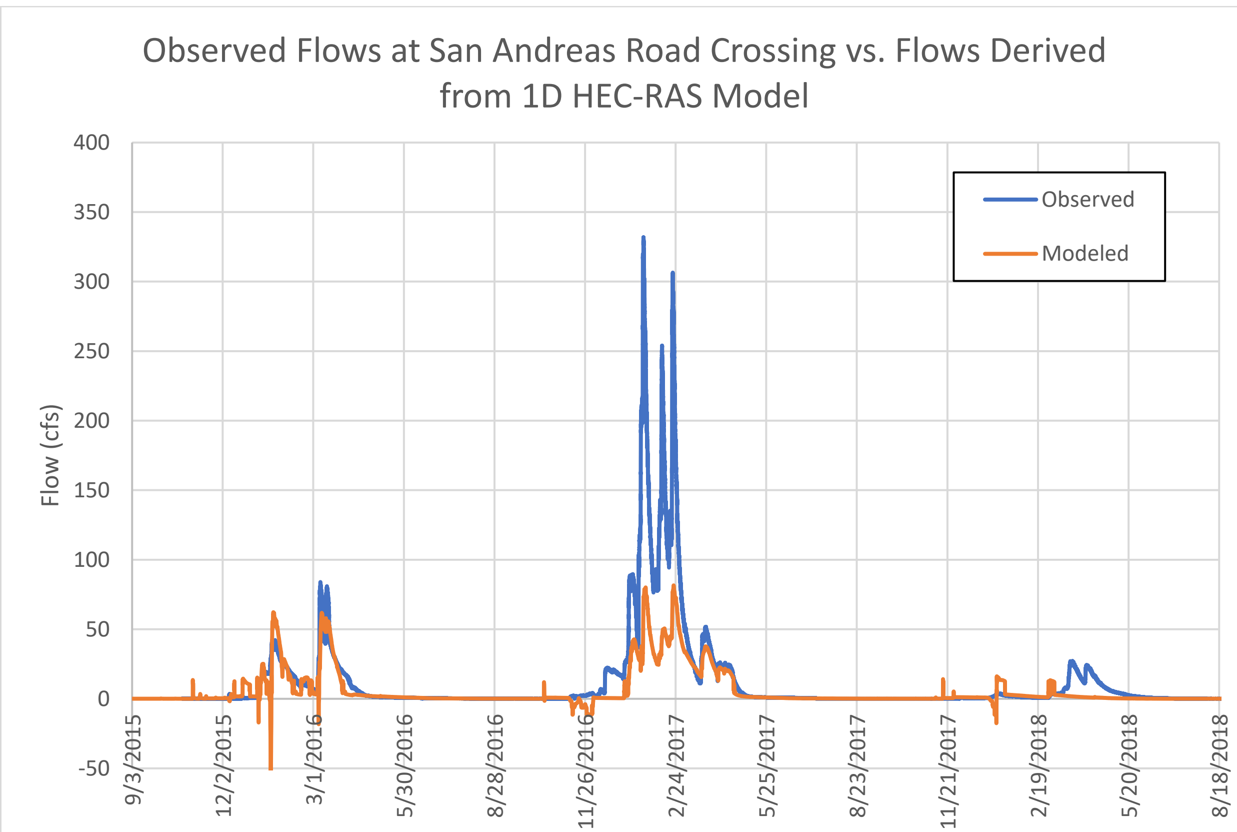


Figure 6: Period of overlap in the modeled and observed streamflow records in Watsonville Slough.

2.1.2. Determining the Dry Season/Wet Season Demarcation

Because the Watsonville CAP study will model both a wet season flow condition and a dry season flow condition, the demarcation between wet and dry in the hydrologic system needed to be defined. To do so, a box and whisker plot of the long-term monthly precipitation record was generated (Figure 7). Upon inspection of the box and whisker plot, the Dry Season was defined as the months of May through September, and the Wet Season as the months of October through April.

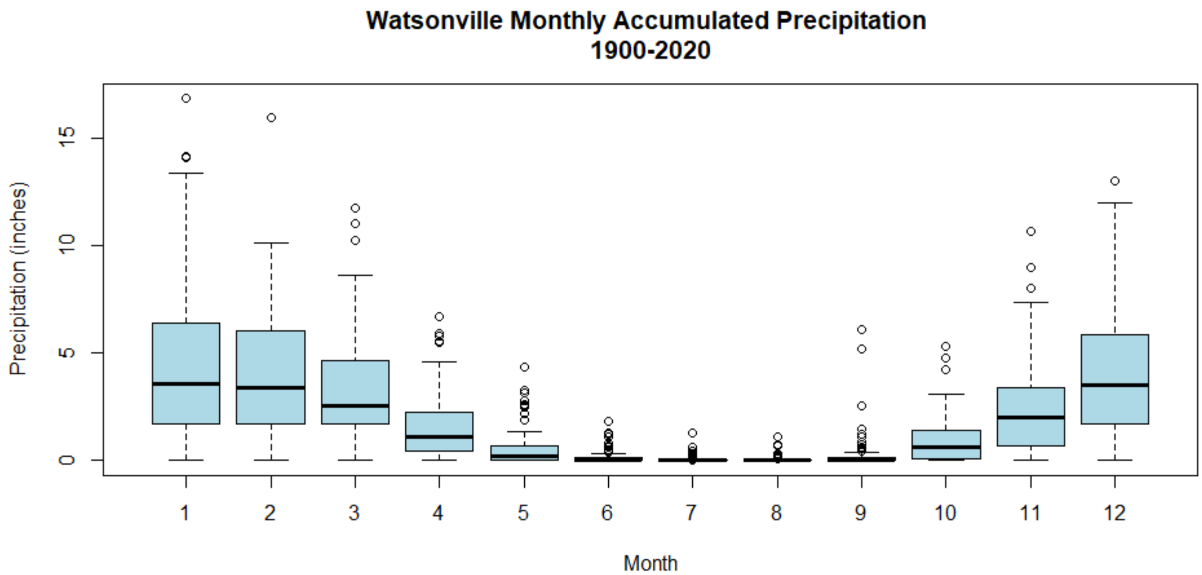


Figure 7: Box and whisker plot of monthly precipitation depths at Watsonville Waterworks rain gage.

2.1.3. Converting Monthly Precipitation to Monthly Accumulated Flow Volume

Converting the monthly precipitation depths (inches) into monthly accumulated flow volumes (acre-feet) is an important step in the hydrologic analysis because it allows us to synthetically extend the flow record from 6 years to 112 years. We recognize that converting from precipitation to flow at the monthly timestep is highly imprecise, and oversimplifies the hydrologic processes occurring in the watershed. However, there are several reasons the lack of precision of this approach is deemed acceptable:

1) This is an ecosystem restoration project, so the primary concern is to select a "typical" wet period and dry period for quantifying ecosystem benefits.
2) Monthly precipitation data is the only data in our project area with a relatively long period of record.
3) The synthetic flow volume record derived from precipitation is just one of several lines of analysis used to characterize the hydrologic behavior of the project area.
4) As will be described in the tide analysis in Section 2.2, under typical flow conditions and an open lagoon mouth, inundation of the marshplain is determined primarily by tidal forcing. While streamflow does have an effect on water levels in the system, that effect is seen predominantly in the low range of the tidal cycle, as a washing out of the tidal signal (Balance Hydrologics, 2014). In the high range of the tidal cycle, streamflow

inputs from Watsonville Slough and backwatering effects caused by streamflow in the Pajaro River result in only marginal increases to water levels (less than +0.2 feet during typical flow conditions) and the tide stage drives the water level in the project area. And it is only during the high range of the tidal cycle that water levels are high enough to escape the slough channel and inundate the marshplain. Sensitivity analyses were performed with the hydraulic model to evaluate multiple different wet season streamflow hydrographs to confirm this understanding. The results of this sensitivity analysis are discussed in greater detail in Section 2.1.4.

The process of converting from monthly precipitation to monthly accumulated flow volume involves the following steps, each of which is described in greater detail in the following subsections:

i. Aggregate instantaneous flow values into monthly accumulated flow volumes.
ii. Develop regression equations to relate monthly precipitation depths to the corresponding monthly flow volumes.
iii. Develop wet season and dry season duration curves for monthly precipitation record and apply regression equations to convert into synthetic monthly flow volume duration curves.

2.1.3.1. Aggregate Instantaneous Streamflow Values into Monthly Accumulated Flow Volume

The “Accumulation over Period” function in HEC-DSSVue was used to calculate monthly accumulated flow volumes from the instantaneous flow records for the observed flow record. Figure 8 shows the instantaneous flow values, the monthly aggregated flow volumes, and the corresponding precipitation depths for the period of flow record.

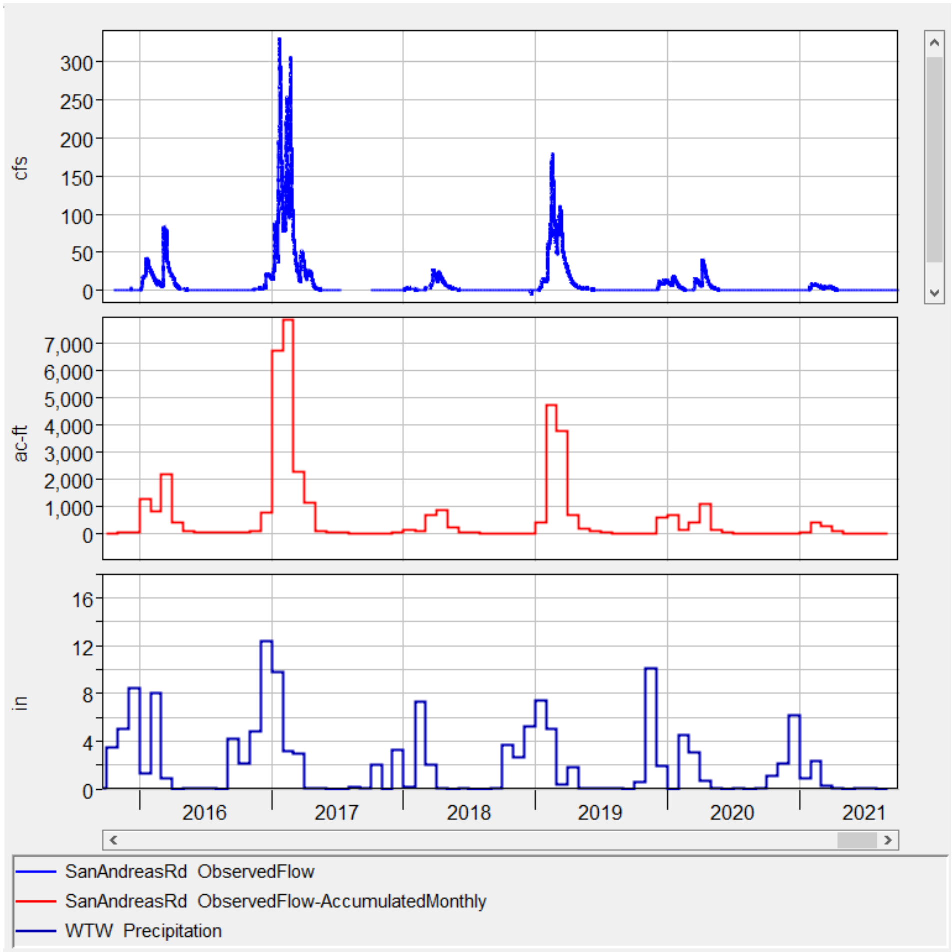


Figure 8: 15-minute flow values (blue) and monthly accumulated flow volumes (red) for the observed flow record from the PV Water gage located at San Andreas Road, compared to monthly precipitation (navy) at Watsonville Waterworks rain gage.

2.1.3.2. Developing Regression Equations

The simplifying assumption that there is a linear relationship between monthly precipitation totals and monthly accumulated flow volume was used. Regression equations were developed to convert between the two. Lending support to this assumption is a finding from the Watsonville Sloughs Hydrology Report. According to their HEC-HMS model, annual runoff rates, as a function of rainfall, fit very well to linear curves (Balance Hydrologics, 2014).

In the current analysis, regression equations were developed for the wet season and dry season separately, in recognition of the fact that the watershed is likely to respond differently to rainfall in each season (e.g., due to factors like antecedent soil moisture and evapotranspiration).

There were several decisions to consider in the derivation of these regression equations:

1) Should the linear regressions use a y-intercept?
2) Should outliers be removed from the selected flow record to improve goodness of fit?

With respect to the y-intercept question, it was decided that the nature of this analysis already involves some gross oversimplifications of hydrologic processes, and to estimate a y-intercept is to falsely introduce additional precision (and falsely suggest an additional level of accuracy) that doesn't exist in the approach.

With respect to the question of treatment of outliers, the sensitivity of the regression equations to outliers was evaluated by removing apparent outliers and calculating changes to the regression slopes and root mean square errors (RMSEs). Outliers were defined as having a square error that exceeded the mean of the square errors plus three standard deviations, where the square error equals the square of the observed flow volume minus the regression-predicted flow volume. Using this definition, there was one outlier in the Dry Season data set (i.e., May 2018, observed flow = 201.63 ac-ft, observed precipitation = 0.04 inches) and one outlier in the Wet Season data set (i.e., February 2017, observed flow = 7,868.5 ac-ft, observed precipitation = 9.76 inches).

The results of the sensitivity analysis are provided in Table 5. In the case of the Dry Season regression equation, the removal of the outlier did not change the slope significantly. However, in the case of the wet season, removing the extremely wet month of February 2017 reduced the slope of the regression line by 18% and improved the RMSE by 18%. Despite that reduction, the RMSE for the wet season regression is still quite high. This is a product of the reductiveness and simplicity of the monthly flow aggregation approach. Translating precipitation to runoff is an inexact science, even with vast amounts of data and at the hourly timestep, let alone with a short data record at the monthly timestep. There are some months in the record with zero precipitation and nonzero flow, and vice versa, and these contribute to the high RMSEs. Nevertheless, for the reasons that were laid out at the start of Section 2.1.3, the lack of precision in this approach is deemed acceptable for the purposes of this ecosystem restoration project.

Table 2: Regression equations and goodness of fit with and without apparent outliers.

	n	Slope	R-squared	RMSE (ac-ft)
Dry Season	26	112.56	0.441	49.2
Dry Season, Remove Outliers	25	110.55	0.664	31.0
Wet Season	38	325.76	0.564	1363.2
Wet Season, Remove Outliers	37	266.06	0.542	1113.8

Based on the above considerations, the linear regression equations with no y-intercepts and with apparent outliers removed were selected. The resulting set of regression equations that form the basis for the flow volume duration curves in the next section are summarized in Table 6. The scatterplots with regression equations are presented in Figures 9 and 10.

Table 3: Summary of precipitation to flow volume linear regression equations.

	Multiplier to convert from monthly precipitation to monthly accumulated flow volume
Dry Season	110.55
Wet Season	266.06

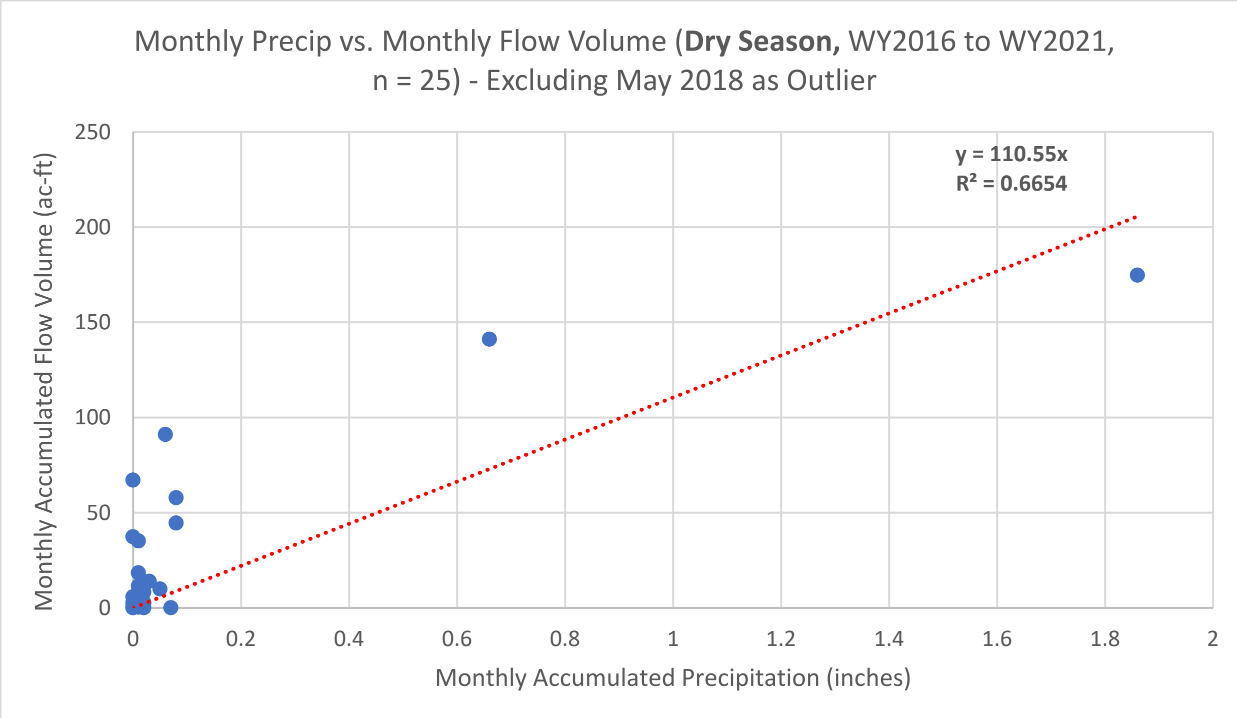


Figure 9: Scatterplot and linear regression for Dry Season.

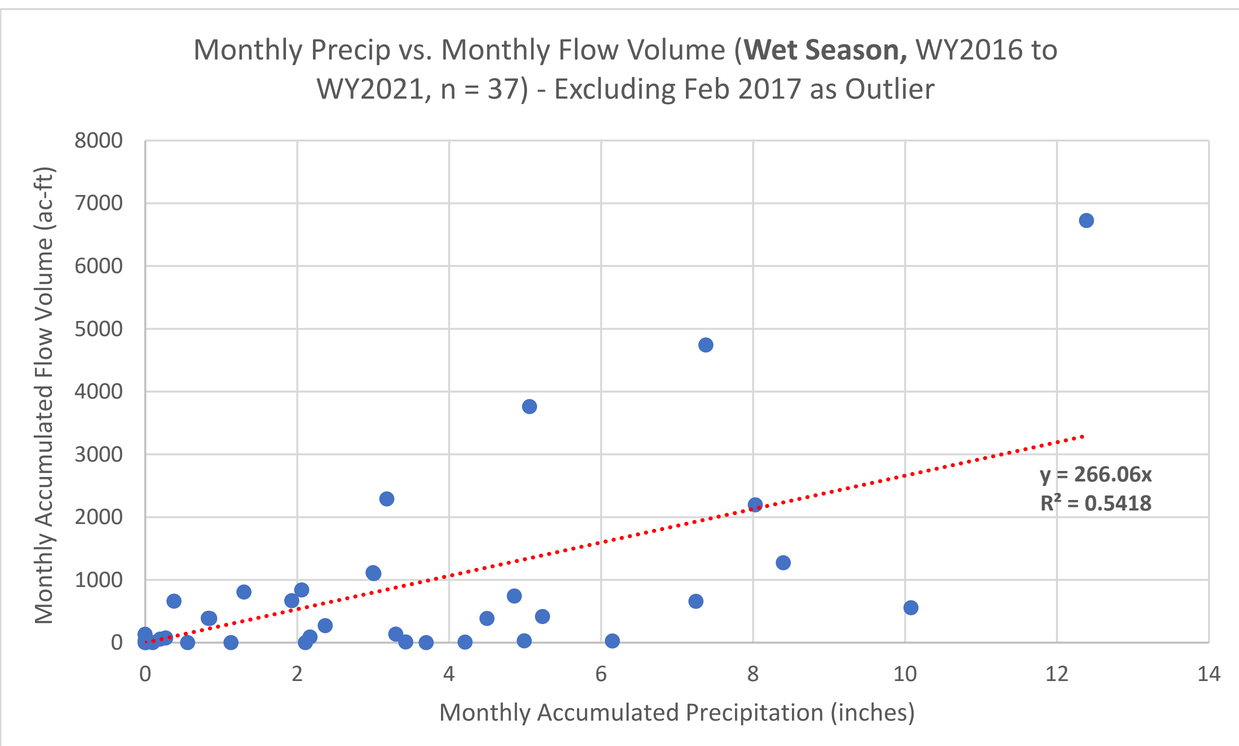


Figure 10: Scatterplot and linear regression for Wet Season.

2.1.3.3. Generate Synthetic Monthly Flow Volume Duration Curves

Duration curves for monthly accumulated flow volume in Watsonville Slough at San Andreas Road for two different data sets in both the dry season and the wet season were generated. The two different data sources for the duration curves are as follows:

1) Observed record of monthly flow volumes
2) Precipitation-derived flow volumes – based on linear regression with the flow record

For curve (1), the duration analysis was done in HEC-SSP on the monthly accumulated flow volume time series. For curve (2), a duration analysis was performed on the full monthly precipitation time series (1908 to 2021) and then the multipliers from the linear regression analysis were applied to those precipitation duration curves.

The results of the monthly precipitation duration analysis are provided in Figure 11 and Table 7. The duration curves for monthly flow volume are presented in Figure 12 and Table 8 for the dry season, and Figure 13 and Table 9 for the wet season.

Note, the curves for the precipitation-derived flow volumes diverge from the observed flow volumes at the lower percent time exceeded values. This is a result of the limited number of data points available for the observed record. Namely, with so few data points, the highest flow volumes in the record have an outsized effect on the skew of the duration curve. Also, the duration curves for the observed flow record flatten out between 0 and 2 percent of time exceeded. This is because the denominator in the duration curve calculations is n = 25 in the dry season and n = 37 in the wet season, and any resolution greater than 1/n is impossible.

These discrepancies between the curves at the low frequency flow volumes are not a major concern in the context of this analysis because the ecosystem restoration modeling approach is focused on typical (i.e., not low frequency) conditions. The low frequency flow events that have the potential to cause the most flooding are considered in Section 4 of this MFR.

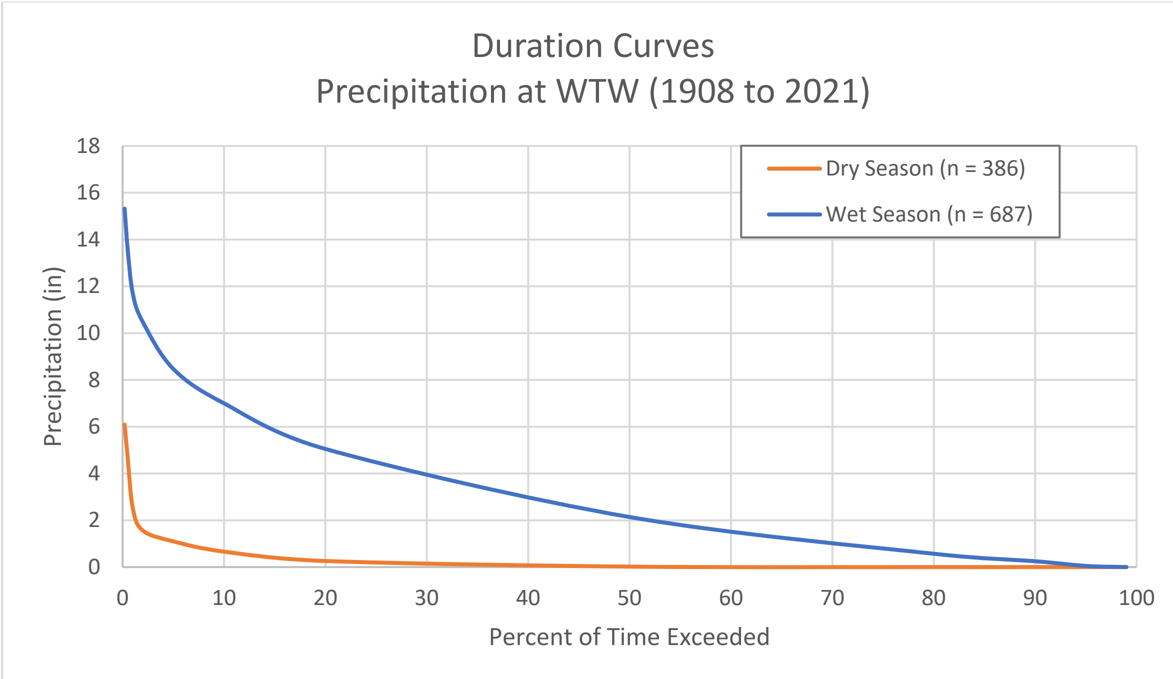


Figure 11: HEC-SSP duration analysis for monthly precipitation depths for dry season and wet season.

Table 4: Tabular results of HEC-SSP duration analysis for precipitation data.

Monthly Accumulated Precipitation (inches)		
Percent of Time Exceeded (1908 to 2021)	**Dry Season (May – Sep)**	**Wet Season (Oct – Apr)**
99	0	0
95	0	0.05
90	0	0.25
80	0	0.57
50	0.02	2.14
20	0.26	5.05
10	0.66	7
5	1.1	8.47
2	1.56	10.47
1	2.53	11.7
0.5	4.69	13.58
0.2	6.09	15.32

Dry Season Duration Curves

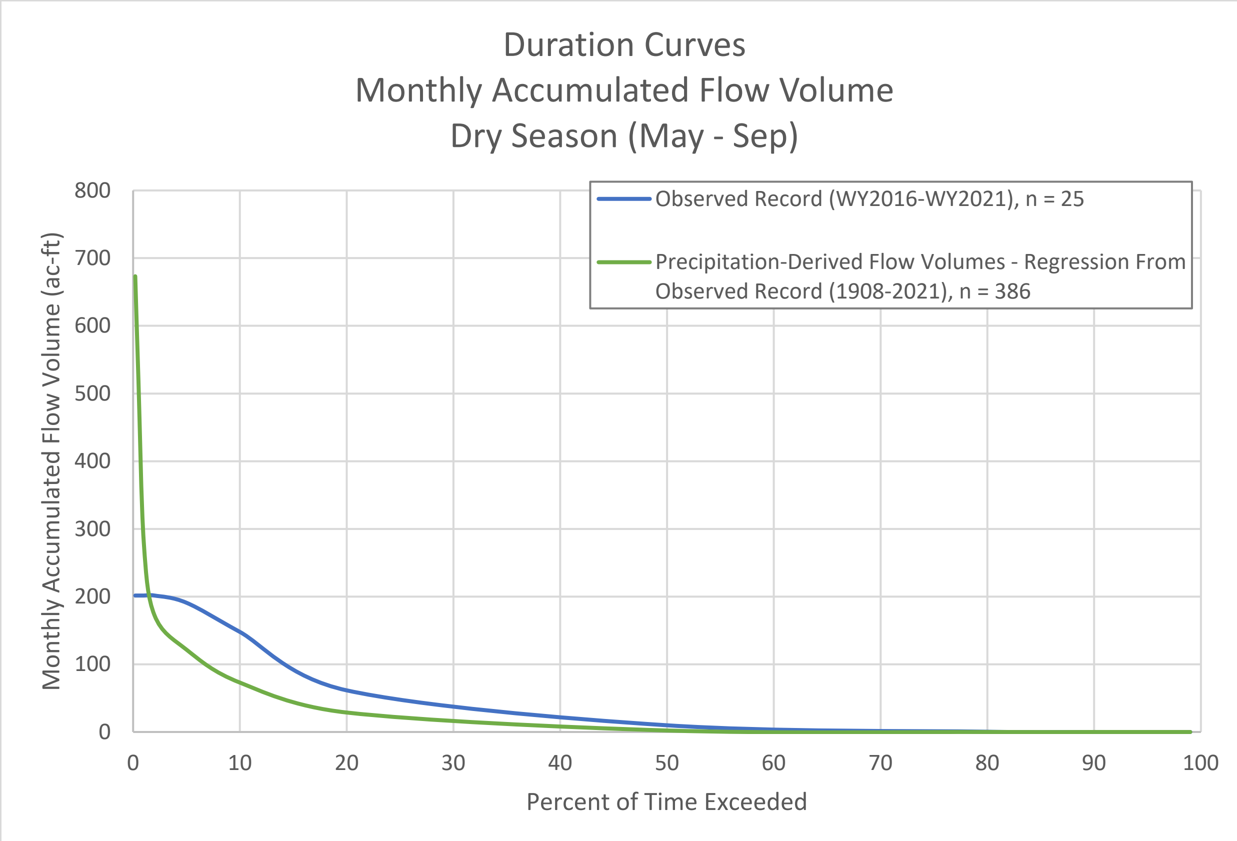


Figure 12: Duration curves for monthly accumulated flow volume in Watsonville Slough during the dry season.

Table 5: Tabular data for the two dry season monthly flow volume duration curves.

Monthly Accumulated Flow Volume (acre-feet) – Dry Season		
Percent of Time Exceeded	**Observed Flow Record, n = 25**	**Derived from Precip-to-Flow Regression, n = 386**
99	0.0	0.0
95	0.0	0.0
90	0.0	0.0
80	0.4	0.0
50	9.9	2.2
20	62	29
10	148	73
5	191	122
2	-	172
1	-	280
0.5	-	518
0.2	-	673

Wet Season Duration Curves

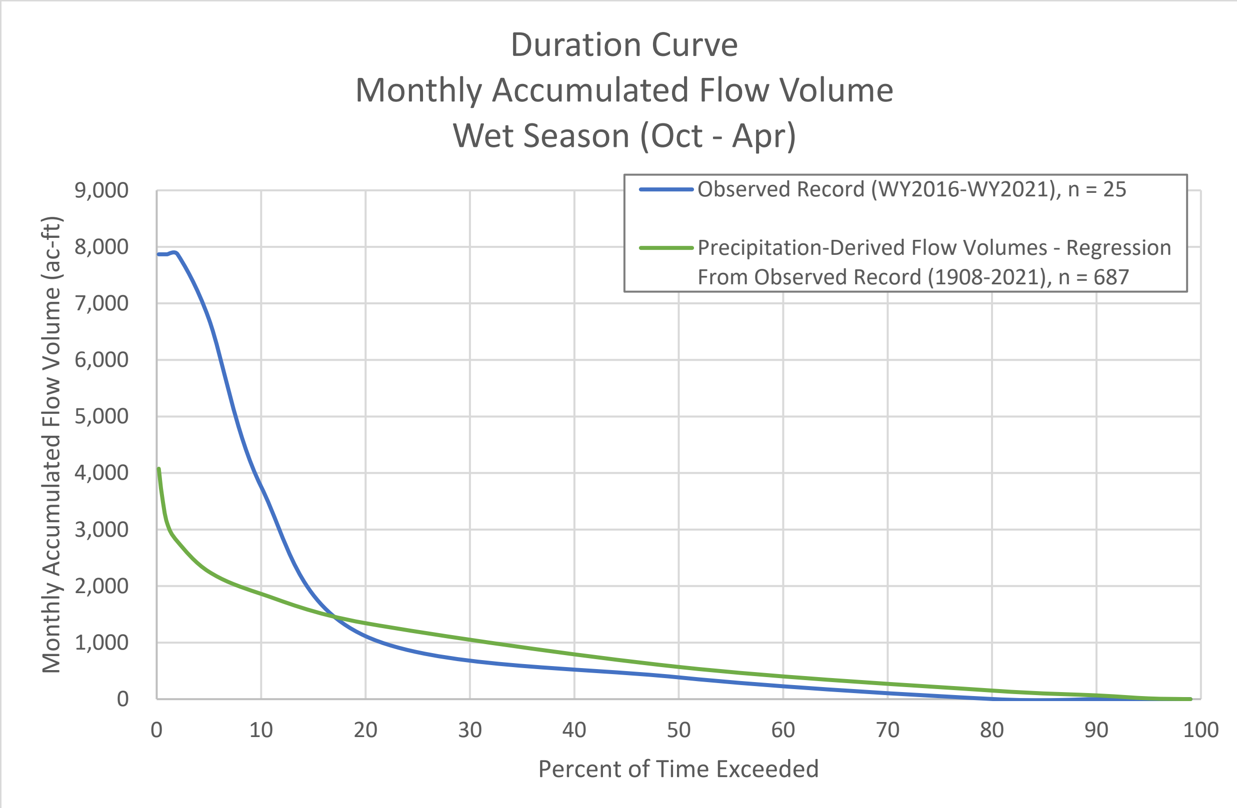


Figure 13: Duration curves for monthly accumulated flow volume in Watsonville Slough during the wet season.

Table 6: Tabular data for the two wet season monthly flow volume duration curves.

Monthly Accumulated Flow Volume (acre-feet) – Wet Season		
Percent of Time Exceeded	**Observed Flow Record, n = 37**	**Derived from Precip-to-Flow Regression, n = 687**
99	0.0	0.0
95	0.0	13.3
90	0.0	66.5
80	2.4	152
50	385	569
20	1,114	1,344
10	3,759	1,862
5	6,723	2,254
2	-	2,786
1	-	3,113
0.5	-	3,613
0.2	-	4,076

2.1.4. Selecting Representative Flow Months

The goal of the analysis was to select the hydrologic conditions that capture the range and variability of inundation that can occur over the course of a typical year. In the context of this hydrologic assessment, it was decided to define “typical” as the 50th percentile (median) flow volume from the precipitation-based duration analyses. For the dry season, the median flow volume based on the long-term precipitation record is approximately 2.2 acre-feet. For the wet season, the median flow volume is approximately 569 acre-feet.

To ensure that the flow hydrographs selected as the hydrologic boundary conditions have realistic temporal patterns, the representative months are selected from the observed flow record. I.e., a dry season month with an accumulated flow volume close to 2.2 acre-feet and a wet season month with an accumulated flow volume close to 569 acre-feet were selected from the observed flow record.

Another constraint for selecting representative months was to select from the time period during which there is a flow record on the Pajaro River at Watsonville (USGS Gage ID: 11159500). Streamflow data at this gage is only available after February 2019. Note, there is a longer-term flow record at a USGS gage upstream of Watsonville at Chittenden, however there are complex patterns of flow loss and gain that occur in the Pajaro River between these two gages, making the flow record at the Chittenden gage suboptimal for our modeling purposes.

The month that best satisfies these criteria for the wet season is January 2020, which has an accumulated flow volume of 667.5 acre-feet.

The month that best satisfies these criteria for the dry season is July 2020, which has an accumulated flow volume of 2.69 acre-feet.

2.1.4.1. Pajaro River Flow Considerations

While the selection of representative flow months was based primarily on the flows in Watsonville Slough, the flows in the Pajaro River were also taken into consideration. In the open lagoon state, flows in the Pajaro River indeed have an influence on water levels in the project area. As described in the Watsonville Sloughs Hydrology Study (Balance Hydrologics, 2014), water levels in Watsonville Slough, as measured at a gage just downstream of Shell Road, are affected by flows on the order of 100 cfs and greater in the Pajaro River. These effects are seen in the water level record as a “washing out” of the tidal fluctuations during the low range of the tidal cycle. However, for the purposes of quantifying ecosystem benefits via changes in marshplain hydroperiod, we are primarily concerned with capturing increases in water surface elevations (WSEs) due to streamflow inputs at the *high* range of the tidal cycle, as water levels must exceed ~6 feet NAVD88 (note, MHHW = 5.48 feet NAVD88) to spread onto the marshplain. The increases in WSE at the high tidal range are more sensitive to the upstream boundary condition of flows in Watsonville Slough than to the downstream backwatering effects from flows in the Pajaro River. That is why the flow analysis in this MFR focused on characterizing typical streamflow in Watsonville Slough.

Nevertheless, because flows in the Pajaro River are a hydrologic boundary condition for the project area, and indeed have an influence on water levels, a duration analysis was performed for the long-term (WY1939 to WY2022) daily flow record at the Pajaro River gage at Chittenden (USGS Gage ID: 11159000). Figure 14 presents the annual flow duration curve. The threshold of 100 cfs identified in the Watsonville Sloughs Hydrology Study corresponds to an 85th percentile flow magnitude.

The peak flow in the Pajaro River during the period selected as the typical wet season boundary condition (i.e., January 2020) is 213 cfs, which exceeds that 100 cfs threshold. Thus, the month selected as representative of the wet season indeed captures the hydraulic influence of high flows in the Pajaro River on water levels in the project area.

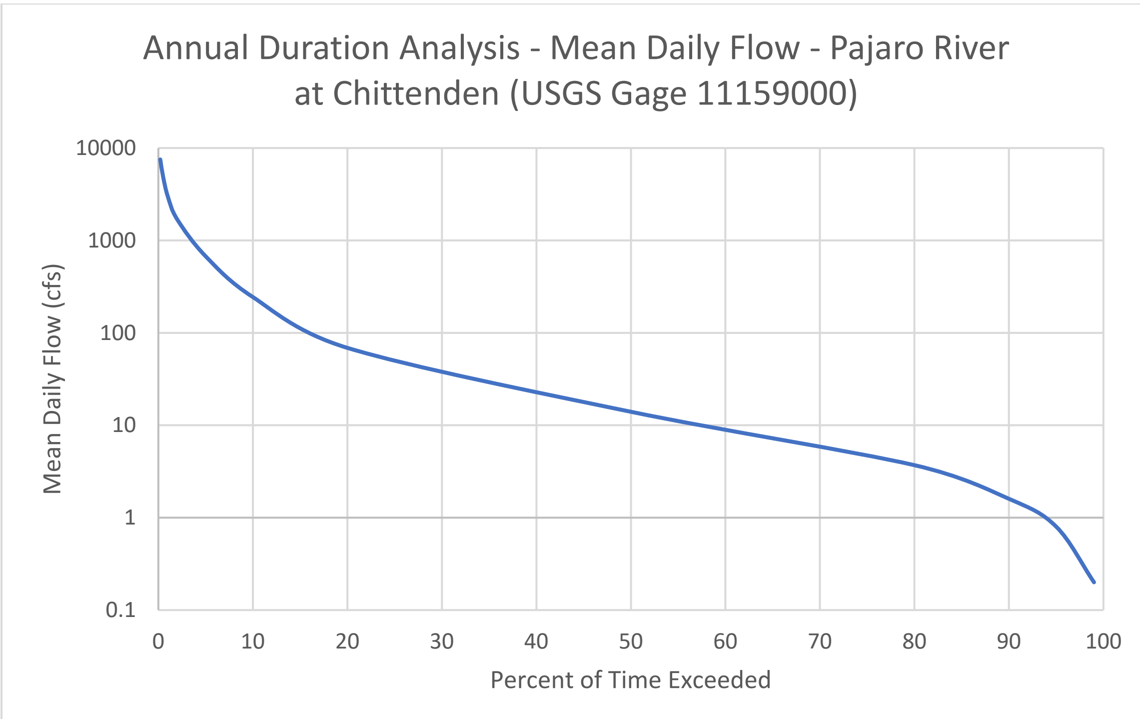


Figure 14: Duration curve for mean daily flow in Pajaro River at Chittenden.

2.1.4.2. Flow Magnitude and Hydrograph Shape Considerations

A final consideration is that of the peak flow magnitude and the shape of the streamflow hydrographs. While the primary criteria for selecting boundary conditions was total flow volume in the system, the temporal distribution of that streamflow volume, and the timing of the peak flow with respect to the king tides is also relevant. (Note, this concern only applies to the wet season, as the dry season hydrographs are effectively uniform, with magnitudes generally less than 1 cfs.)

The peak flow in Watsonville Slough during January 2020 is 18.37 cfs. According to the flow duration curve for the observed flows from WY2016 to WY2021 (Figure 15), that corresponds to a 75th percentile wet season flow, which is considered appropriate for the hydroperiod quantification approach.

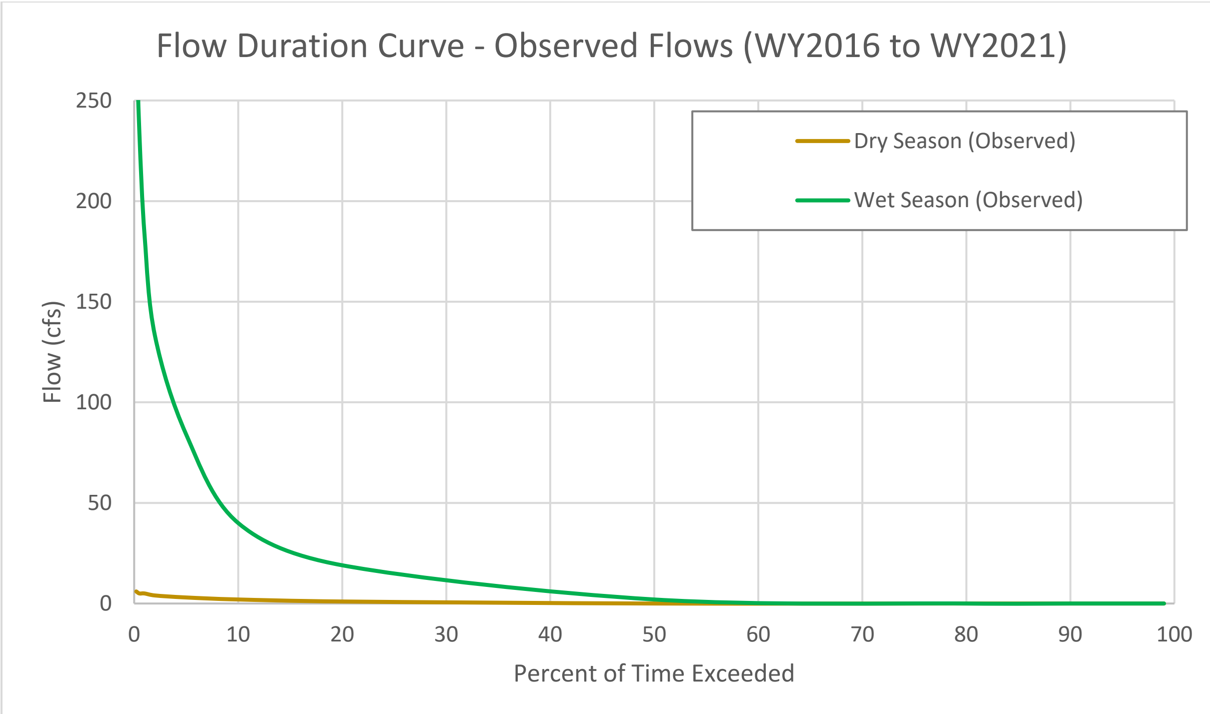


Figure 15: Flow duration curve for observed flows in Watsonville Slough from WY2016 to WY2021.

To evaluate the effect of different timings and magnitudes of peak flow with respect to king tides, sensitivity analyses were performed with the hydraulic model. Three different variations of the January 2020 flow hydrographs (i.e., both Watsonville Slough and Pajaro River flow hydrographs) were combined with the same tide hydrograph, and model results for water surface elevations (WSEs) and marshplain hydroperiods were compared. The three hydrograph variations were: (1) unaltered January 2020 hydrograph; (2) January 2020 hydrograph with a 2x multiplier; (3) January 2020 hydrograph with a temporal shift so that the peak flow coincided with the lowest portion of the monthly tide cycle, rather than the highest. The results of the sensitivity model runs showed that doubling the magnitude of the hydrograph increased peak WSEs in the project area by less than 0.1 feet. Shifting the hydrograph temporally resulted in increases in WSE of up to 0.4 feet during the ebb tides in the lowest portion of the tide cycle, and decreases in peak WSEs during the highest portion of the tide cycle. Ultimately, neither alteration of the January 2020 hydrograph produced significant changes to marshplain hydroperiod, thereby supporting the conclusion that marshplain inundation is more dependent on high tides than on streamflow inputs.

2.2. Tidal Analysis

2.2.1. Available Data

The tide data used in this analysis is from the NOAA tide gage at Monterey, CA – Station ID: 9413450. Verified hourly water levels are available from 1973 to present.

2.2.2. Characterizing Seasonal and Interannual Variability of Tides

Box and whisker plots were compiled for multiple measures of the tide cycle for the full period of record at the Monterey tide gage to determine the typical season variation. Figure 16 shows distribution of the monthly average of daily high TWL and Figure 17 shows the monthly maximum water level. From these plots, it is apparent that the king tides occur in the December/January timeframe, with a secondary peak occurring in the July timeframe.

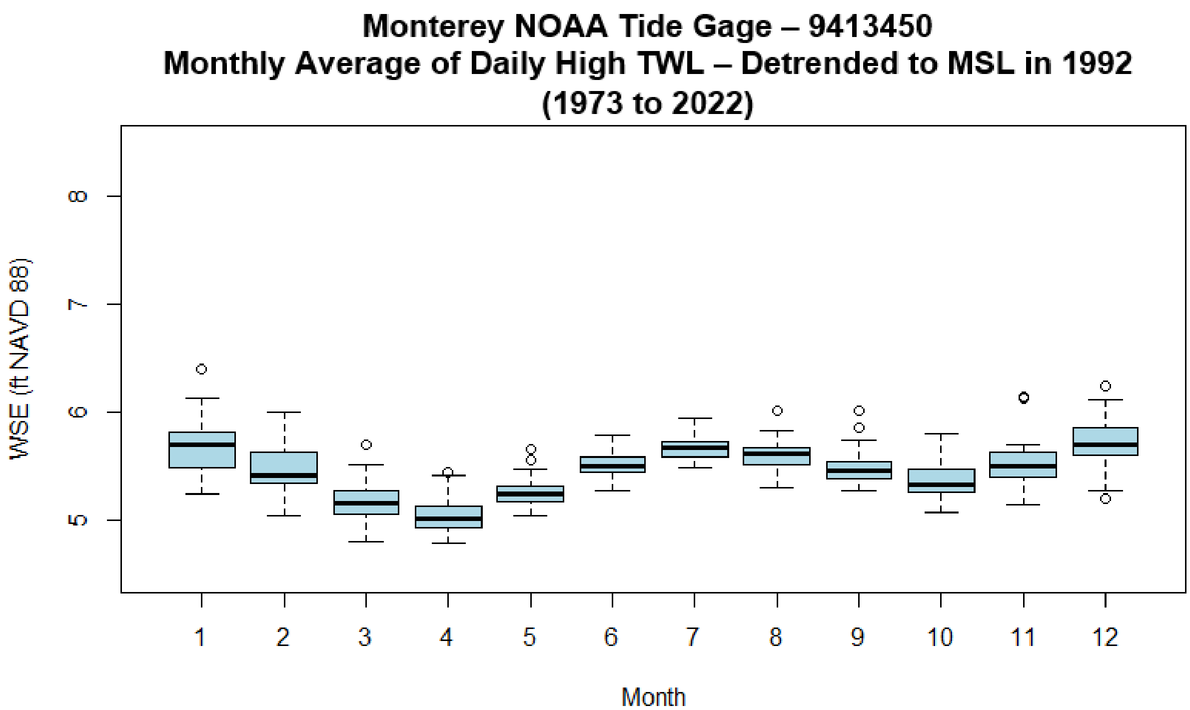


Figure 16: Distribution of Monthly Average Daily High TWL (detrended to MSL in 1992) from 1973 to present at Monterey tide gage.

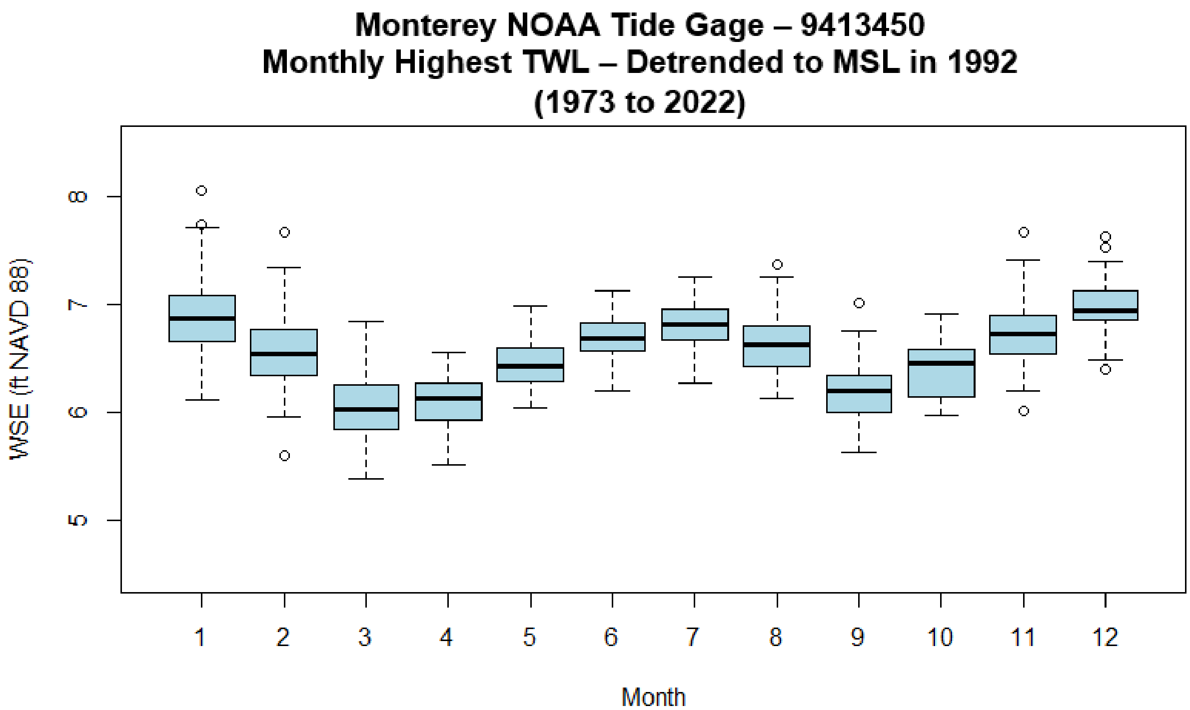


Figure 17: Distribution of Monthly Highest TWL (detrended to MSL in 1992) from 1973 to present at Monterey tide gage.

Interannual variability at the Monterey gage was also considered, which is more or less a measure of ENSO effects. Figure 18 shows the interannual variability since 1990.

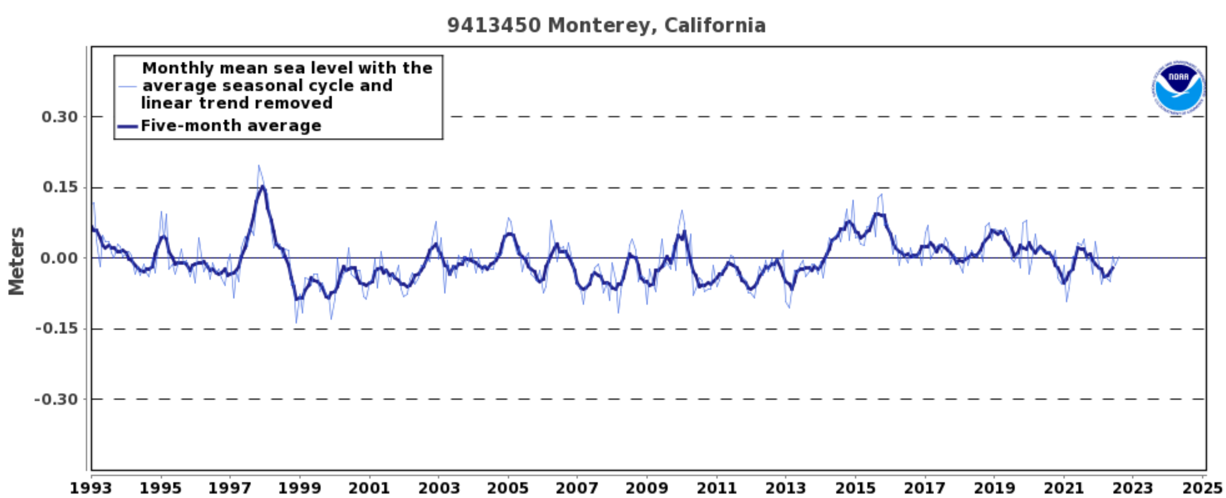


Figure 18: Interannual variability of mean sea level at Monterey tide gage. Figure obtained from NOAA Tides & Currents (https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9413450).

2.2.3. Selecting Representative Total Water Level Hydrographs

There are two characteristics of the project area that should be considered in selecting the appropriate Total Water Level (TWL) hydrographs as downstream boundary conditions. First, water levels in the project area are primarily determined by the tides (i.e., the influence of the tides on hydroperiod in the project area is greater than the influence of streamflow). Second, much of the marshplain that is adjacent to the slough channel is perched several feet above the slough, often at elevations greater than 7 feet NAVD88. This means that if we were to select a TWL hydrograph without sufficiently high water levels, water would rarely, if ever, escape the slough channel and engage the marshplain in the hydraulic model, and that would prevent us from seeing any potential changes to marshplain inundation patterns that may be generated by the proposed project alternatives.

In the case of future conditions modeling, when sea level rise is added to the TWL hydrographs, this issue may be less apparent, as there will be more instances during the simulation periods where the lagoon water level exceeds the ground surface elevation. However, the benefits quantification approach aims to include the potential benefits in the years immediately following implementation, prior to significant sea level rise. Ultimately, the overall alternatives analysis will be more robust if the boundary conditions capture a wider range of lagoon water levels, and that will be achieved by selecting a representative TWL hydrograph for the wet season that includes high tides on the order of 7 feet NAVD88. As can be seen in Figure 19, such tide levels are not exceedingly rare.

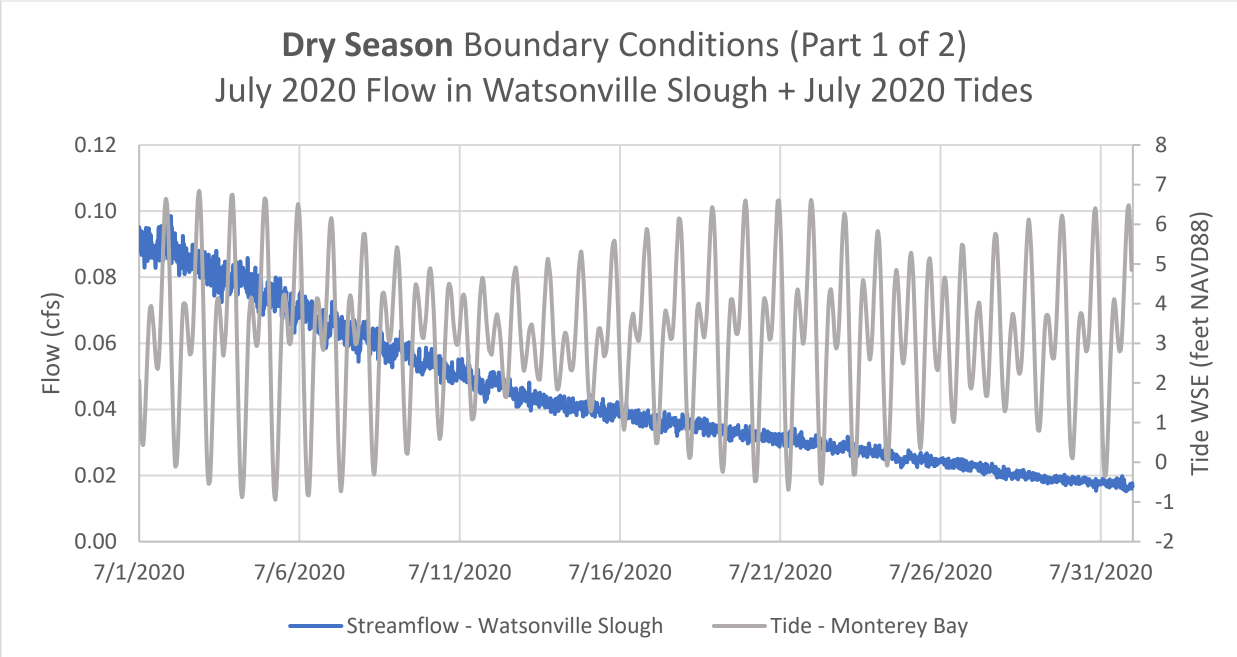
To select a representative wet season TWL hydrograph based on those criteria, we looked at the historic record at the Monterey gage for the time period that coincided with the streamflow gage record (i.e., WY2016 to WY2021), and identified several candidate months that included multiple peak tides in the vicinity of 7 feet NAVD88. These candidates were January 2018, December 2018, and January 2019. January 2019 was selected because the peak tides during this hydrograph coincide with the peak flows of the selected wet season streamflow hydrograph of January 2020. The interannual variability for January 2019 is +0.2 feet, which contributes to the elevated tide levels occurring during this period.

For the dry season, the selected TWL hydrograph should also include a wide range of high tides, though with maximum water levels closer to the median monthly maximum water level during the months of May to September, which is approximately 6.5 feet NAVD88 (see Figure 17). There are many months in the candidate period of record that meet these criteria. For the sake of simplicity, we select the month that coincides with the selected dry season streamflow hydrograph, which is July 2020. The interannual variability for July 2020 is +0.05 feet.

2.3. Summary of Open Lagoon Boundary Conditions

The Open Lagoon, Dry Season hydrologic boundary conditions consist of the July 2020 observed streamflow hydrograph in Watsonville Slough, the July 2020 observed streamflow hydrograph in the Pajaro River, and the July 2020 observed TWL hydrograph in Monterey Bay (Figure 19).

The Open Lagoon, Wet Season hydrologic boundary conditions consist of the January 2020 observed streamflow hydrograph in Watsonville Slough, the January 2020 observed streamflow hydrograph in the Pajaro River, and the January 2019 observed TWL hydrograph in Monterey Bay (Figure 20).



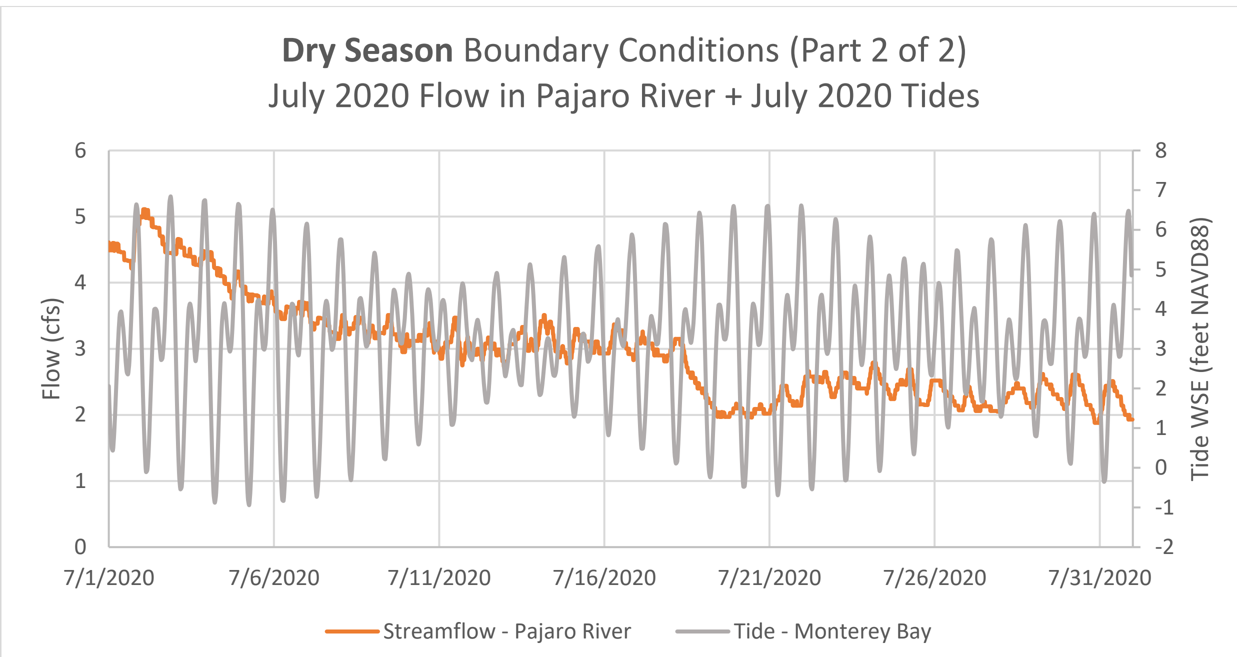
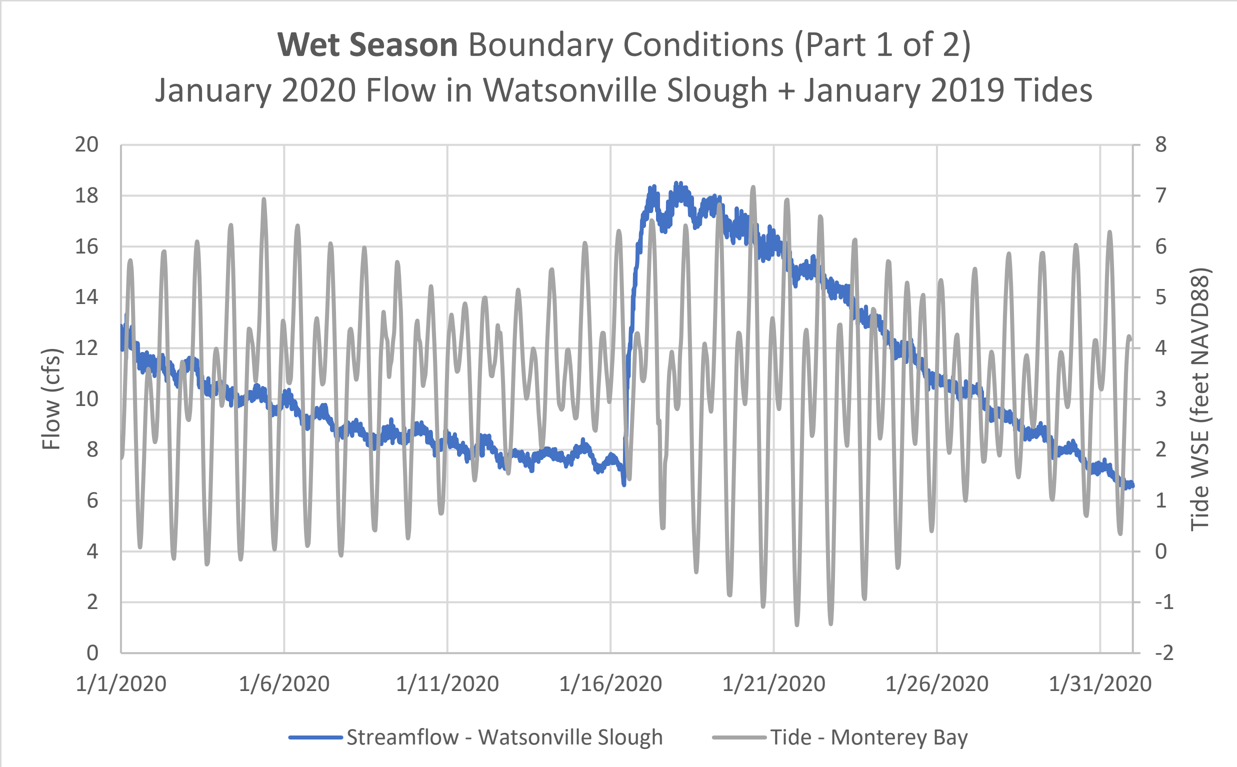


Figure 19: Open lagoon, dry season boundary conditions.



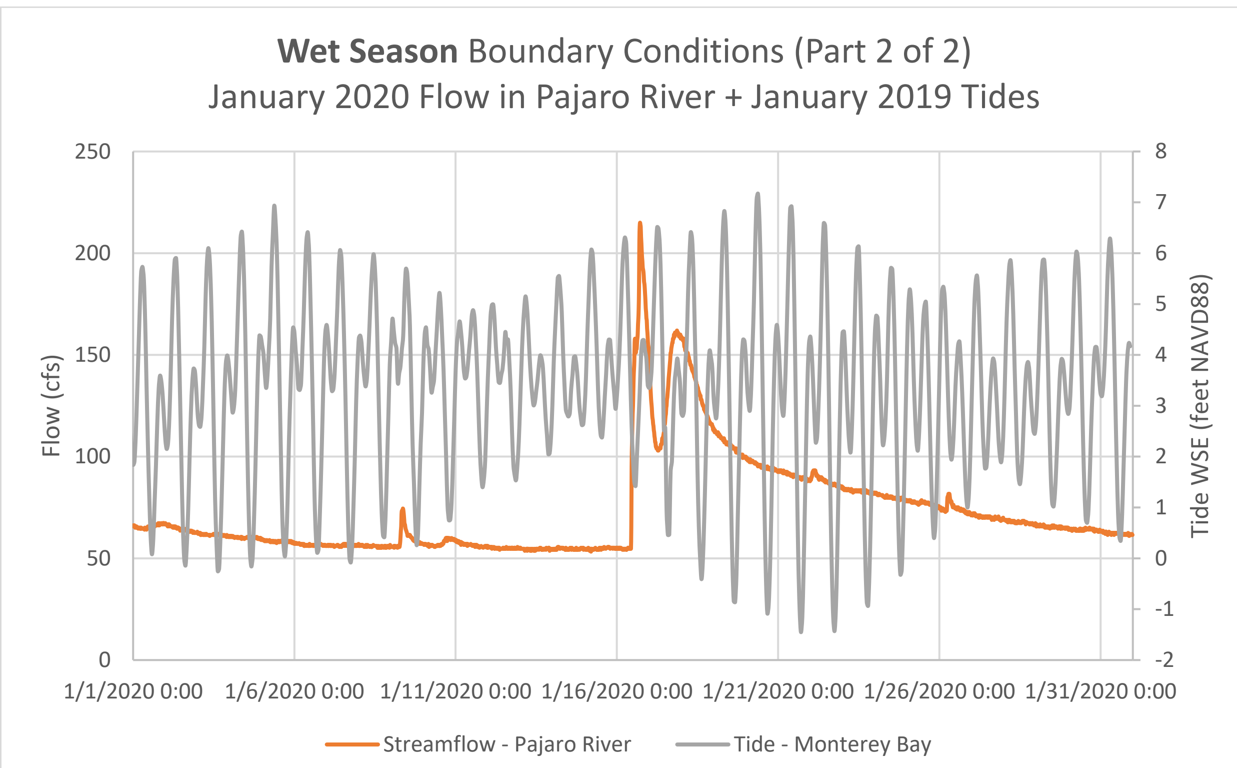


Figure 20: Open lagoon, wet season boundary conditions.

3. CLOSED LAGOON HYDROLOGY

As explained in Section 1, the hydrologic regime in the project area is complicated by the fact that the mouth of the Pajaro Lagoon periodically closes, due to the formation of a barrier beach. The processes involved in dictating whether the lagoon mouth is open or closed are complex and interdependent. This CAP study will employ a parametric lagoon model called Lagoon QCM (Behrens et al., 2015) in order to simulate these interdependent processes in the Pajaro Lagoon system, and thereby estimate how frequently the lagoon will be open or closed as conditions change into the future, with and without project alternatives.

As with the open lagoon condition, the ecosystem benefits quantification approach used in this CAP study requires the selection of a representative set of hydrologic boundary conditions for the closed lagoon condition.

3.1. General Approach and Assumptions

The considerations for selecting a representative simulation event under the Closed Lagoon condition are different than for the Open Lagoon. Special considerations / assumptions / constraints include the following:

- Model a real-world, observed closure event, so that calibration of the hydraulic model is possible.
- Lagoon water level data and a lagoon closure record is only available from 2011 to present.
- There were eight closure events during that time, many of which are unsuitable for modeling purposes. Reasons that a closure event might be unsuitable include:
    - The lagoon temporarily opened and then closed again during the closure period (e.g., due to a coastal storm/wave overwash) – this can't be modeled in HEC-RAS with a continuous simulation.
    - The lagoon was closed for too short (less than 1 month) – HEC-RAS model results would be nonrepresentative of "typical" closure event
    - The lagoon was closed for too long (greater than 3 months) – Too long of model runtimes

3.2. Selecting a Representative Closure Event

The non-federal sponsor's consultant (ESA) has produced a figure that compiles the available record for lagoon water levels, inflows, and ocean total water levels, and indicates thereon the closure events and breaches (Figure 21). This figure and related conversations with lagoon hydrology specialists at ESA informed our selection of closure event to be modeled. The selected event is closure period between approximately November 2017 and January 2018 (identified with the red box in Figure 21).

This closure event is the most suitable for the ecosystem restoration modeling approach for three primary reasons:

1) It captures a wide range of water levels in the lagoon, and therefore demonstrates the inundation patterns on the marshplain under the various project alternatives across the widest range of hydrologic conditions.
2) The state of the lagoon closure is not so dynamic as to preclude continuous simulation in HEC-RAS. I.e., the lagoon closure does not partially breach and then reclose, as is the case in several other candidate closure events.

3) The event is relatively recent, and therefore our HEC-RAS terrain is more accurate than if we selected an older event. The HEC-RAS terrain is based on topobathymetric data from 2018 to 2020. The lagoon hypsometry is variable in time, especially at the lagoon mouth. The hydraulic model results in the closed lagoon condition are sensitive to the lagoon hypsometry, so it was important to use an event that aligned with our model terrain.

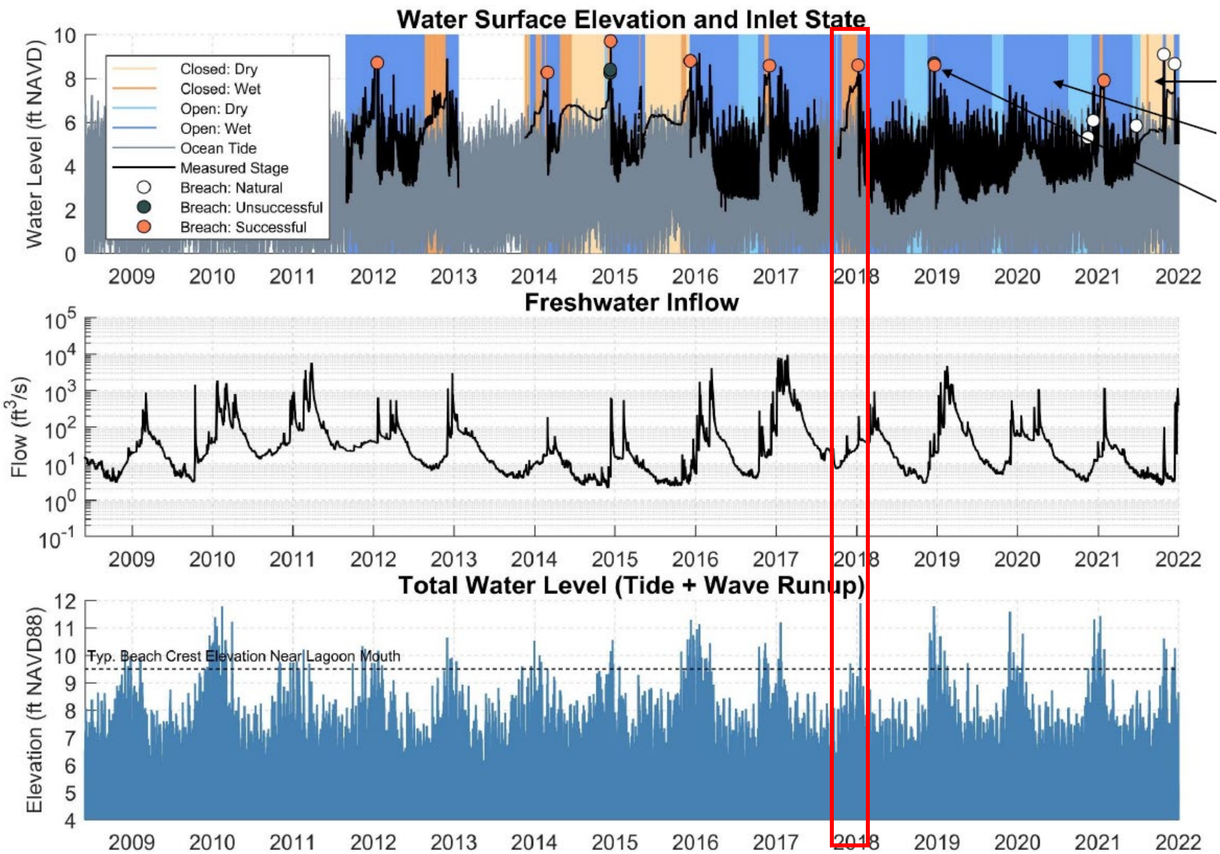


Figure 21: Historical record of water levels in Pajaro Lagoon, freshwater inflow into the lagoon, and total water level in Monterey Bay, with lagoon closure state and breach events indicated. The red box highlights the closure period that was selected for hydraulic modeling for the Watsonville CAP feasibility study. Figure adapted from preliminary results provided by ESA.

4. Extreme Event Hydrology

This project will rely on the FEMA Flood Insurance Study (FIS) for the extreme event streamflow. The information contained in the FIS is considered authoritative. The FIS that covers the project area is Study #06087CV001C, Santa Cruz County and Incorporated Areas, Effective Date: 29 September 2017. The peak discharges published in the FIS for Watsonville Slough and for the Pajaro River are reproduced in Table 10.

The FEMA FIRM is provided in Figure 22. It shows that the entire project area is located in Zone AE, much of it in the Regulatory Floodway, with a base flood elevation between 13 and 15 feet NAVD88. At a water surface elevation of 15 feet, the entire project area is submerged by at least 5 feet of water, and it is expected that there will be no measurable flood impacts due to the proposed project alternatives. Nevertheless, extreme event discharges will be modeled with HEC-RAS to evaluate any potential flood impacts from the proposed alternatives.

Table 7: Peak flows in Watsonville Slough and Pajaro River as published in the Effective FEMA FIS.

Annual Exceedance Probability (AEP)	Peak Discharge in Watsonville Slough, below confluence with Struve Slough (cfs)	Peak Discharge in Pajaro River, downstream of confluence with Salsipuedes Creek (cfs)
10%	1,320	14,250
2%	2,980	32,500
1%	3,910	43,600
0.2%	6,400	76,200

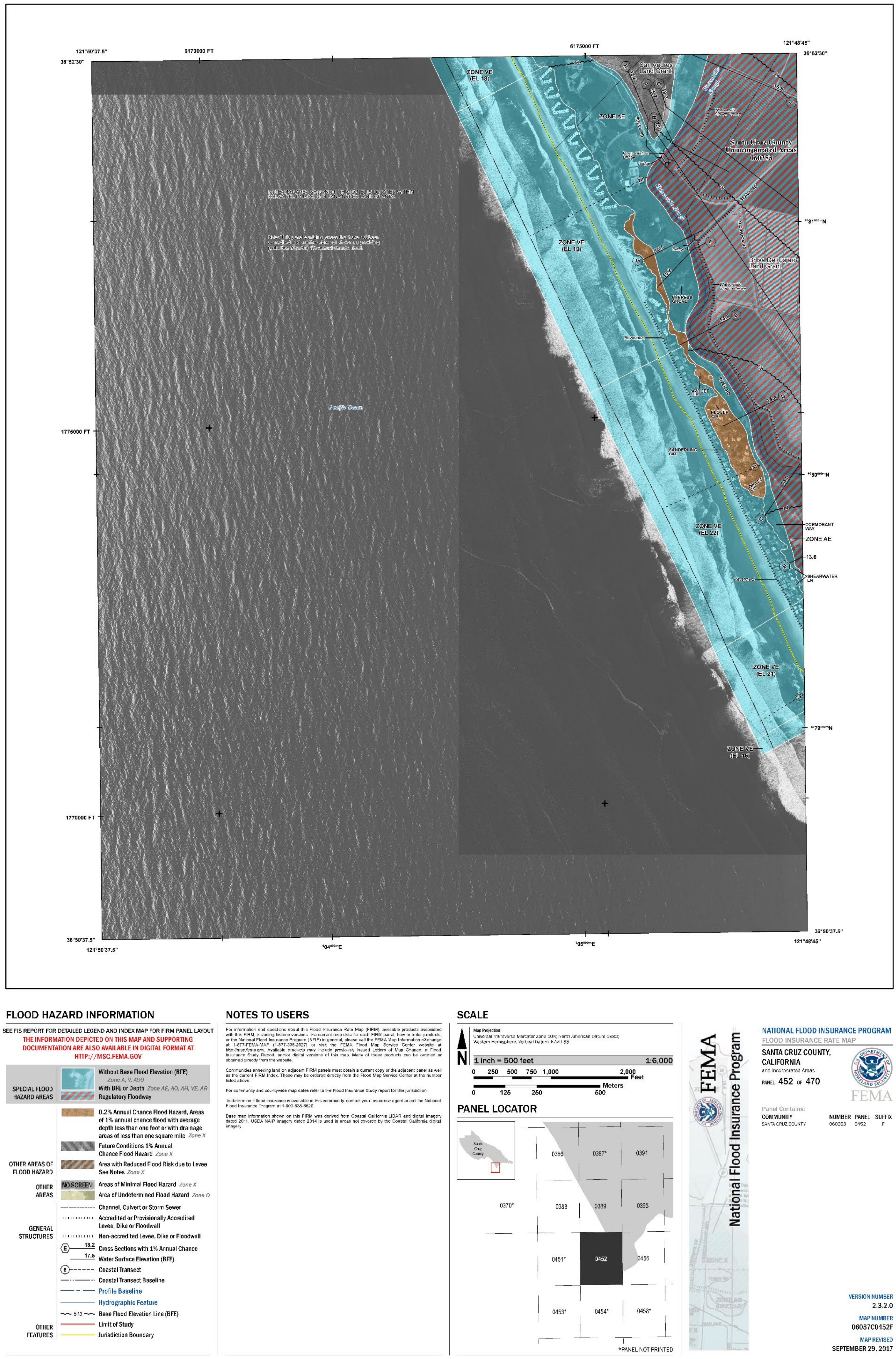


Figure 22: FEMA Flood Insurance Rate Map (FIRM) for project area. Map effective date 29 September 2017

5. References

Balance Hydrologics, Inc. 14 February 2014. Watsonville Sloughs Hydrology Study. Prepared for Santa Cruz Resource Conservation District.

Balance Hydrologics, Inc. August 2022. Watsonville Sloughs Hydrologic Monitoring Summary Report, Santa Cruz County, California, Water Year 2021.

Behrens, D. K., Brennan, M., & Battalio, B. (2015). A quantified conceptual model of inlet morphology and associated lagoon hydrology. *Shore and Beach*, *83*(3), 33-42.

Federal Emergency Management Agency (FEMA). 29 September 2017. Flood Insurance Study, Santa Cruz County, California and Incorporated Areas. Study Number 06087CV001C.

Attachment B. HEC-RAS Results – Percent Time Inundated Raster Maps

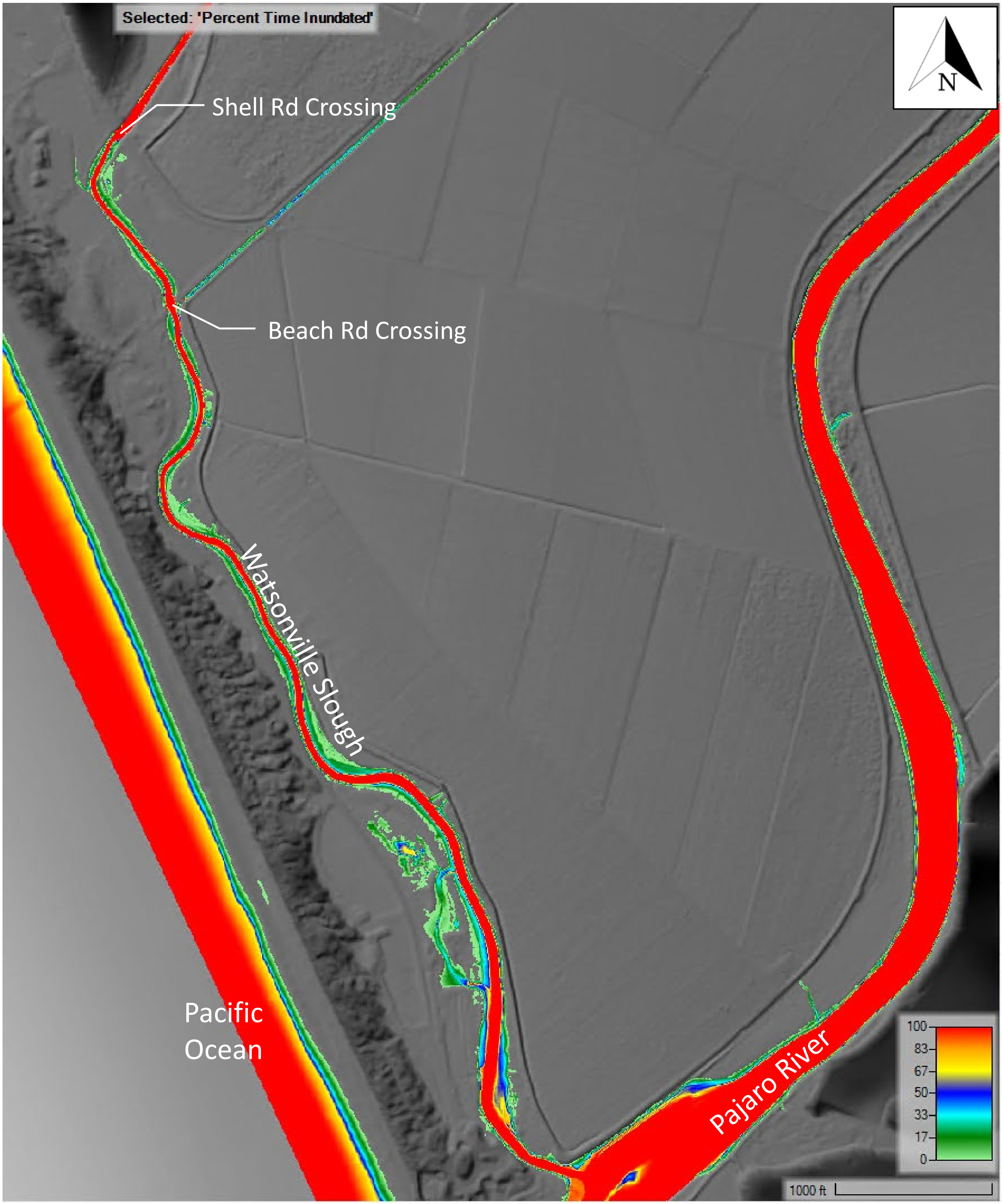


Figure 1: Percent time inundated – No Action; Year 0; Open Lagoon, Dry Season

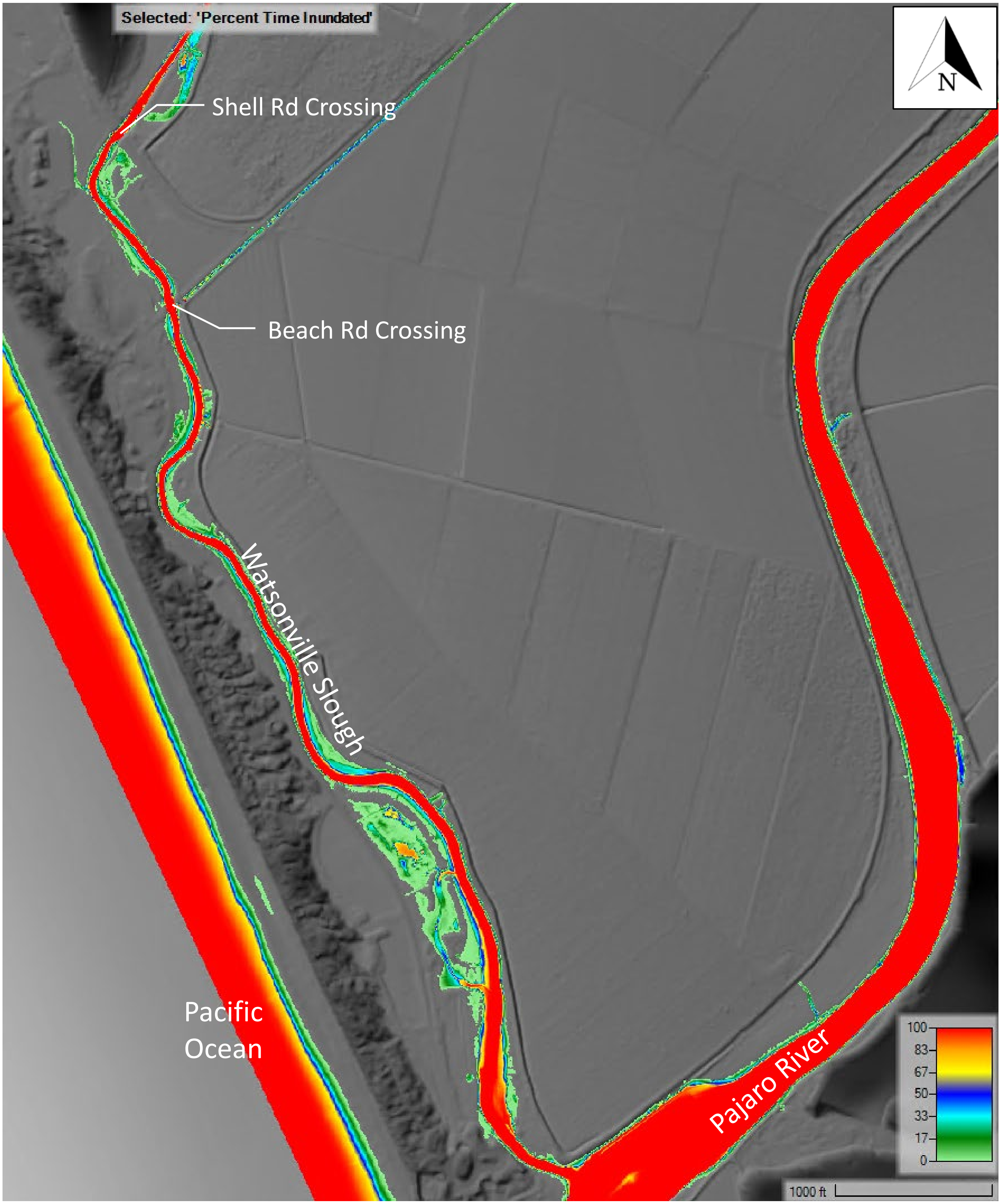


Figure 2: Percent time inundated – No Action; Year 0; Open Lagoon, Wet Season

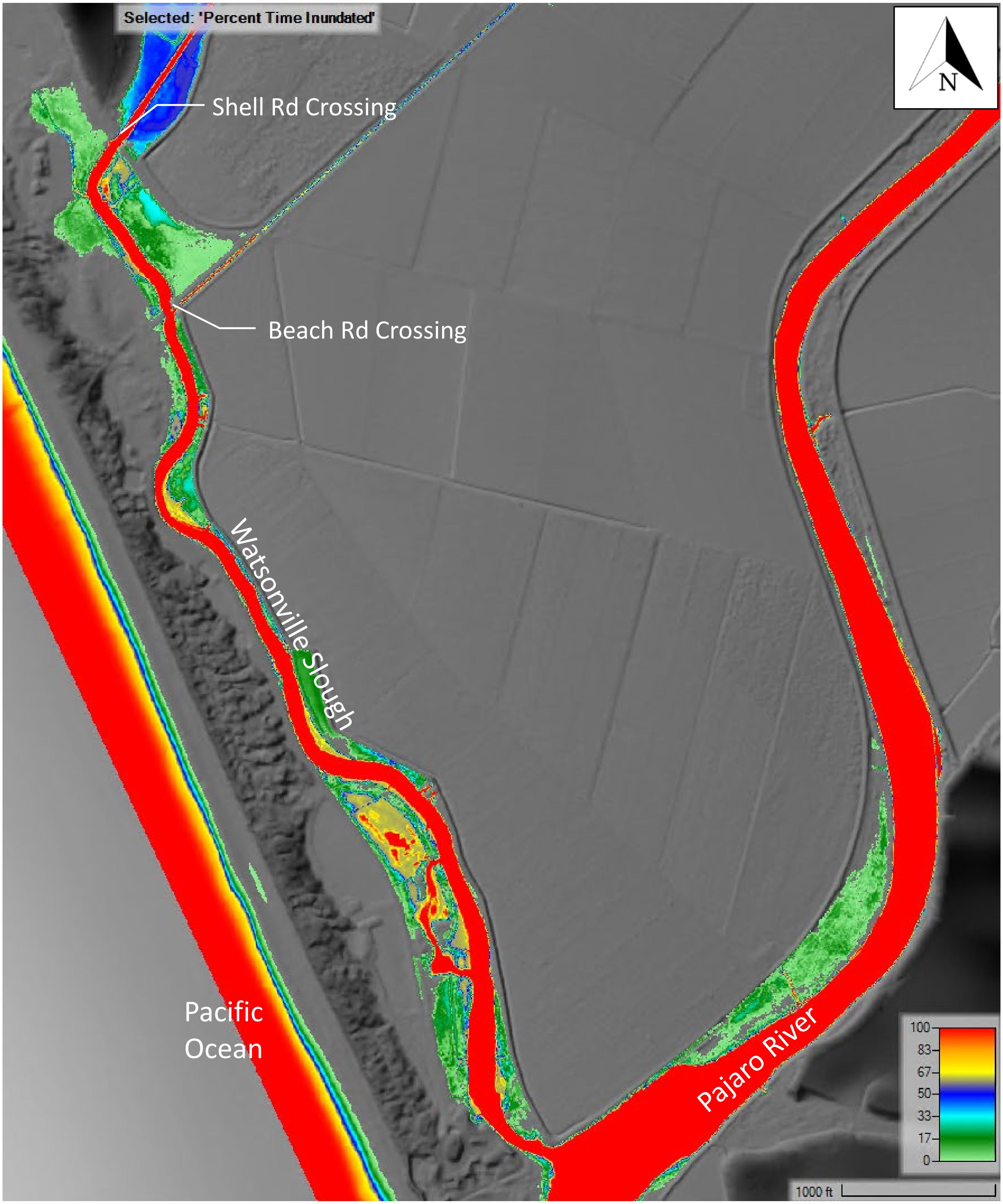


Figure 3: Percent time inundated – No Action; Year 0; Closed Lagoon, Wet Season

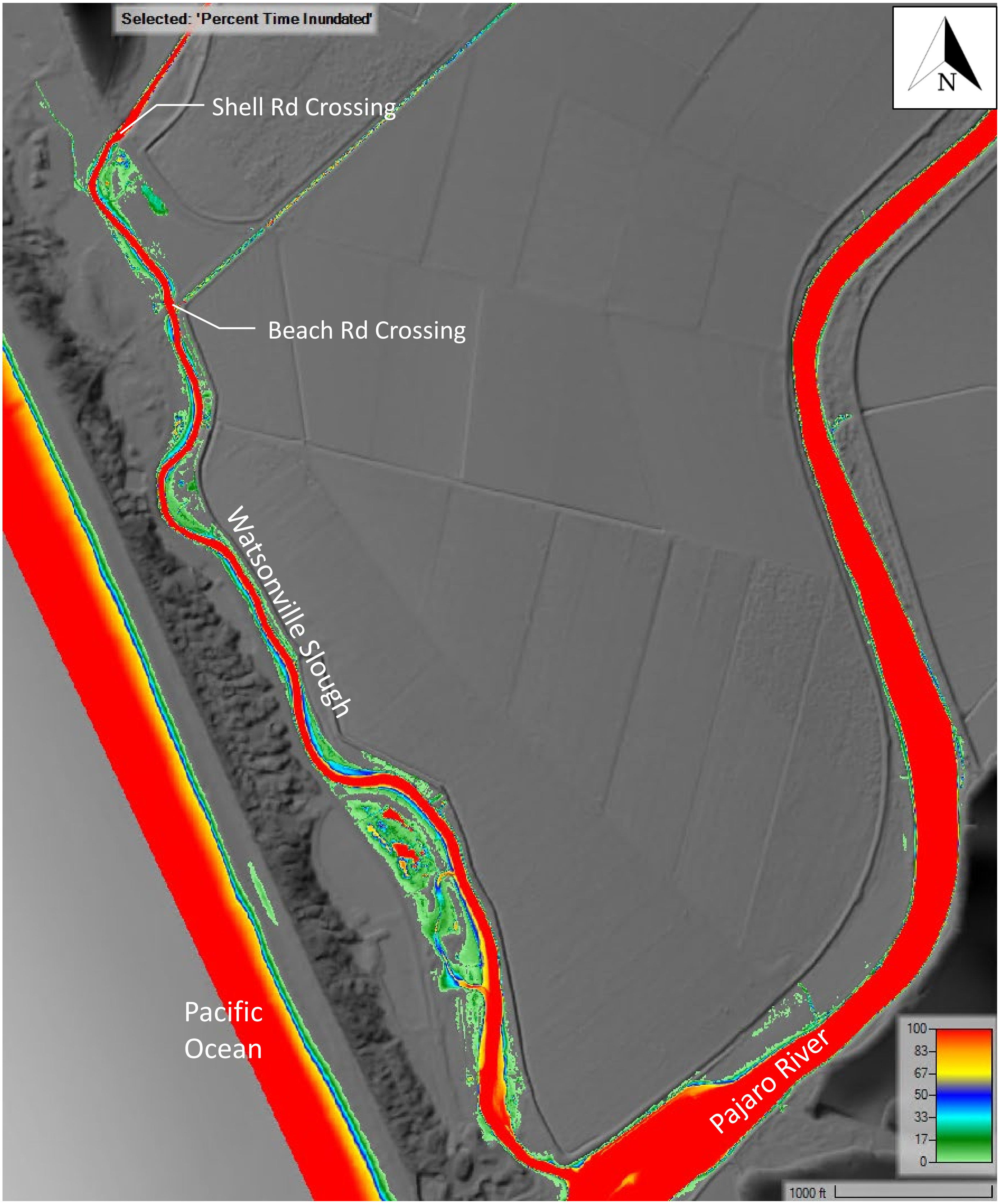


Figure 4: Percent time inundated – No Action; Year 25; Open Lagoon, Dry Season

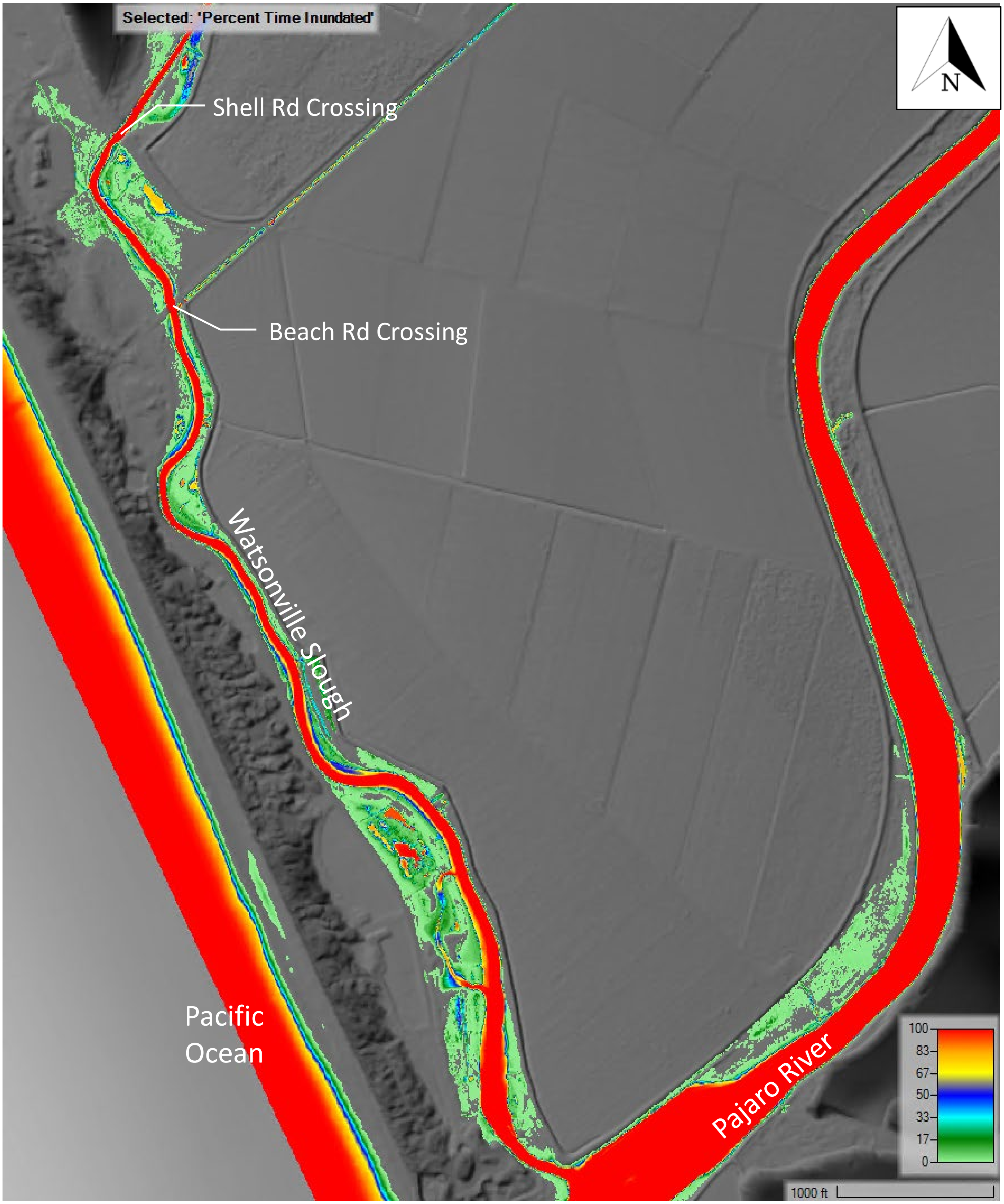


Figure 5: Percent time inundated – No Action; Year 25; Open Lagoon, Wet Season

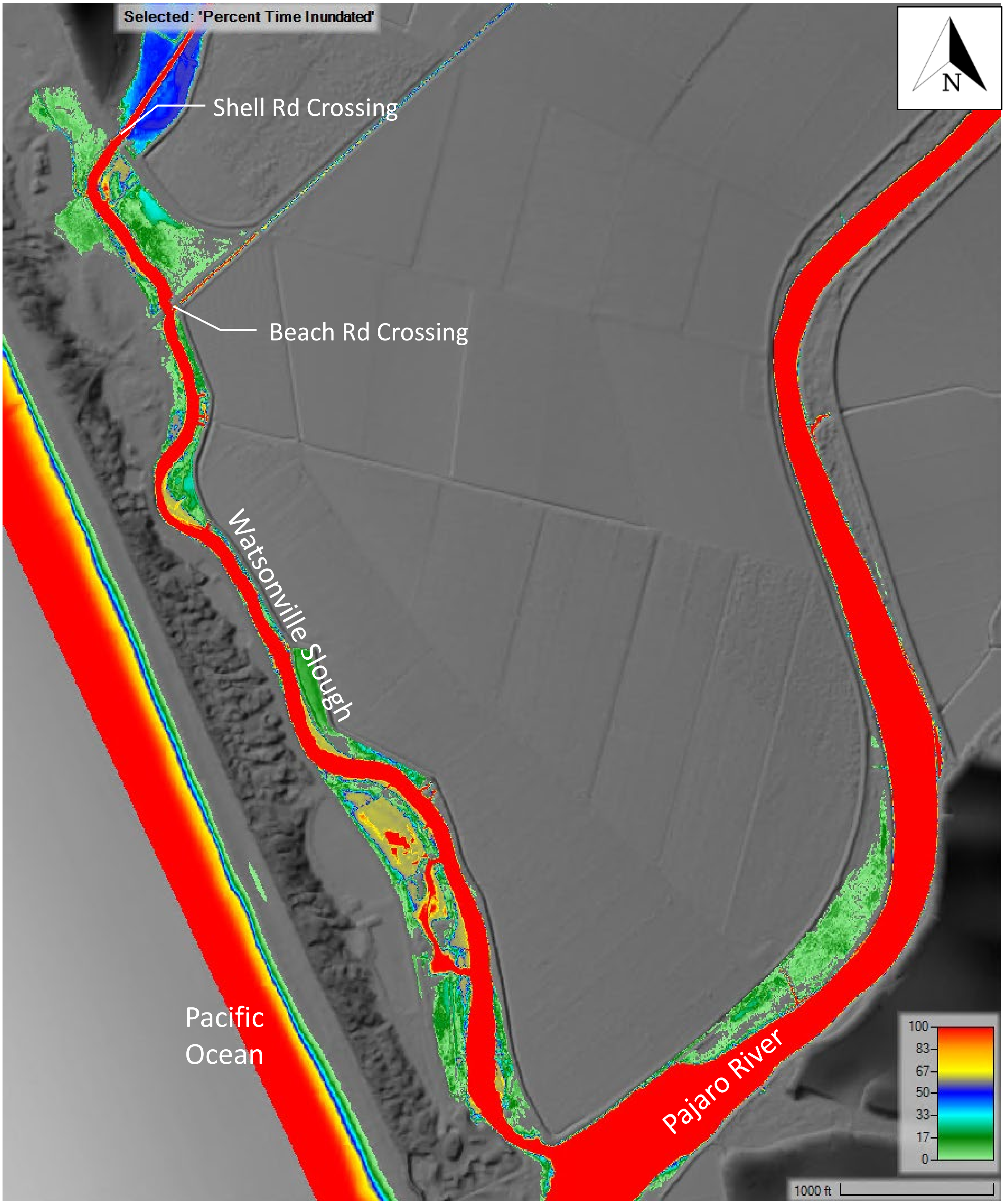


Figure 6: Percent time inundated – No Action; Year 25; Closed Lagoon, Wet Season

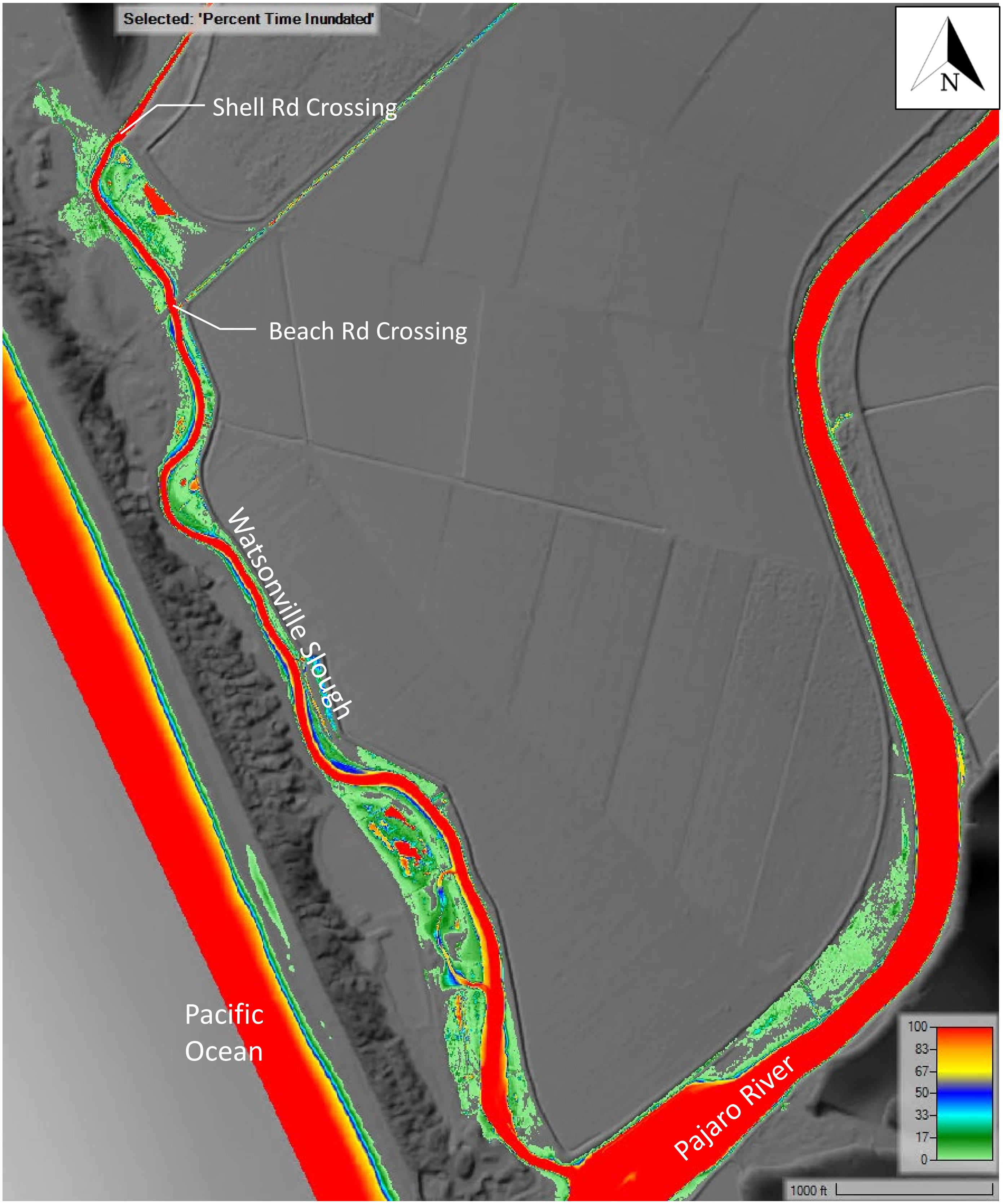


Figure 7: Percent time inundated – No Action; Year 50; Open Lagoon, Dry Season

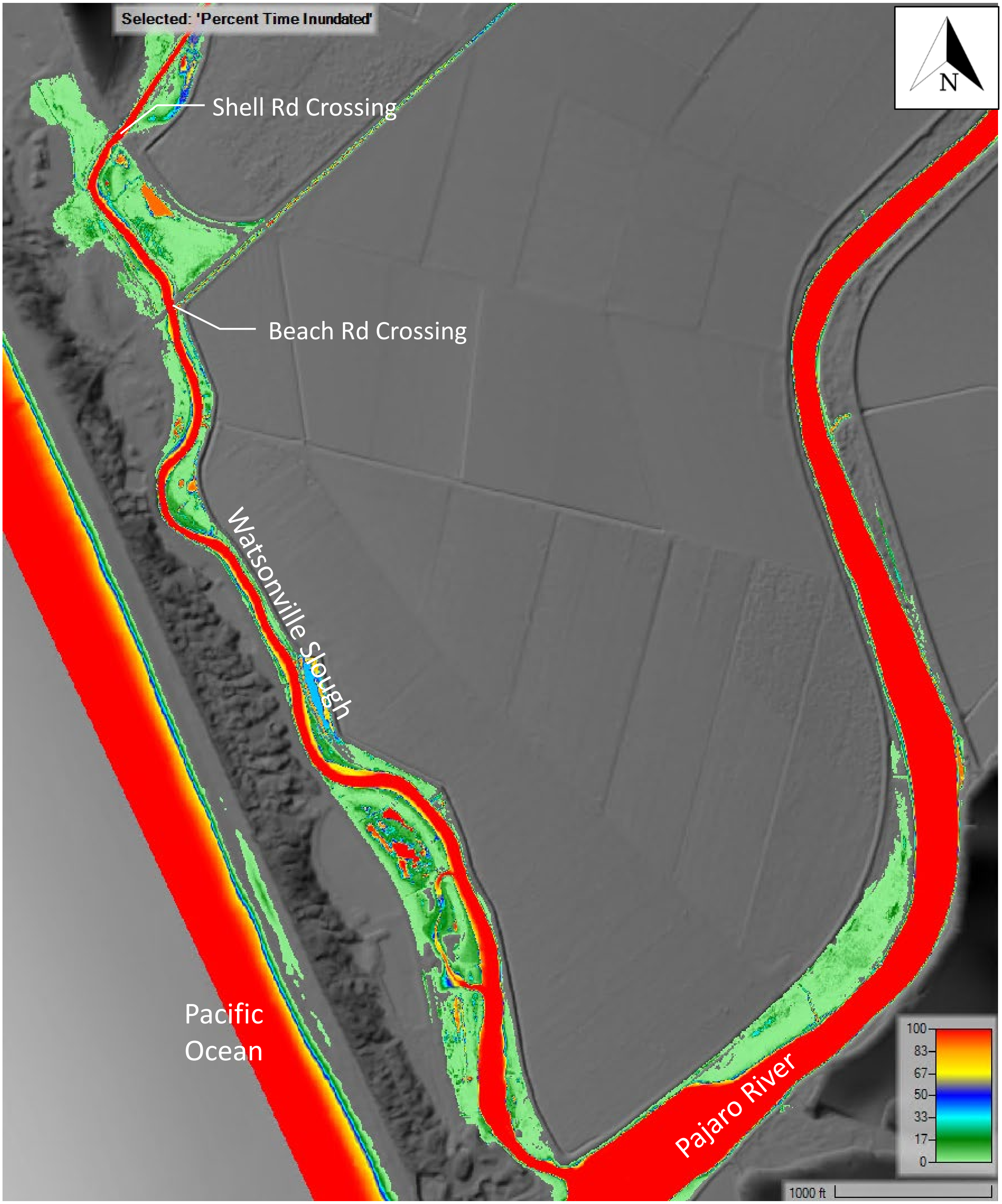


Figure 8: Percent time inundated – No Action; Year 50; Open Lagoon, Wet Season

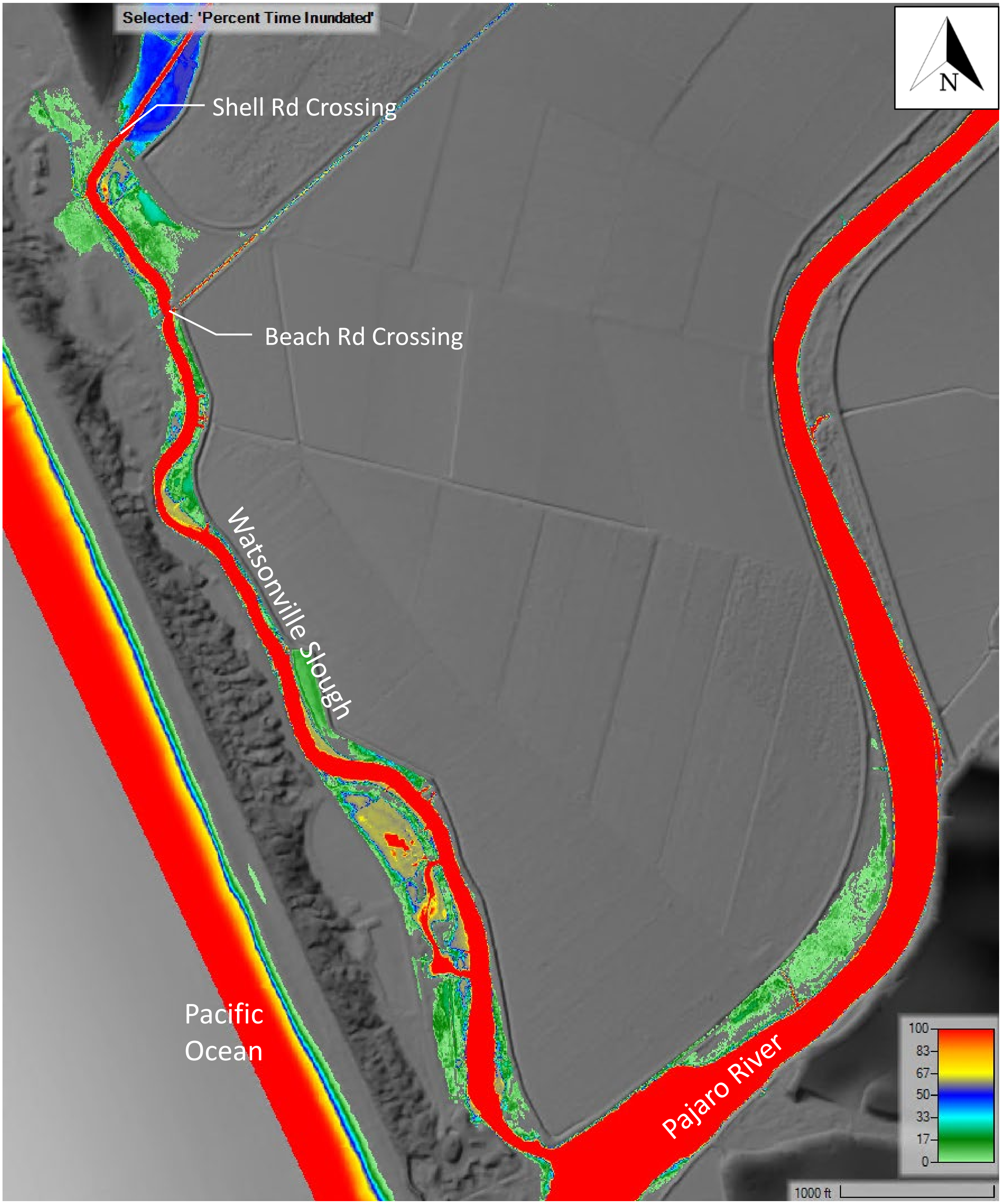


Figure 9: Percent time inundated – No Action; Year 50; Closed Lagoon, Wet Season

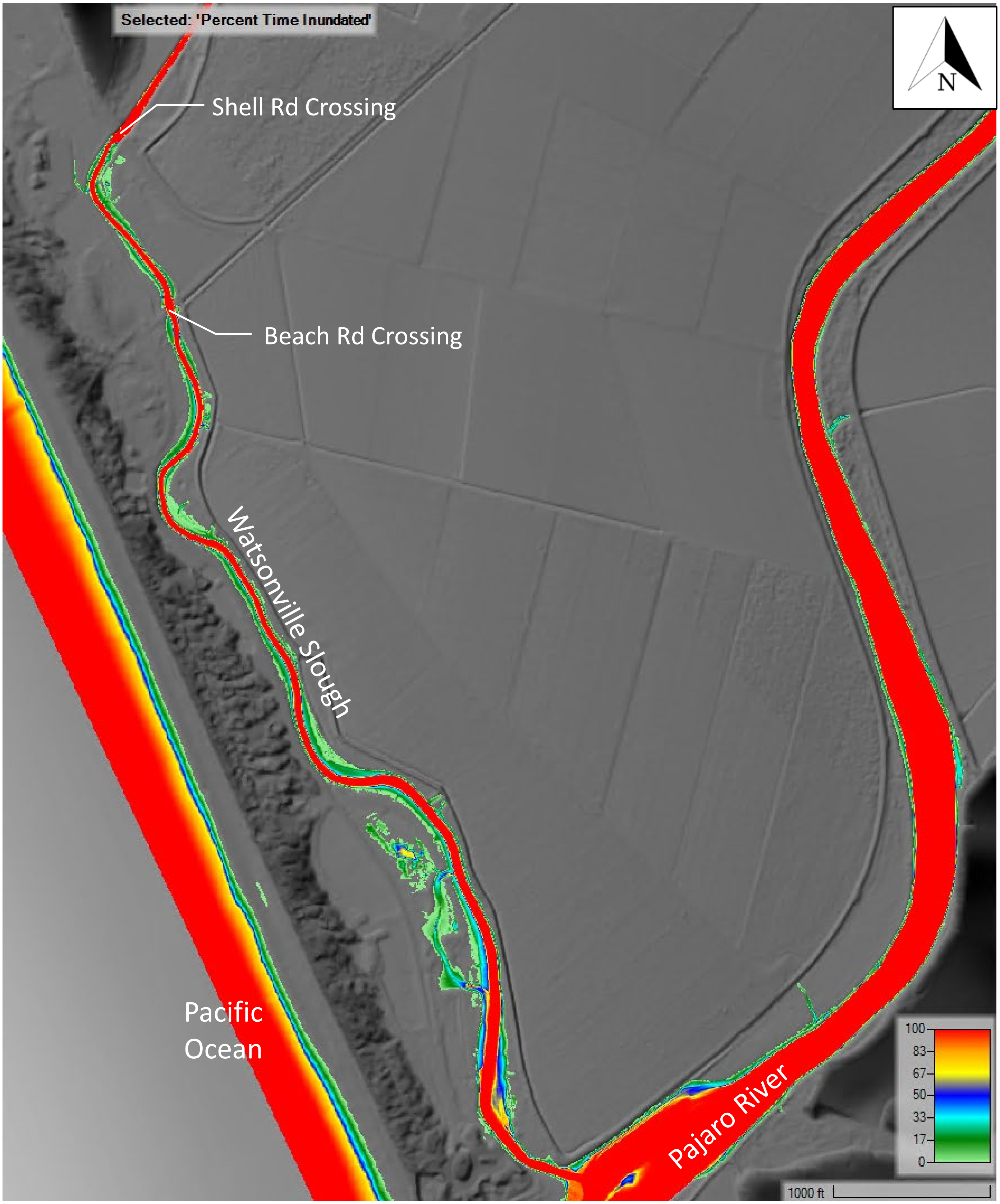


Figure 10: Percent time inundated – Crossing Improvements; Year 0; Open Lagoon, Dry Season

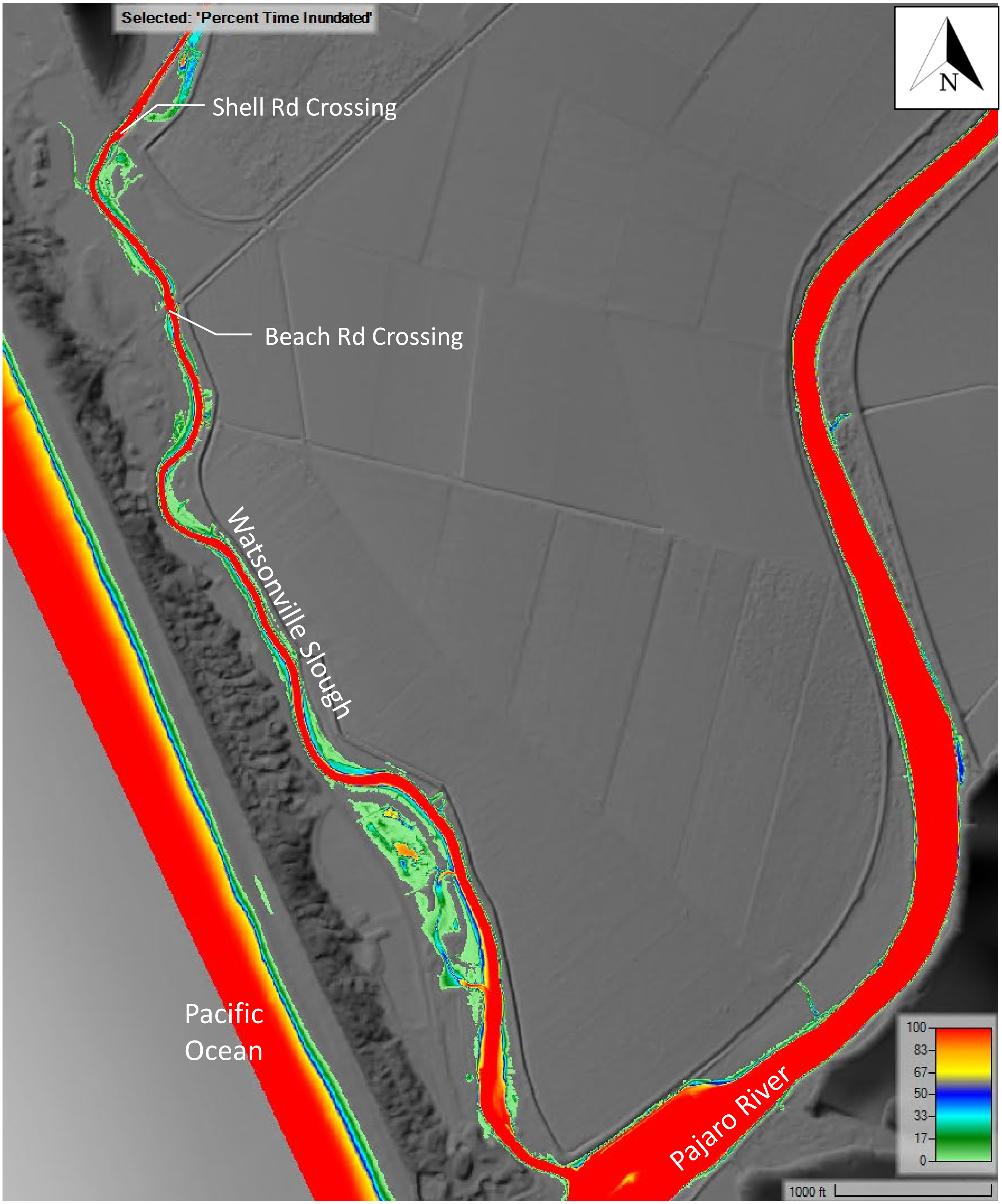


Figure 11: Percent time inundated – Crossing Improvements; Year 0; Open Lagoon, Wet Season

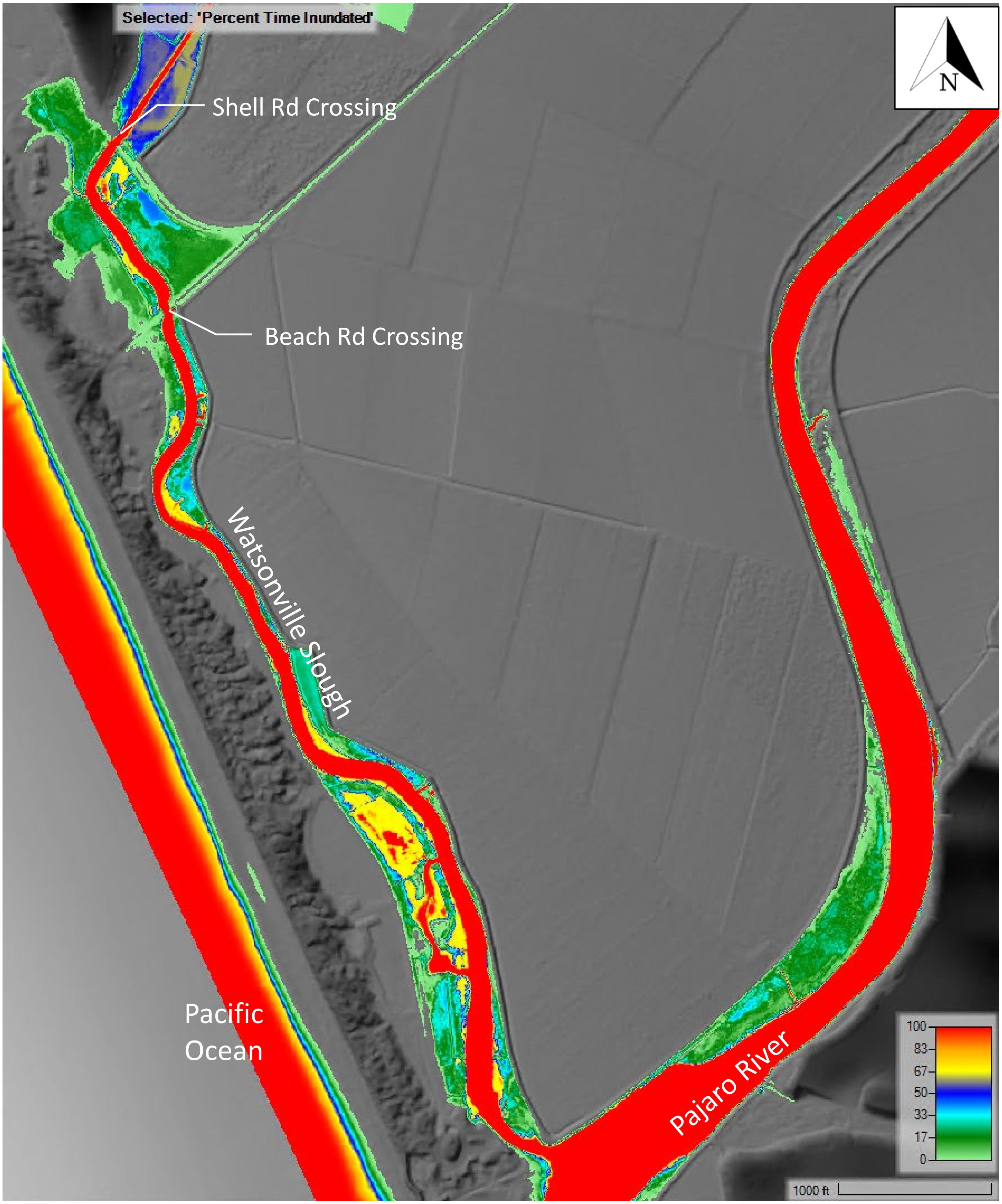


Figure 12: Percent time inundated – Crossing Improvements; Year 0; Closed Lagoon, Wet Season

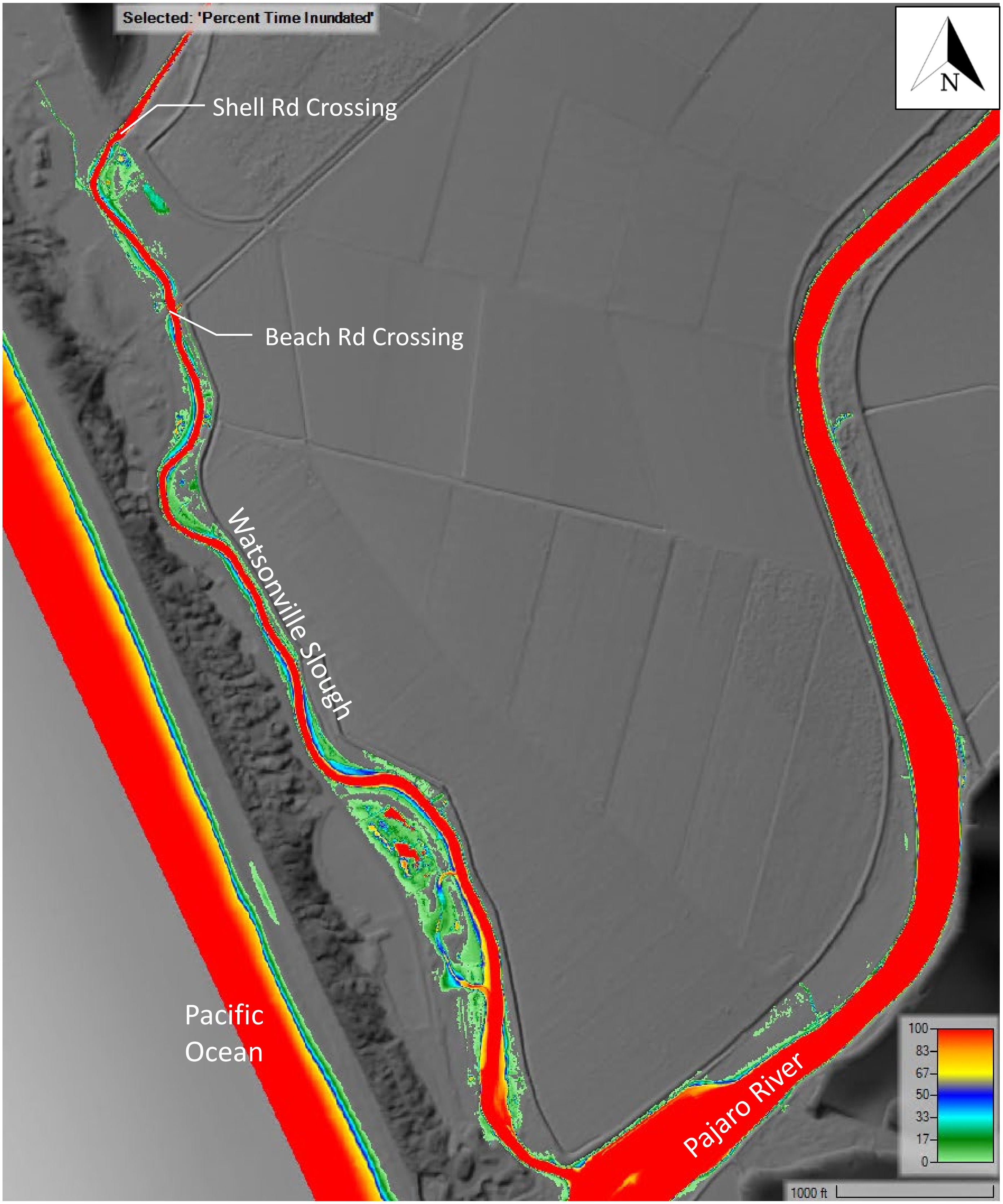


Figure 13: Percent time inundated – Crossing Improvements; Year 25; Open Lagoon, Dry Season

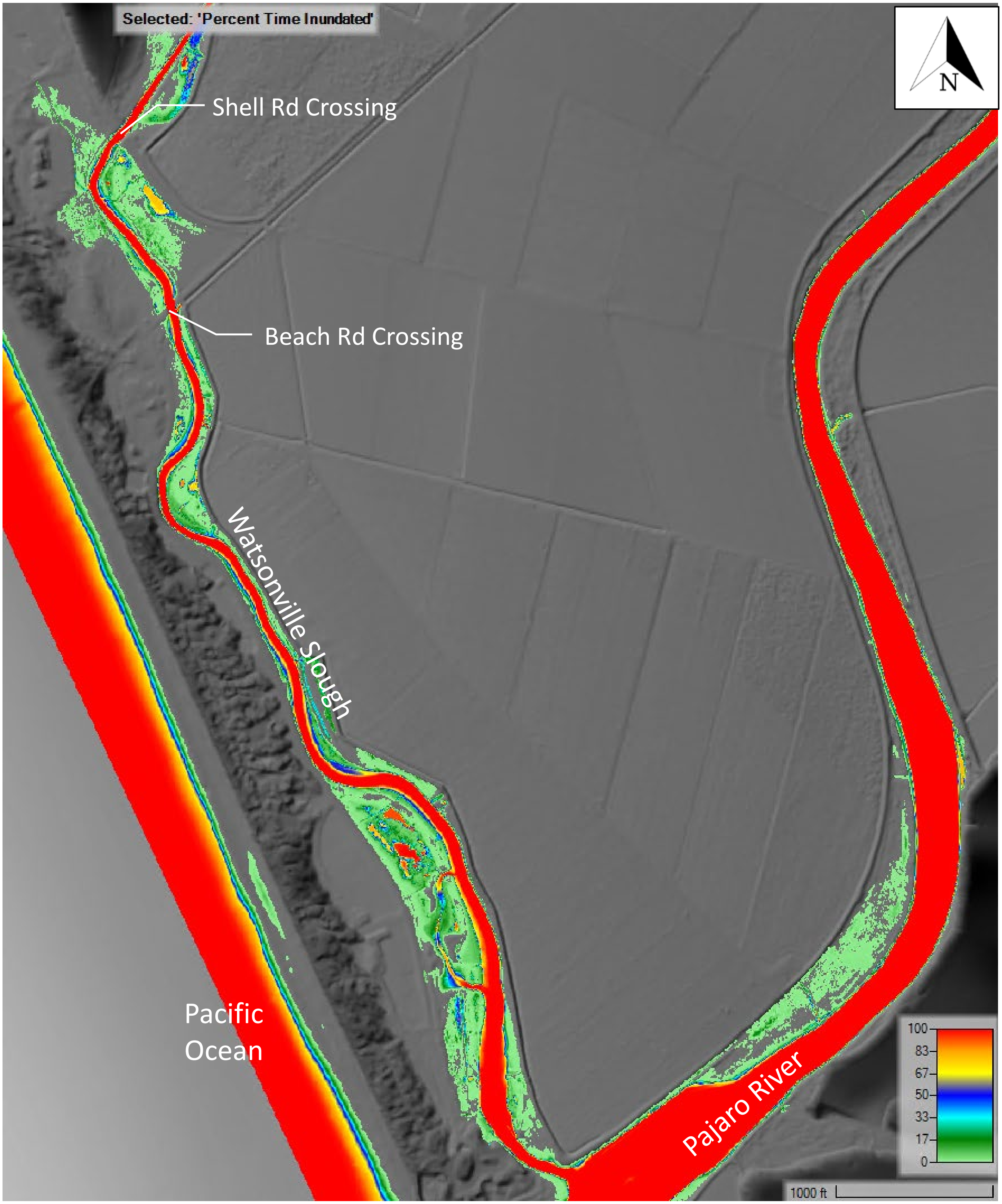


Figure 14: Percent time inundated – Crossing Improvements; Year 25; Open Lagoon, Wet Season

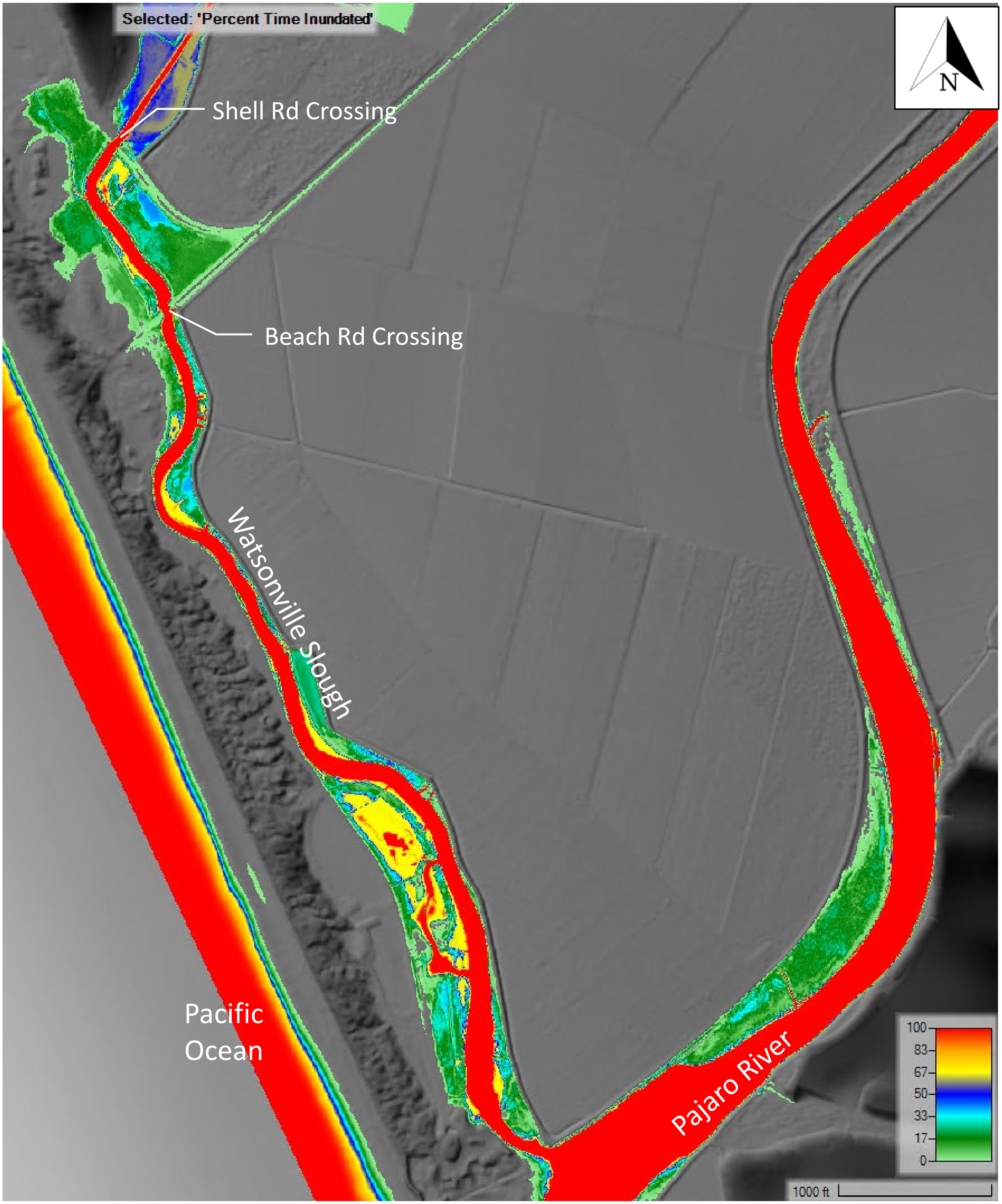


Figure 15: Percent time inundated – Crossing Improvements; Year 25; Closed Lagoon, Wet Season

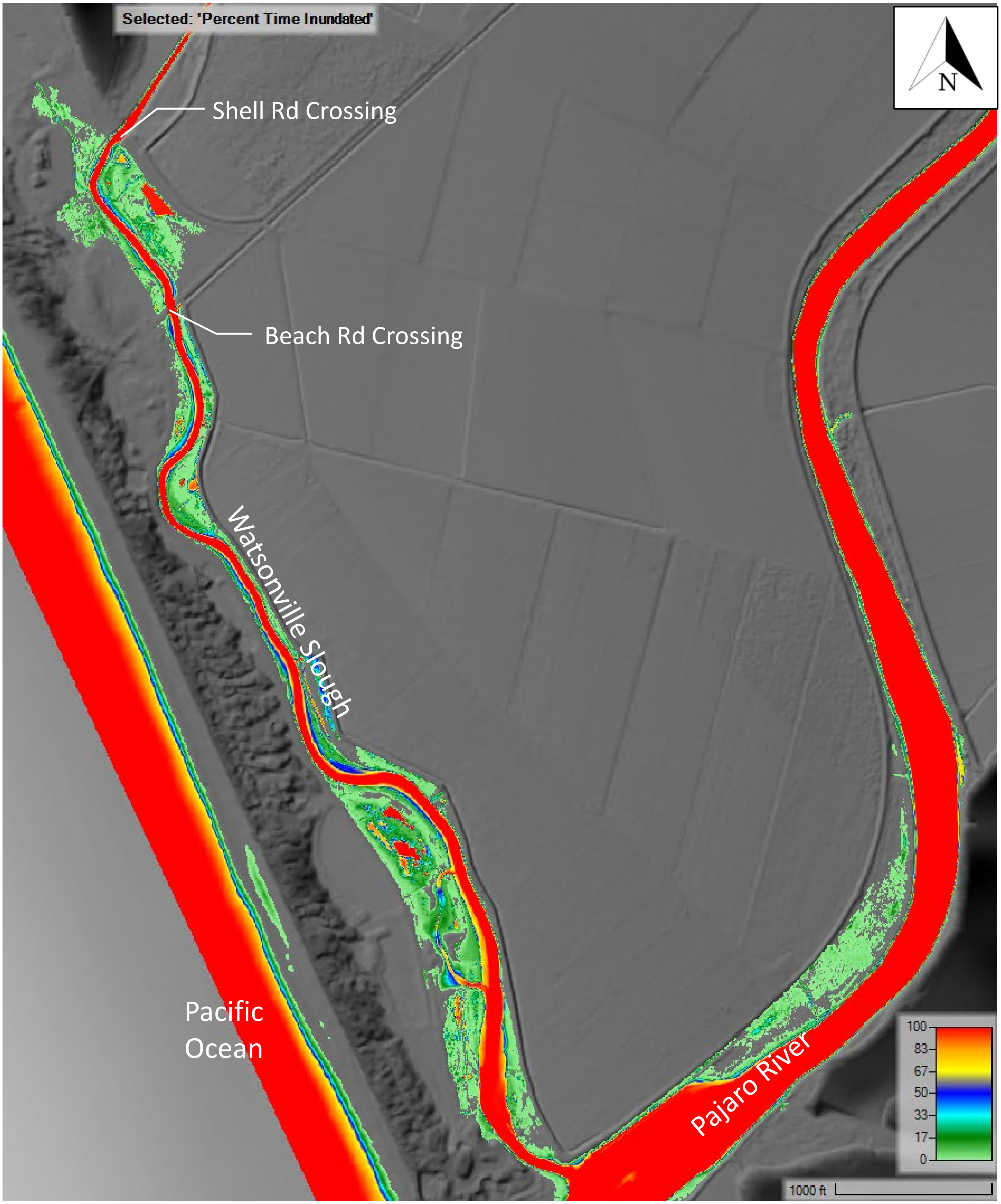


Figure 16: Percent time inundated – Crossing Improvements; Year 50; Open Lagoon, Dry Season

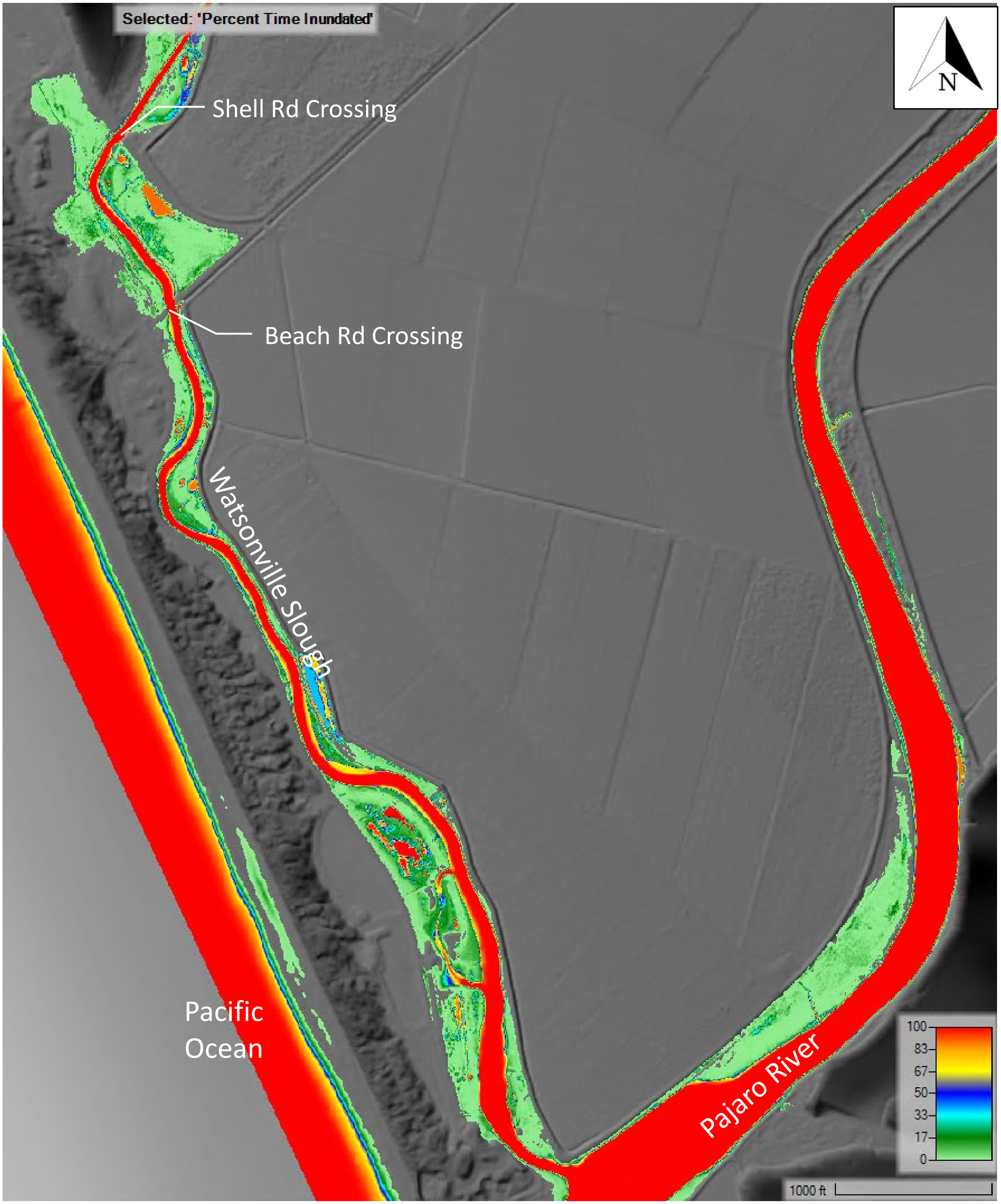


Figure 17: Percent time inundated – Crossing Improvements; Year 50; Open Lagoon, Wet Season

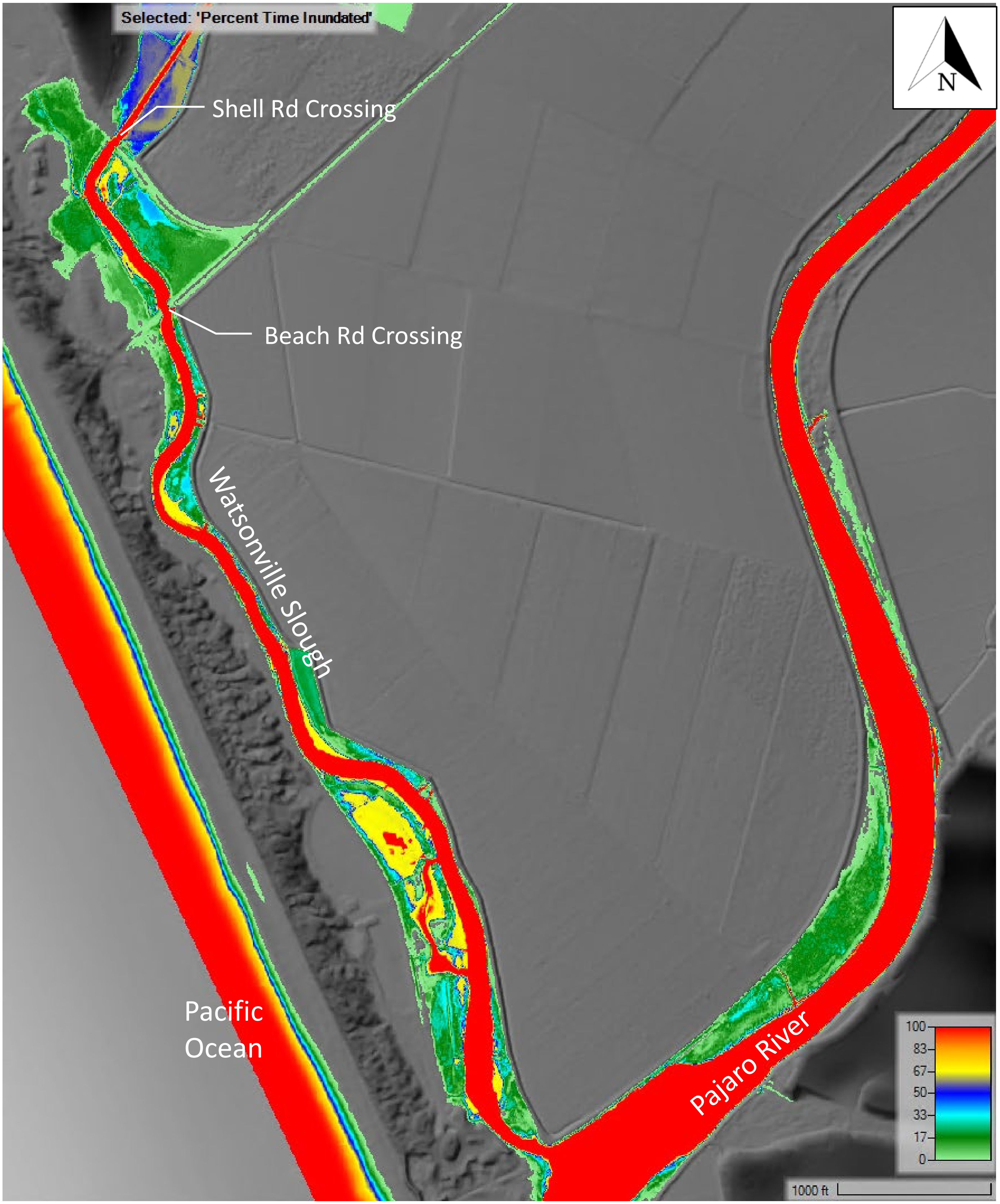


Figure 18: Percent time inundated – Crossing Improvements; Year 50; Closed Lagoon, Wet Season

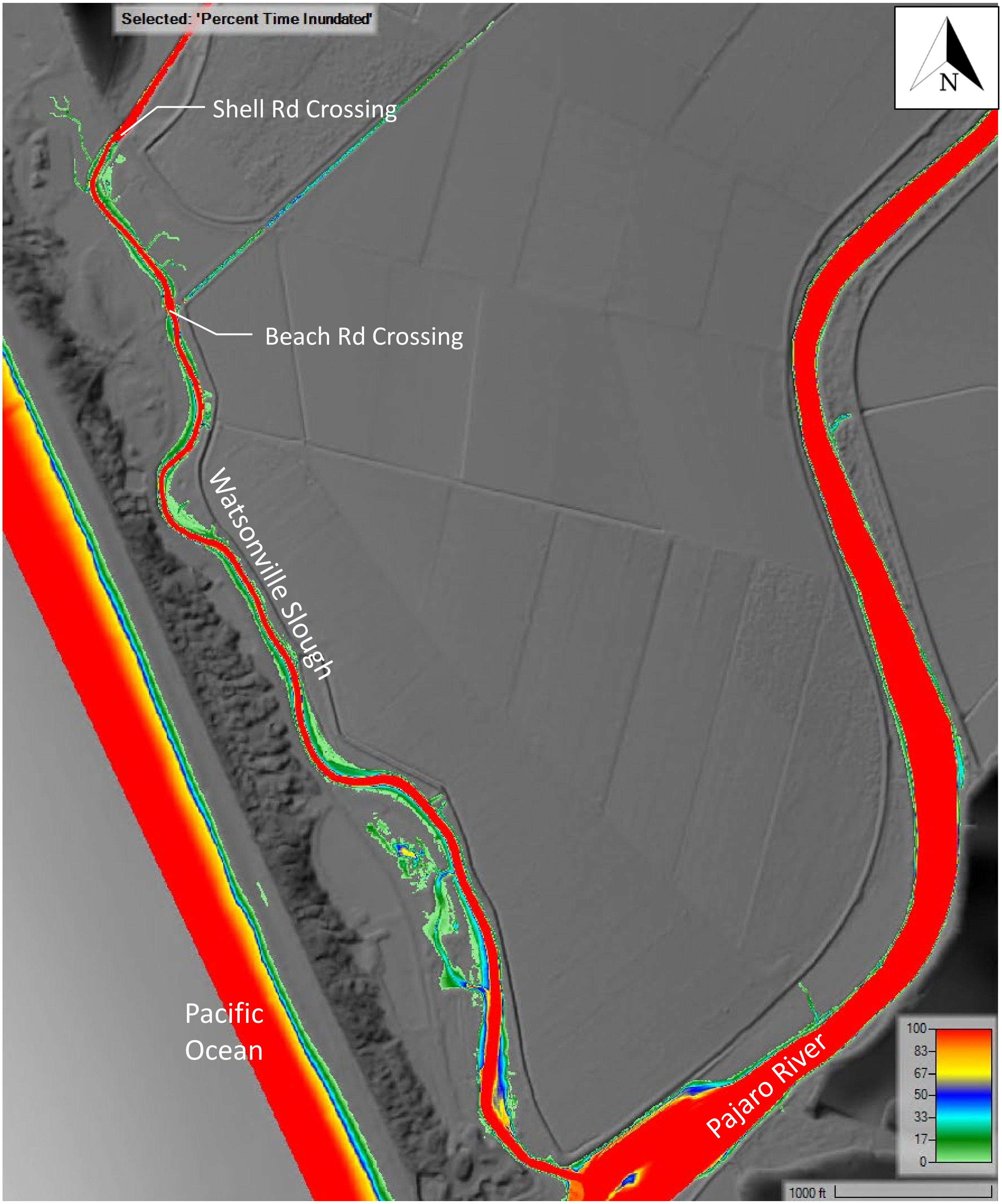


Figure 19: Percent time inundated – Earthwork; Year 0; Open Lagoon, Dry Season

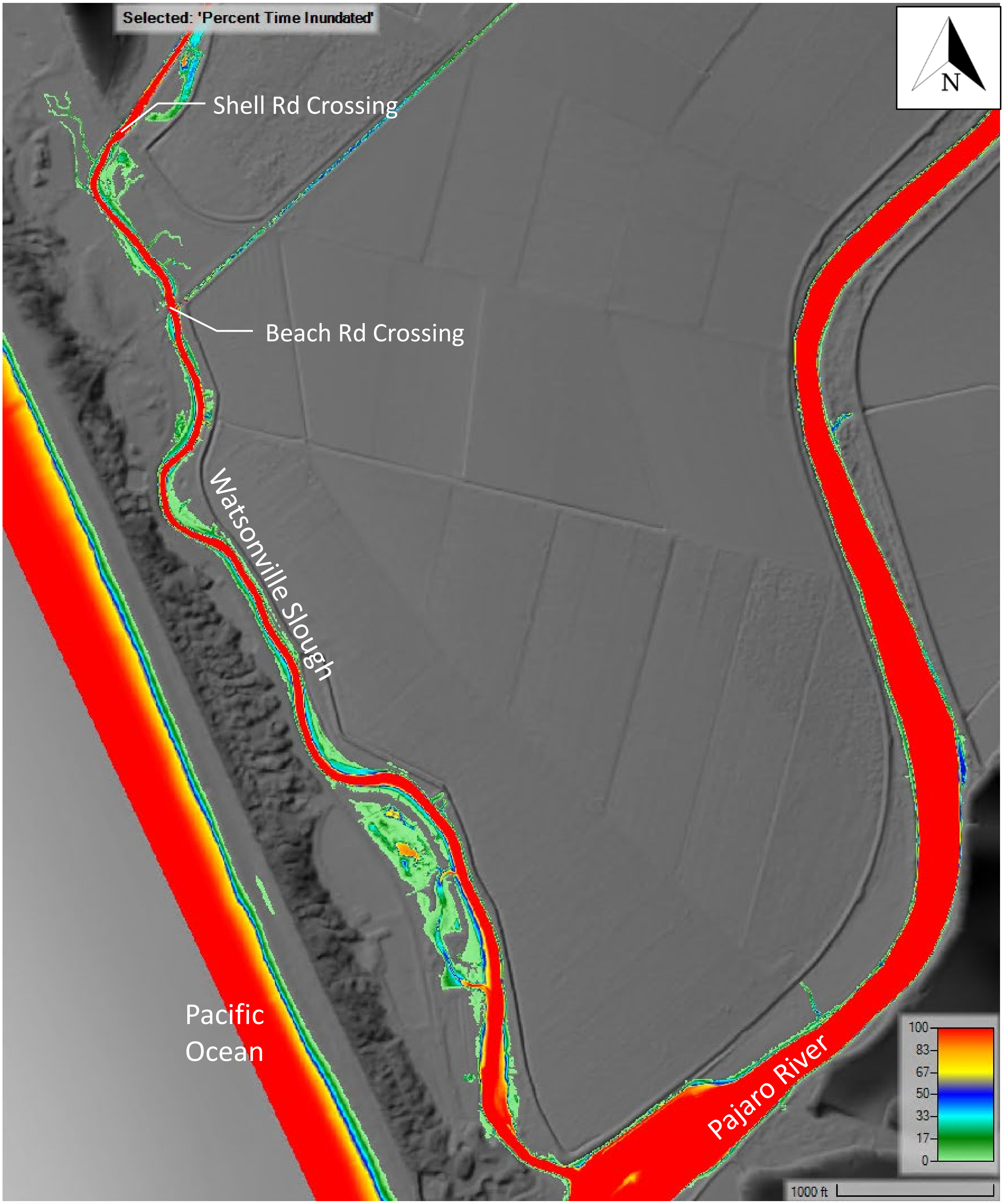


Figure 20: Percent time inundated – Earthwork; Year 0; Open Lagoon, Wet Season

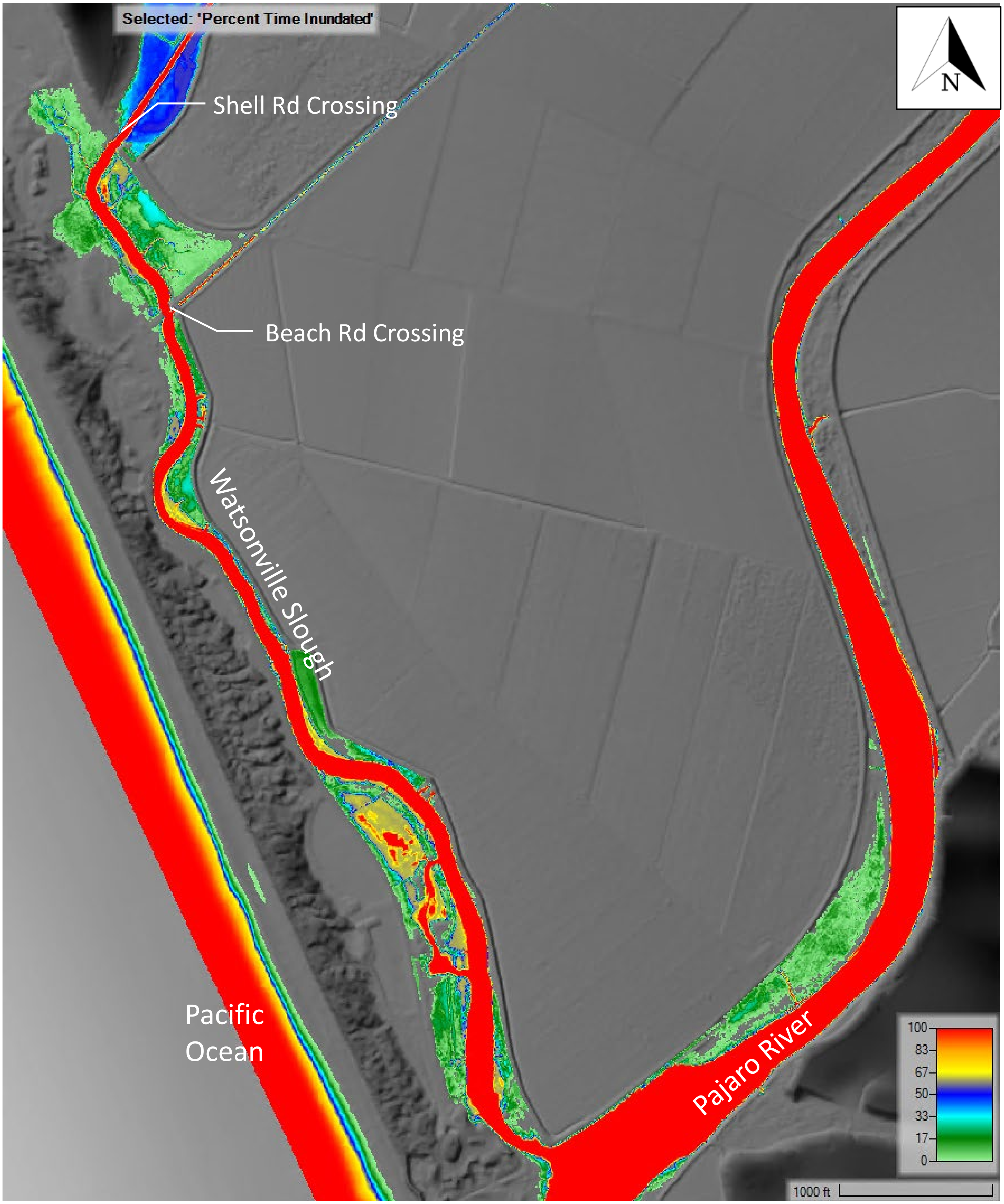


Figure 21: Percent time inundated – Earthwork; Year 0; Closed Lagoon, Wet Season

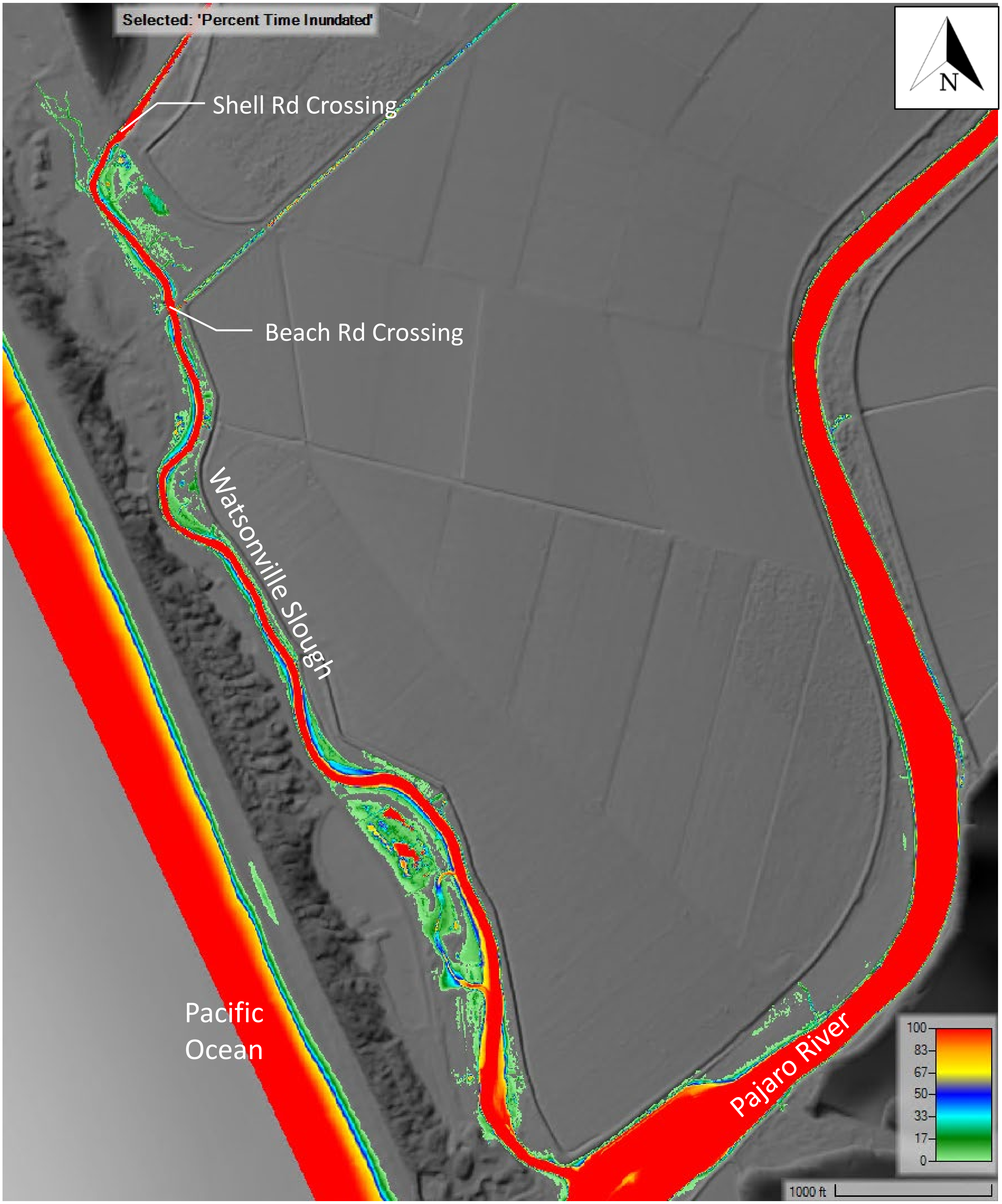


Figure 22: Percent time inundated – Earthwork; Year 25; Open Lagoon, Dry Season

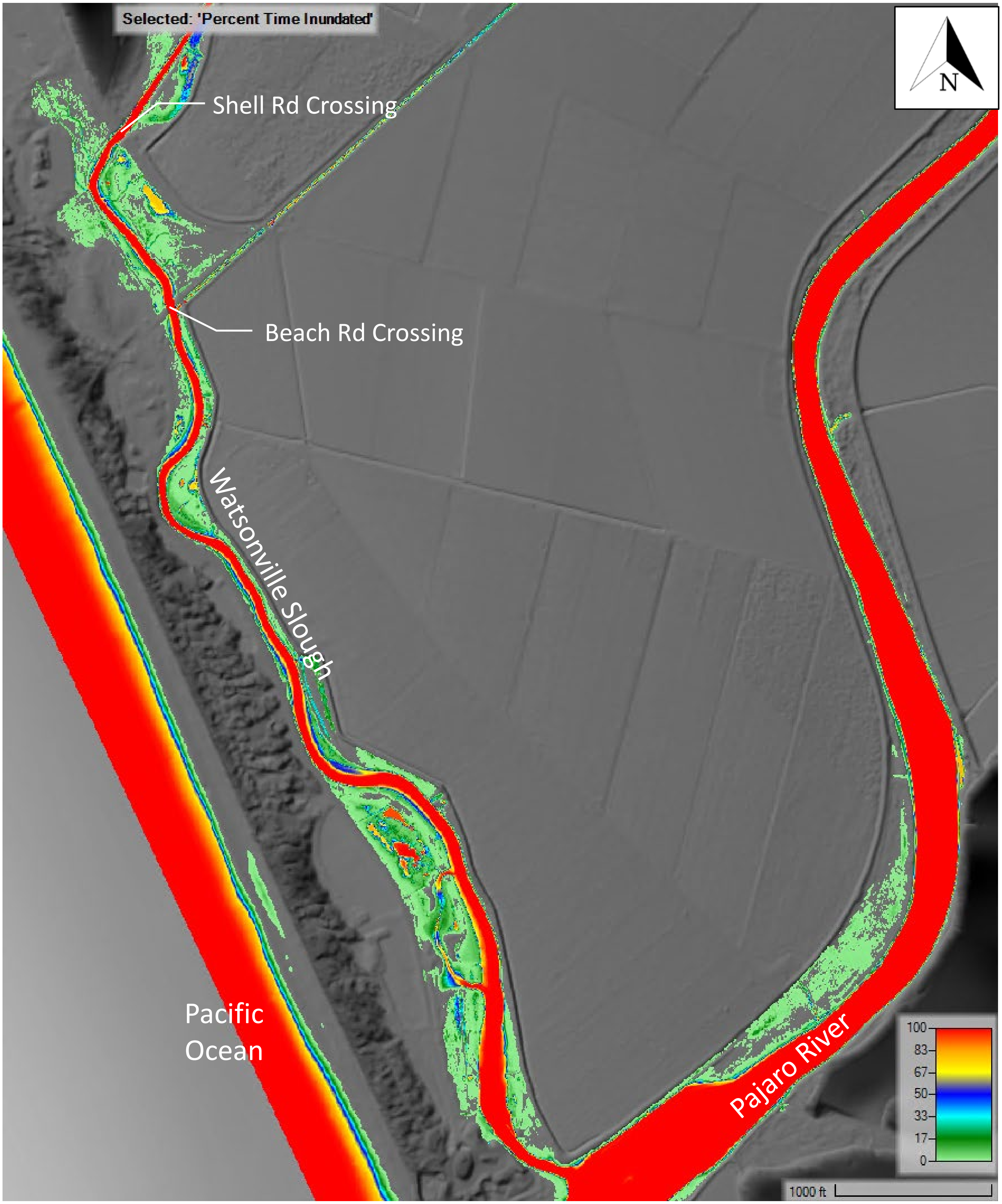


Figure 23: Percent time inundated – Earthwork; Year 25; Open Lagoon, Wet Season

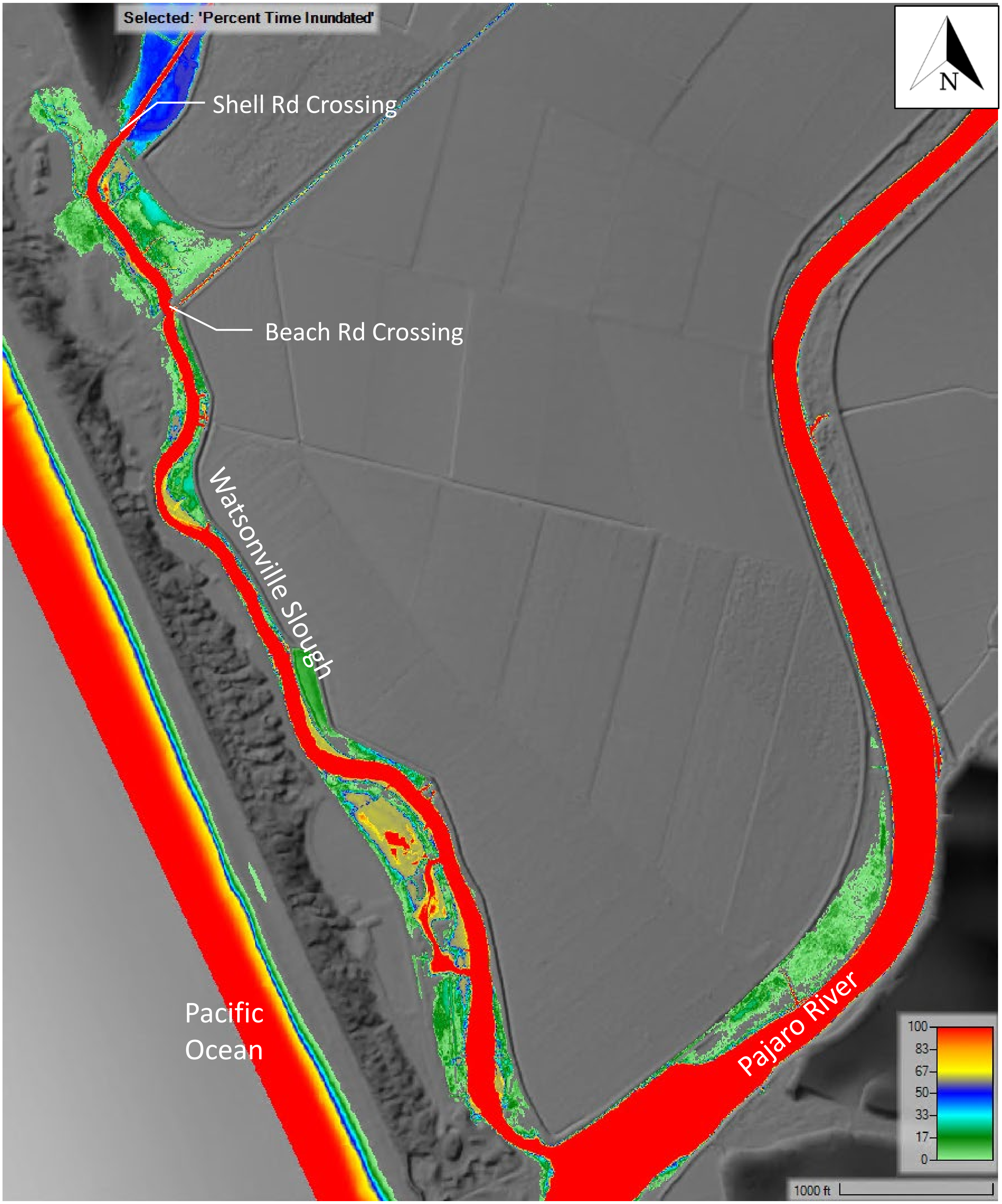


Figure 24: Percent time inundated – Earthwork; Year 25; Closed Lagoon, Wet Season

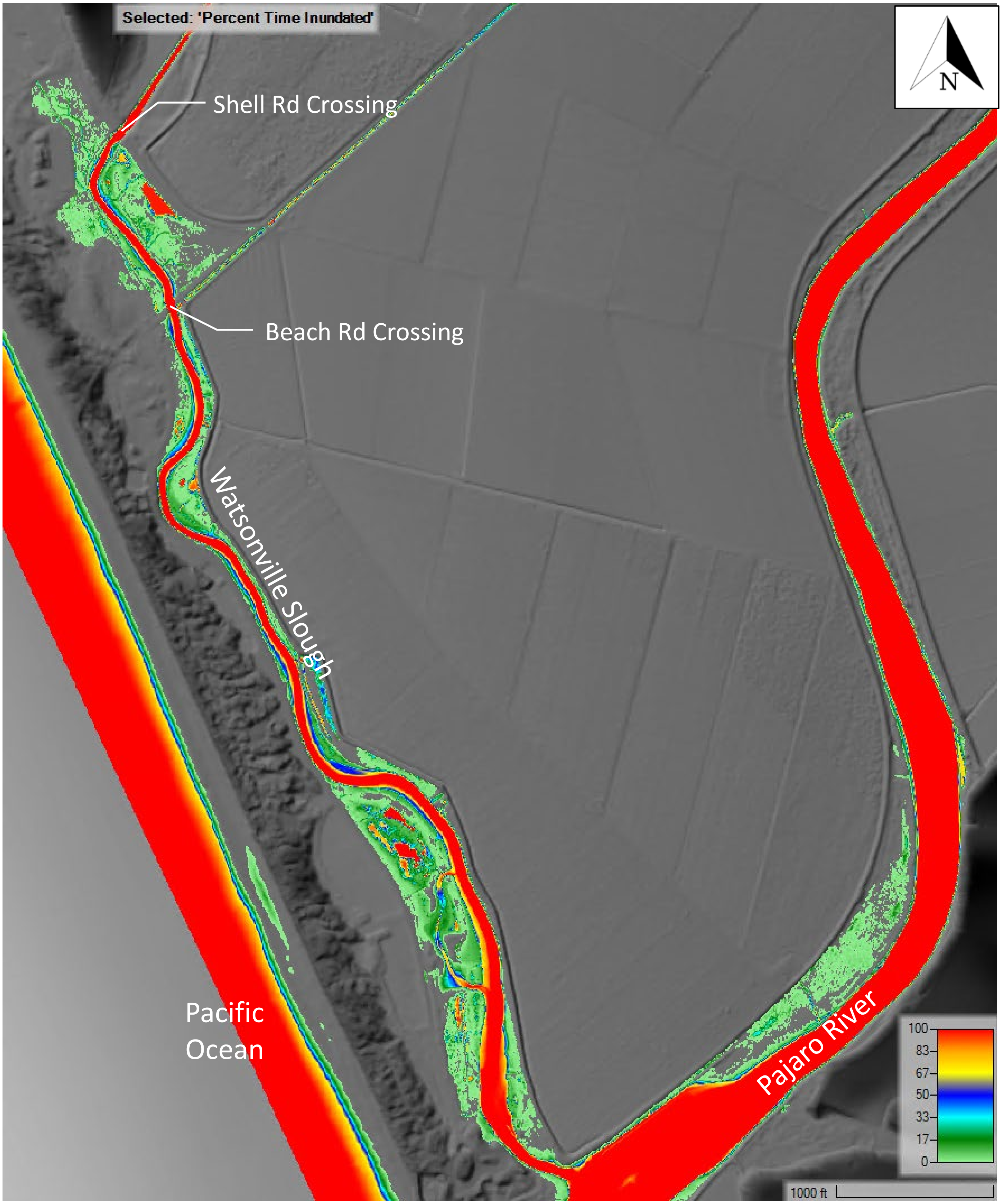


Figure 25: Percent time inundated – Earthwork; Year 50; Open Lagoon, Dry Season

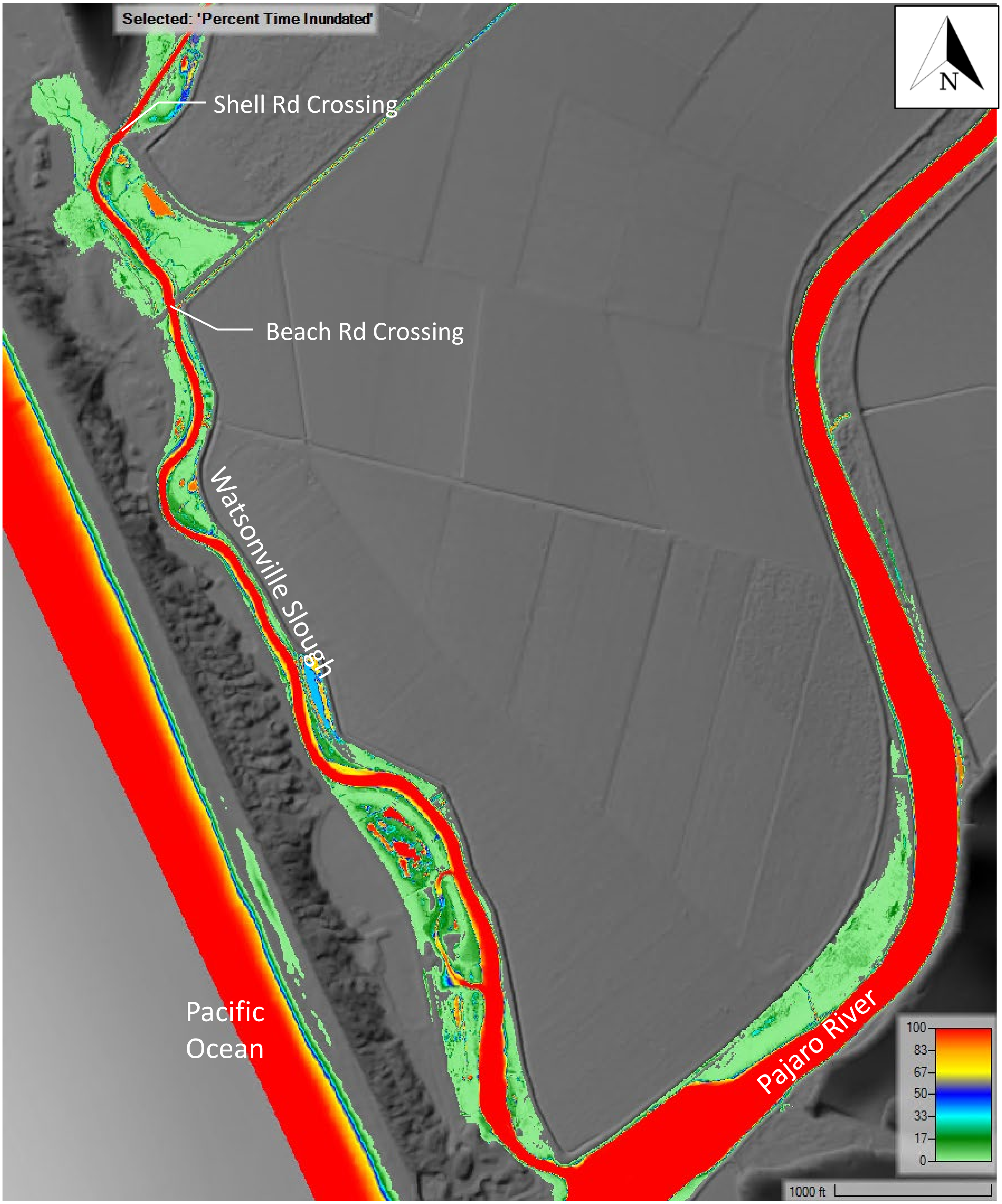


Figure 26: Percent time inundated – Earthwork; Year 50; Open Lagoon, Wet Season

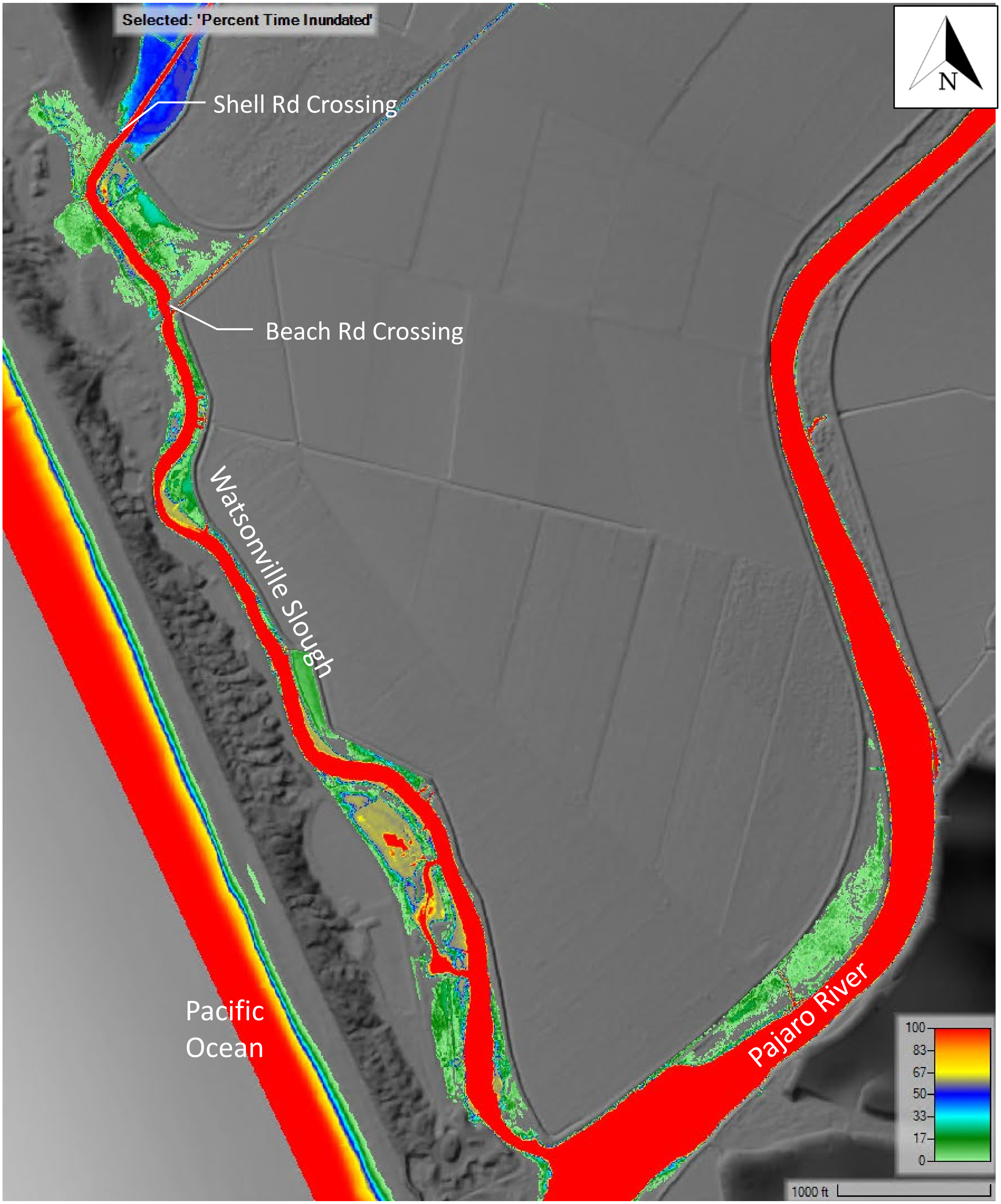


Figure 27: Percent time inundated – Earthwork; Year 50; Closed Lagoon, Wet Season

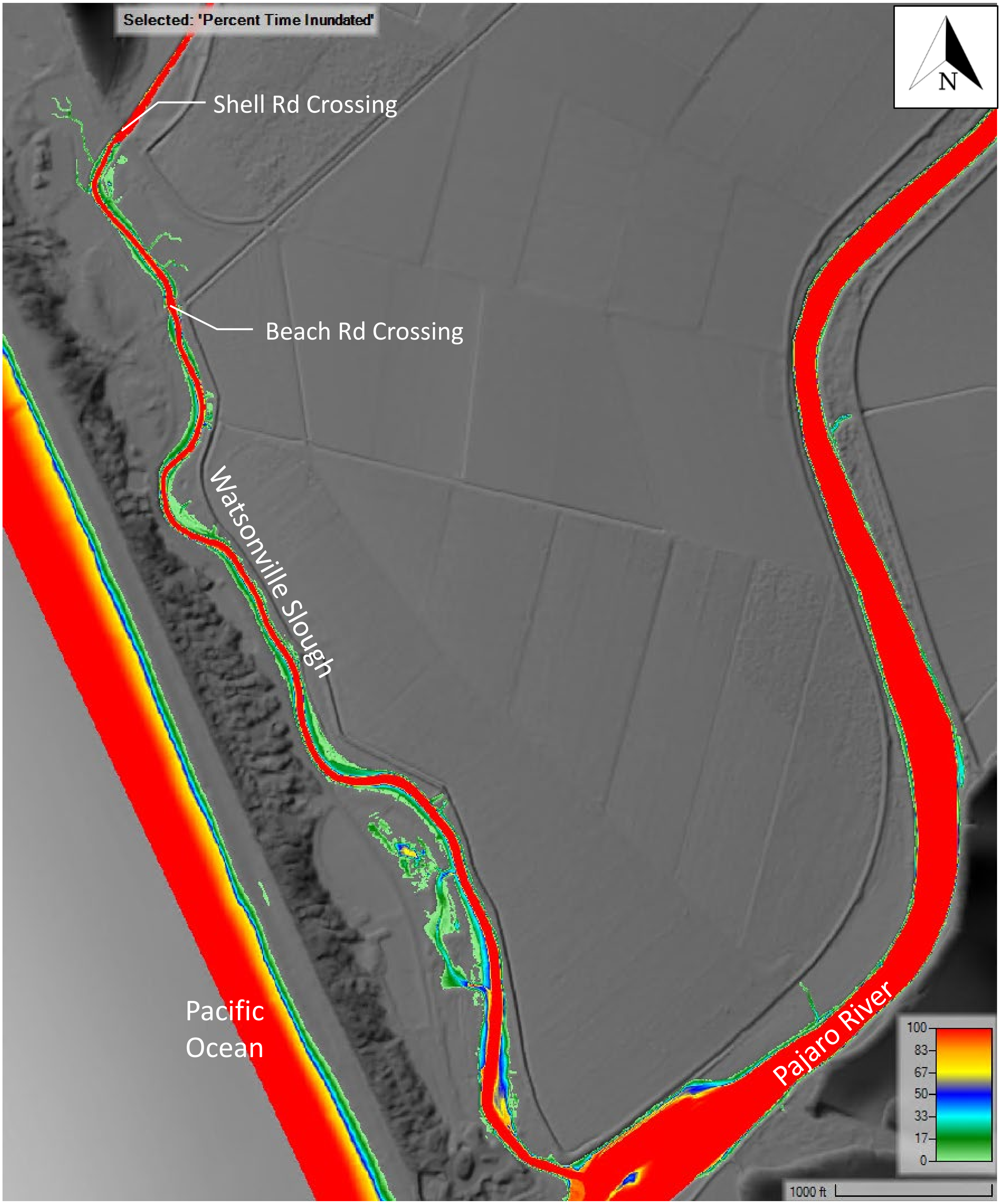


Figure 28: Percent time inundated – Crossing Improvements + Earthwork; Year 0; Open Lagoon, Dry Season

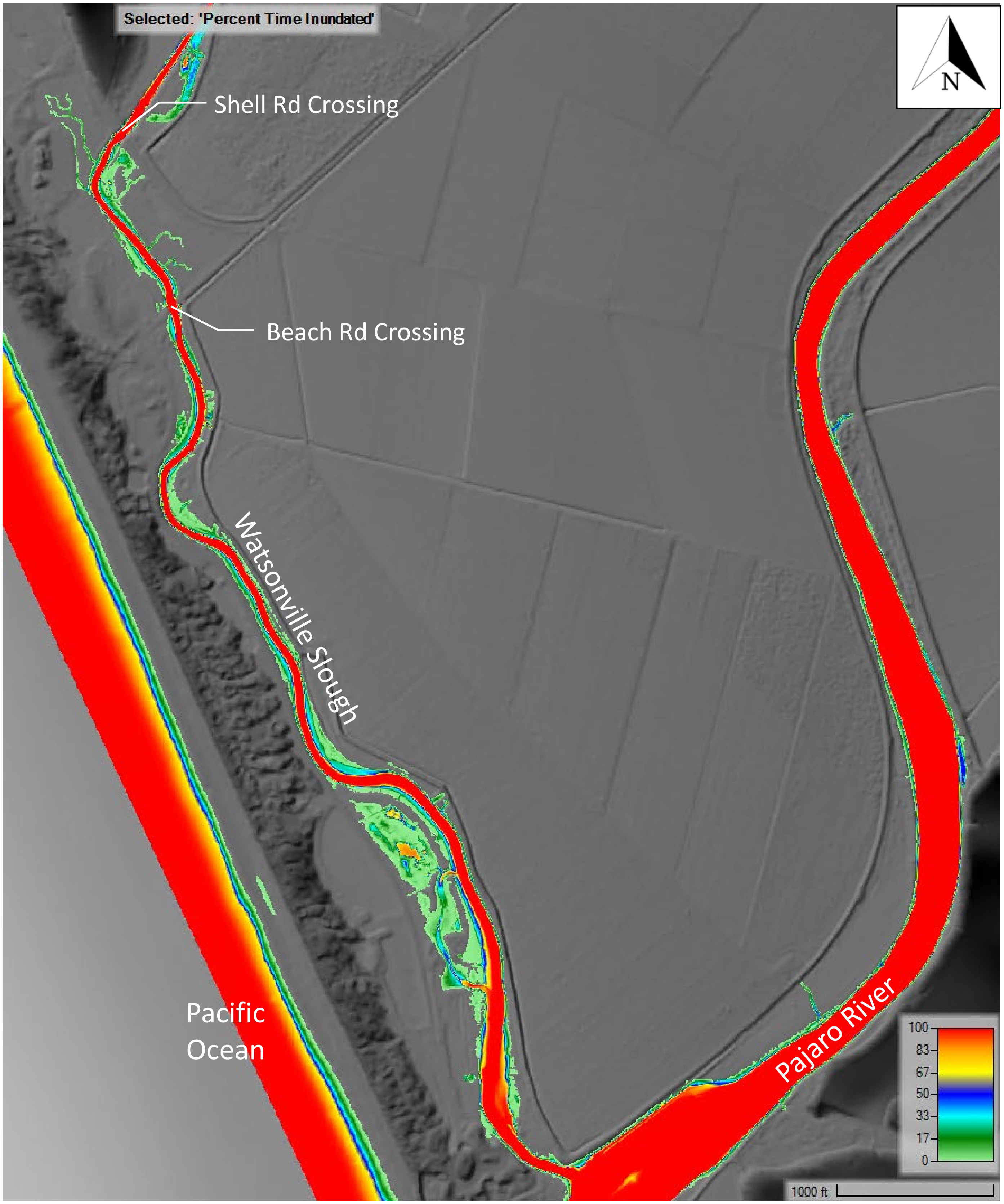


Figure 29: Percent time inundated – Crossing Improvements + Earthwork; Year 0; Open Lagoon, Wet Season

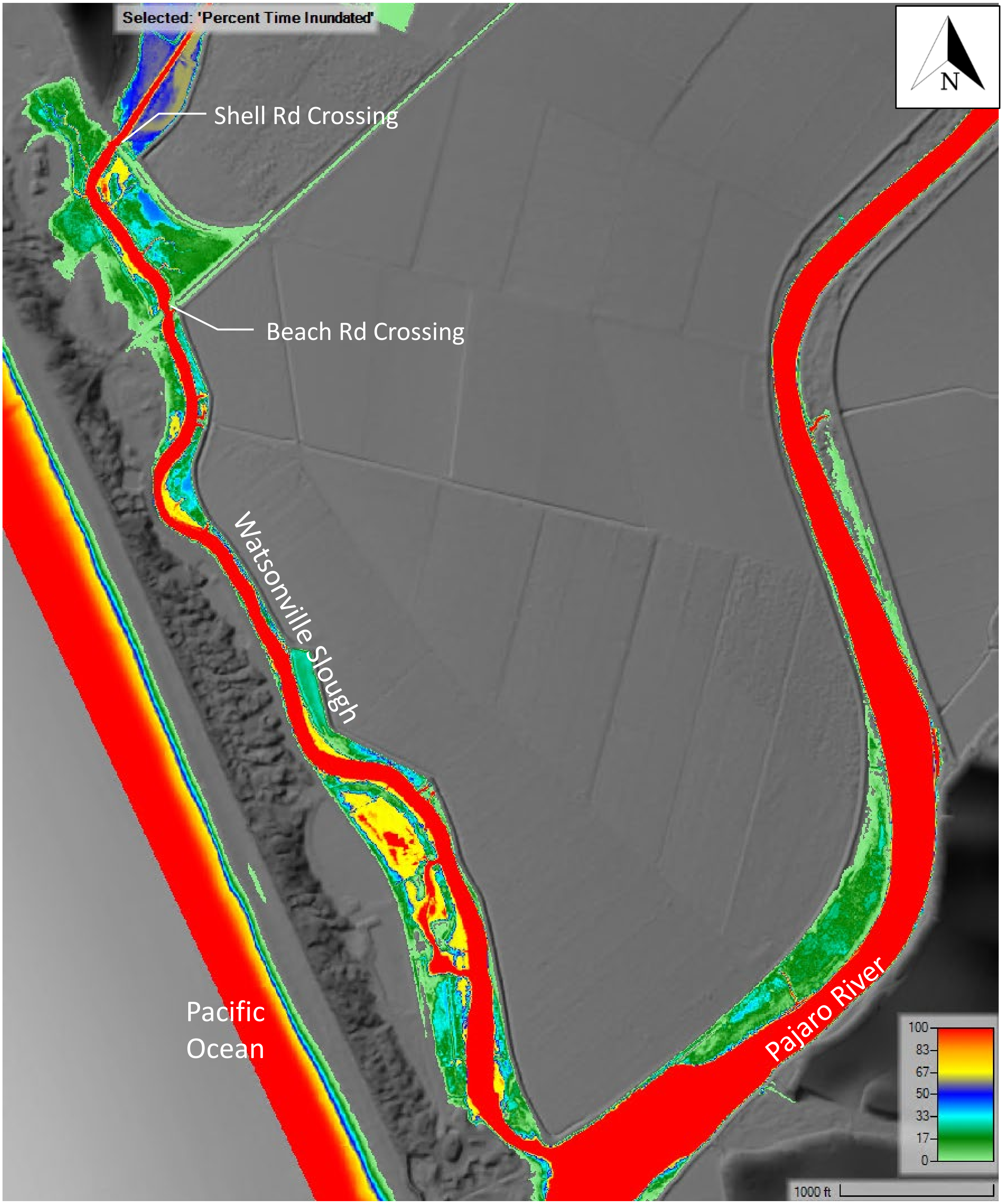


Figure 30: Percent time inundated – Crossing Improvements + Earthwork; Year 0; Closed Lagoon, Wet Season

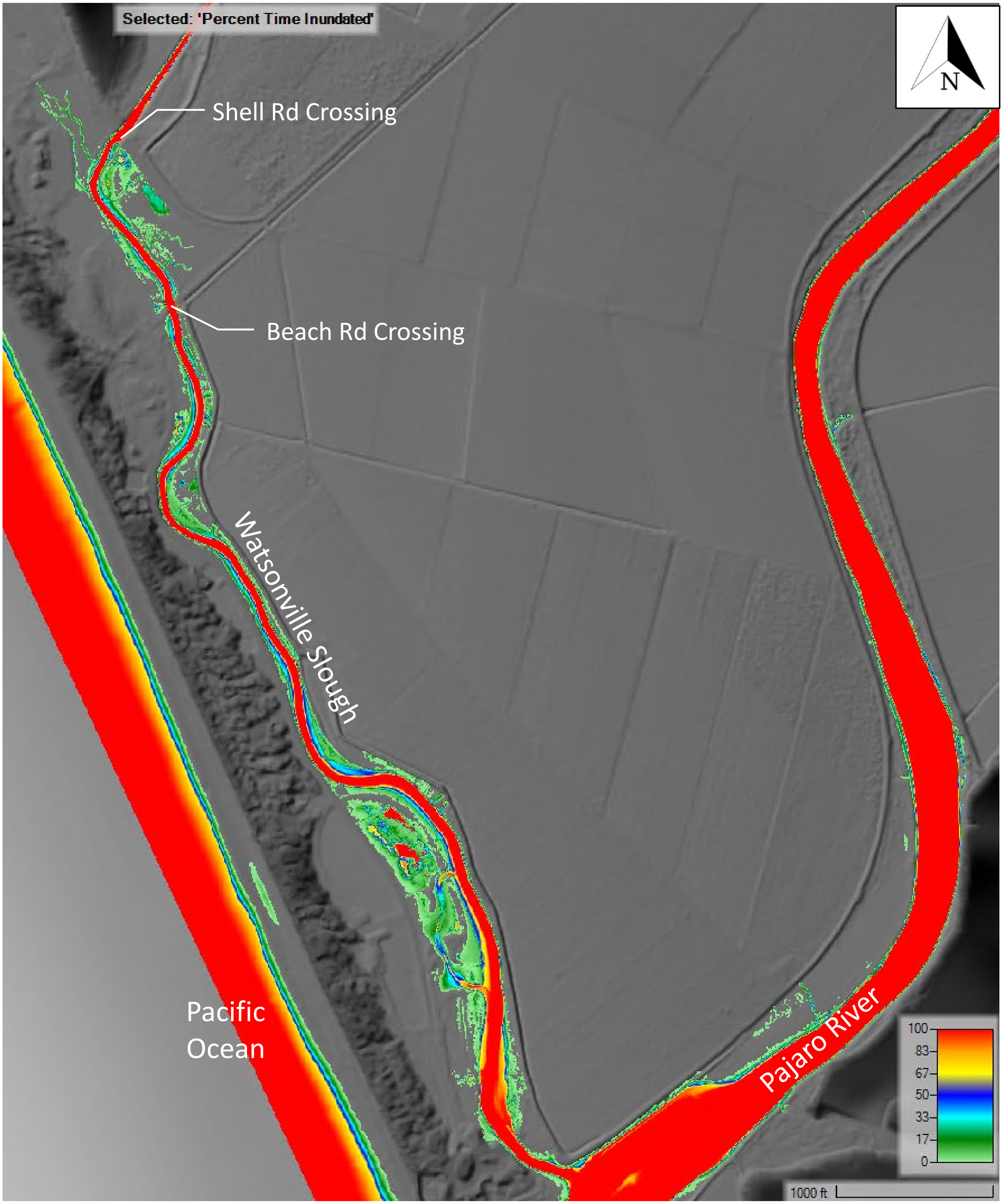


Figure 31: Percent time inundated – Crossing Improvements + Earthwork; Year 25; Open Lagoon, Dry Season

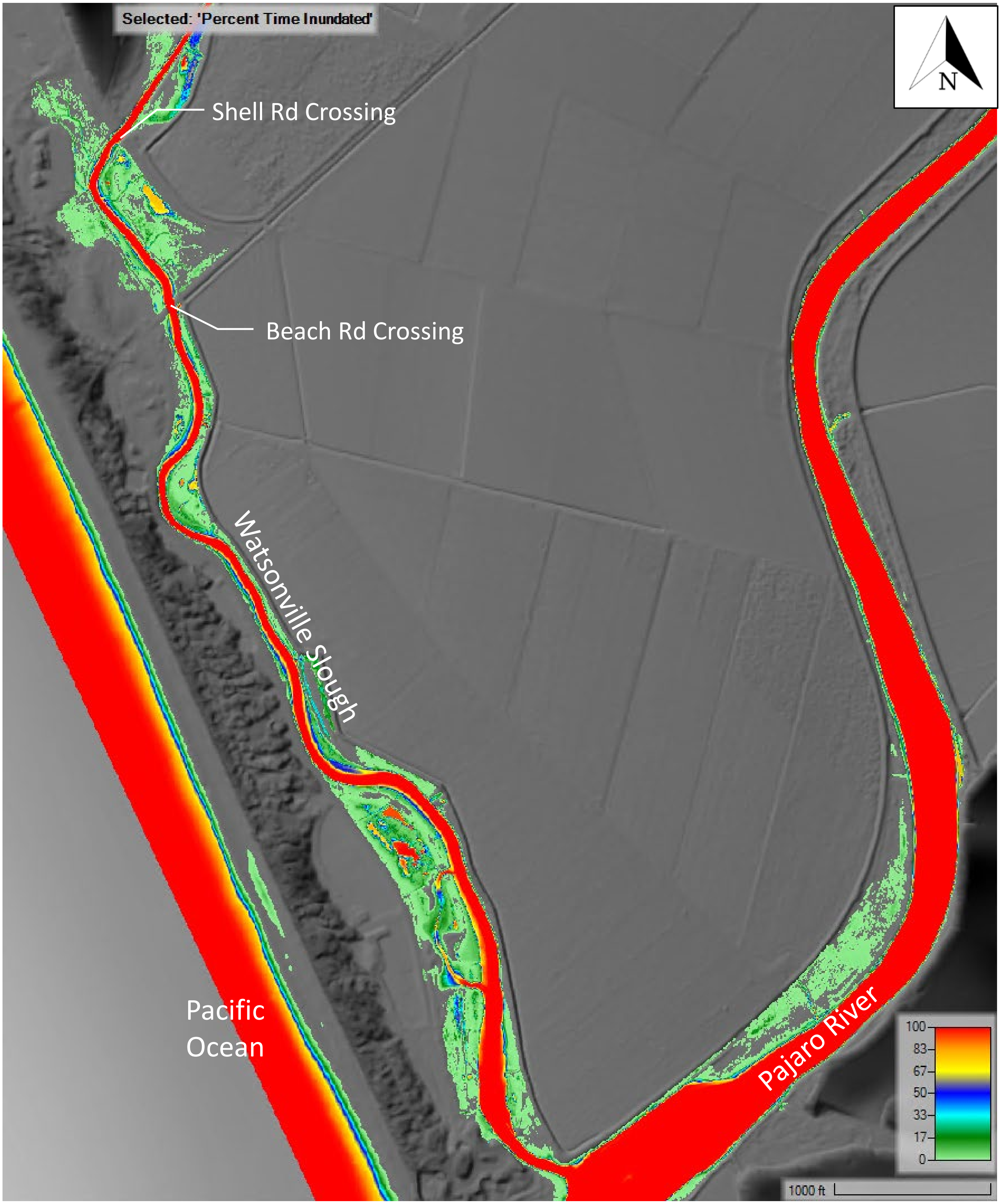


Figure 32: Percent time inundated – Crossing Improvements + Earthwork; Year 25; Open Lagoon, Wet Season

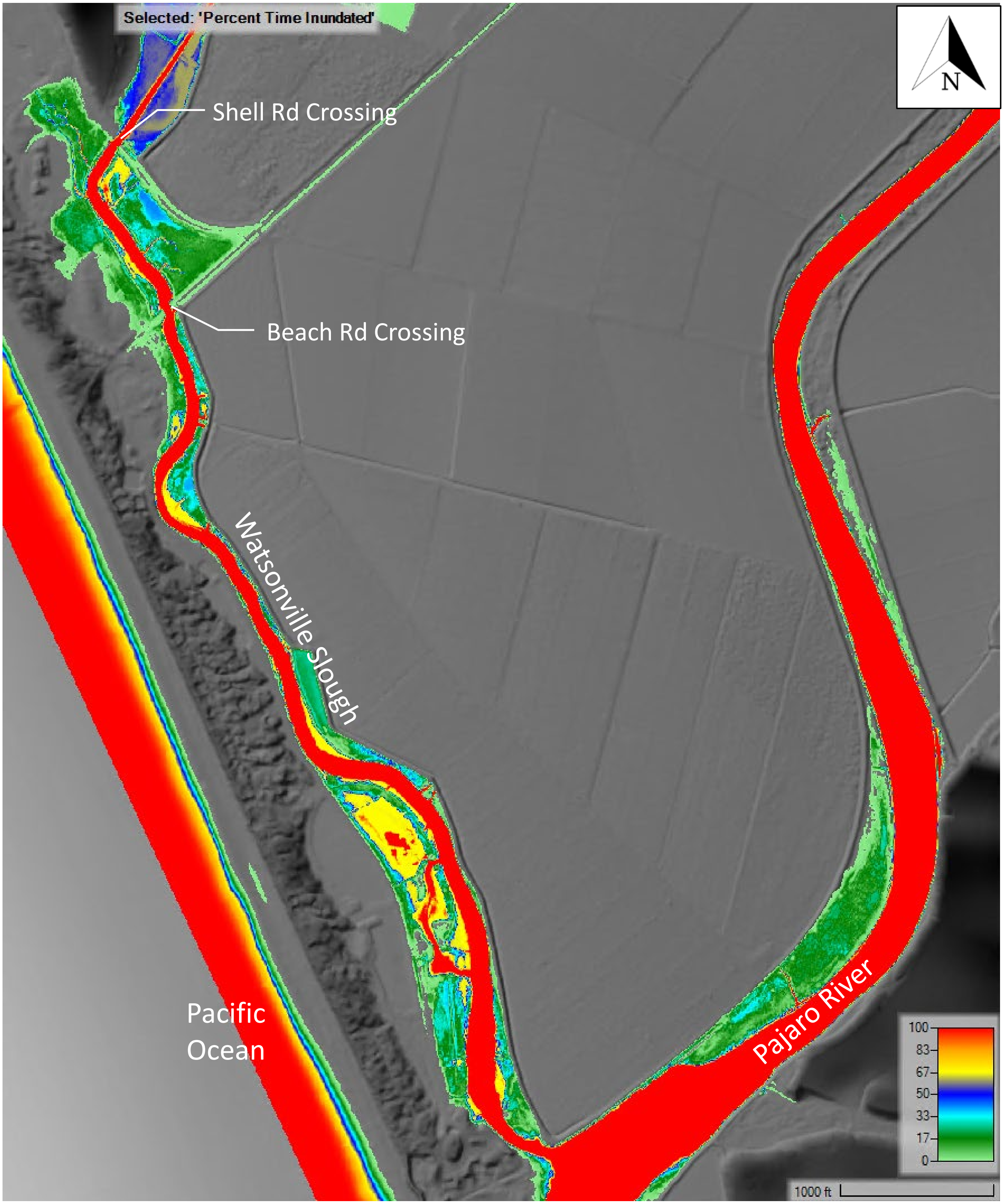


Figure 33: Percent time inundated – Crossing Improvements + Earthwork; Year 25; Closed Lagoon, Wet Season

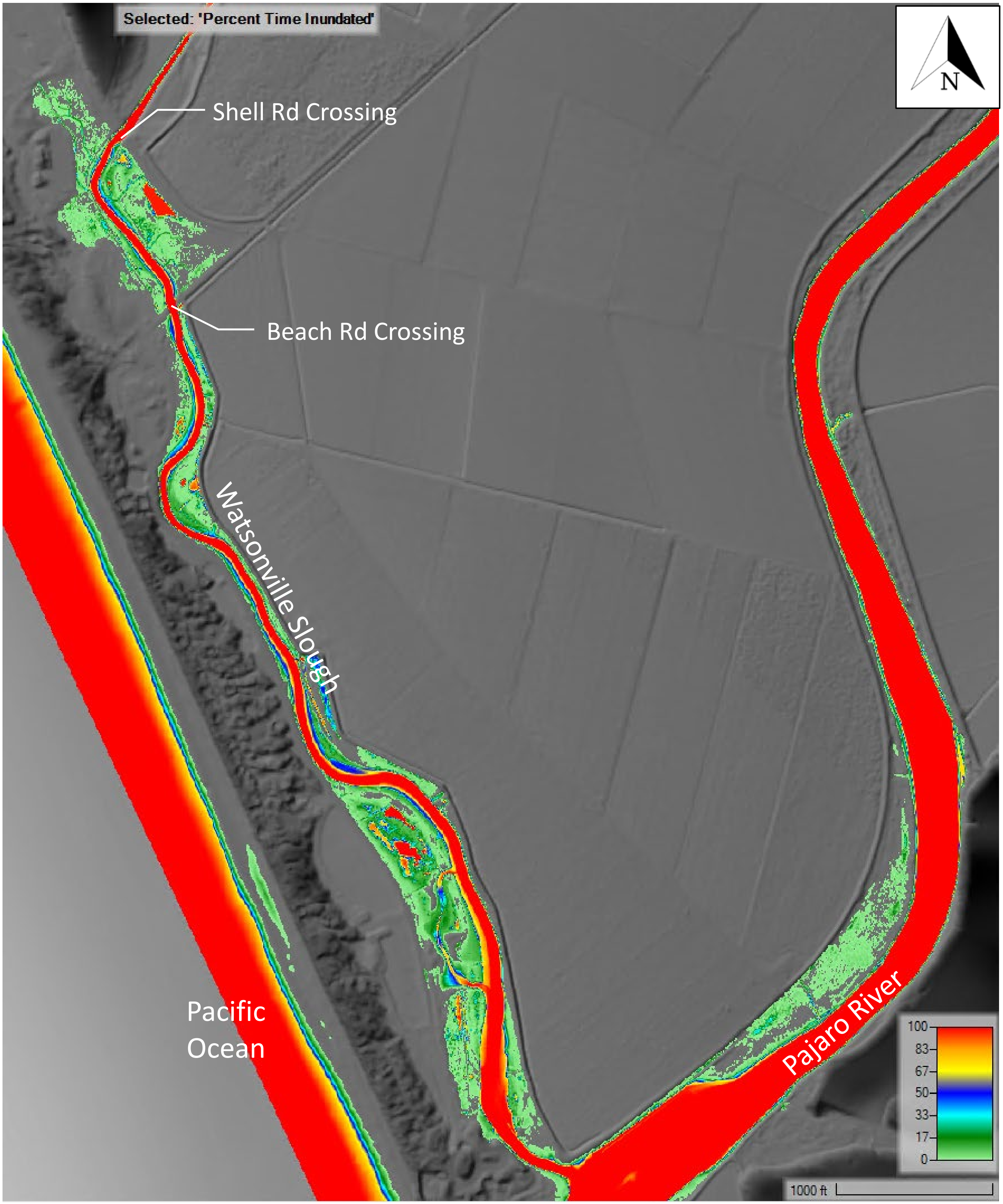


Figure 34: Percent time inundated – Crossing Improvements + Earthwork; Year 50; Open Lagoon, Dry Season

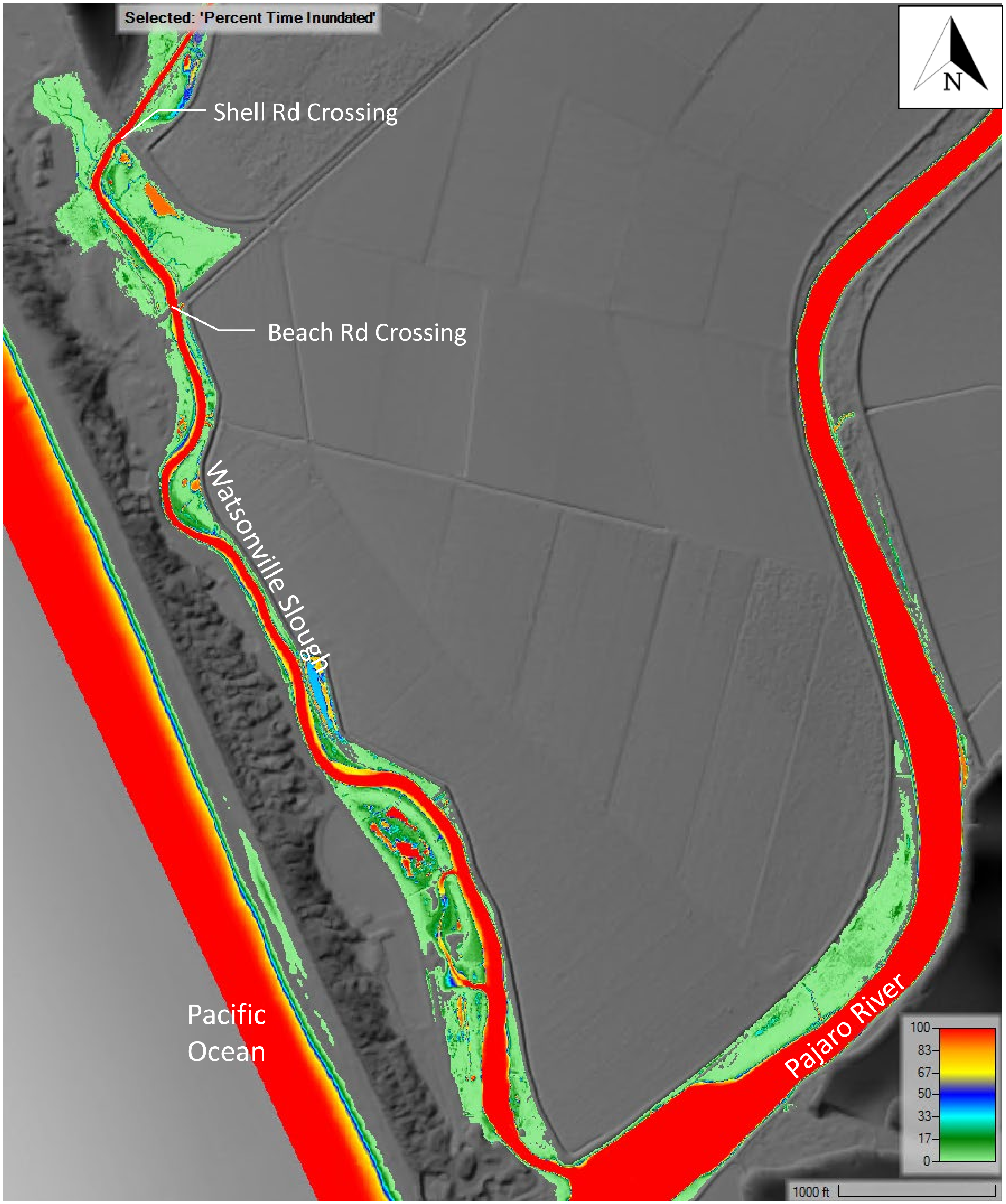


Figure 35: Percent time inundated – Crossing Improvements + Earthwork; Year 50; Open Lagoon, Wet Season

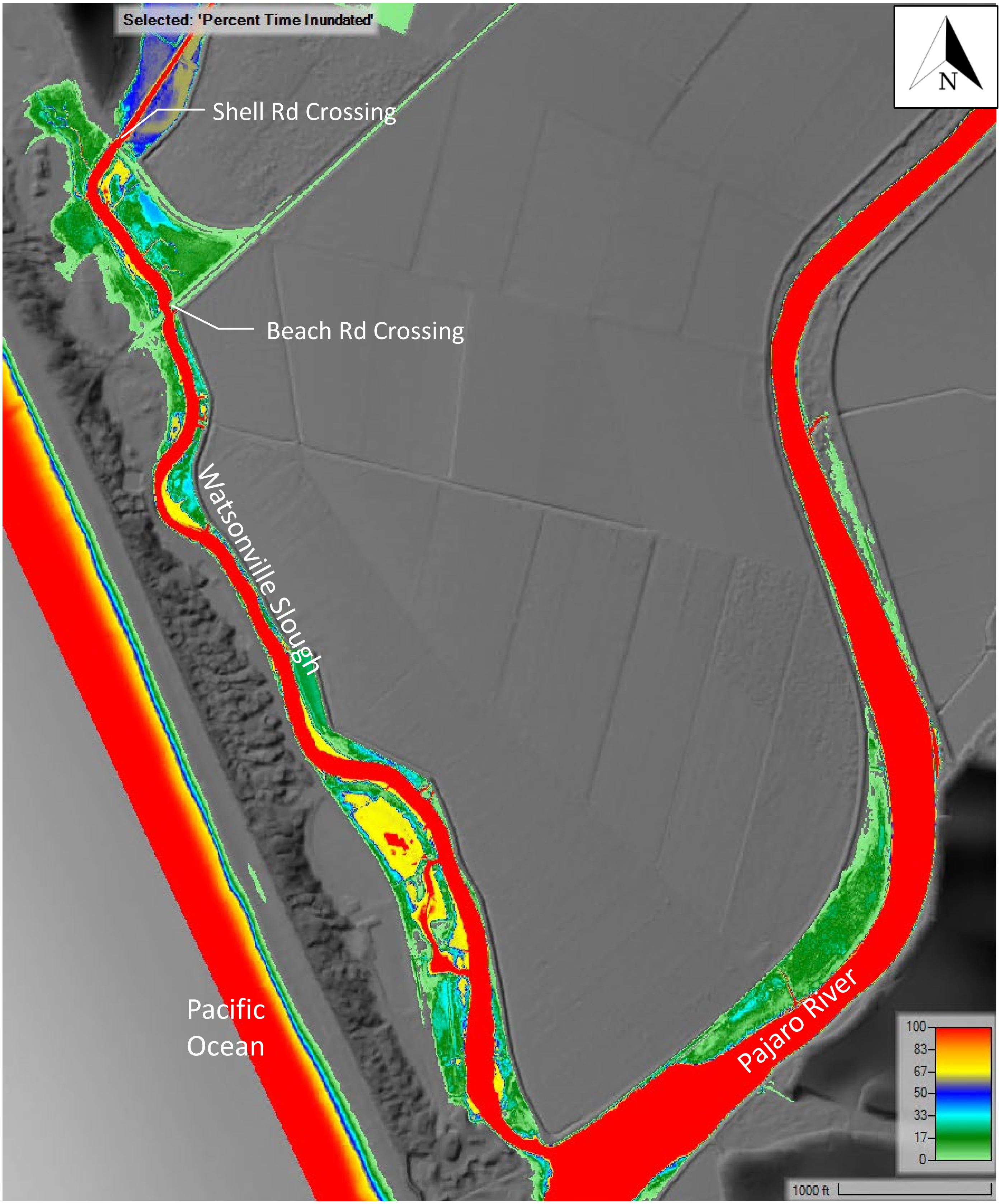


Figure 36: Percent time inundated – Crossing Improvements + Earthwork; Year 50; Closed Lagoon, Wet Season

Attachment C. Annualized Percent Time Inundated (PTI) Heat Maps

State and County Parcels

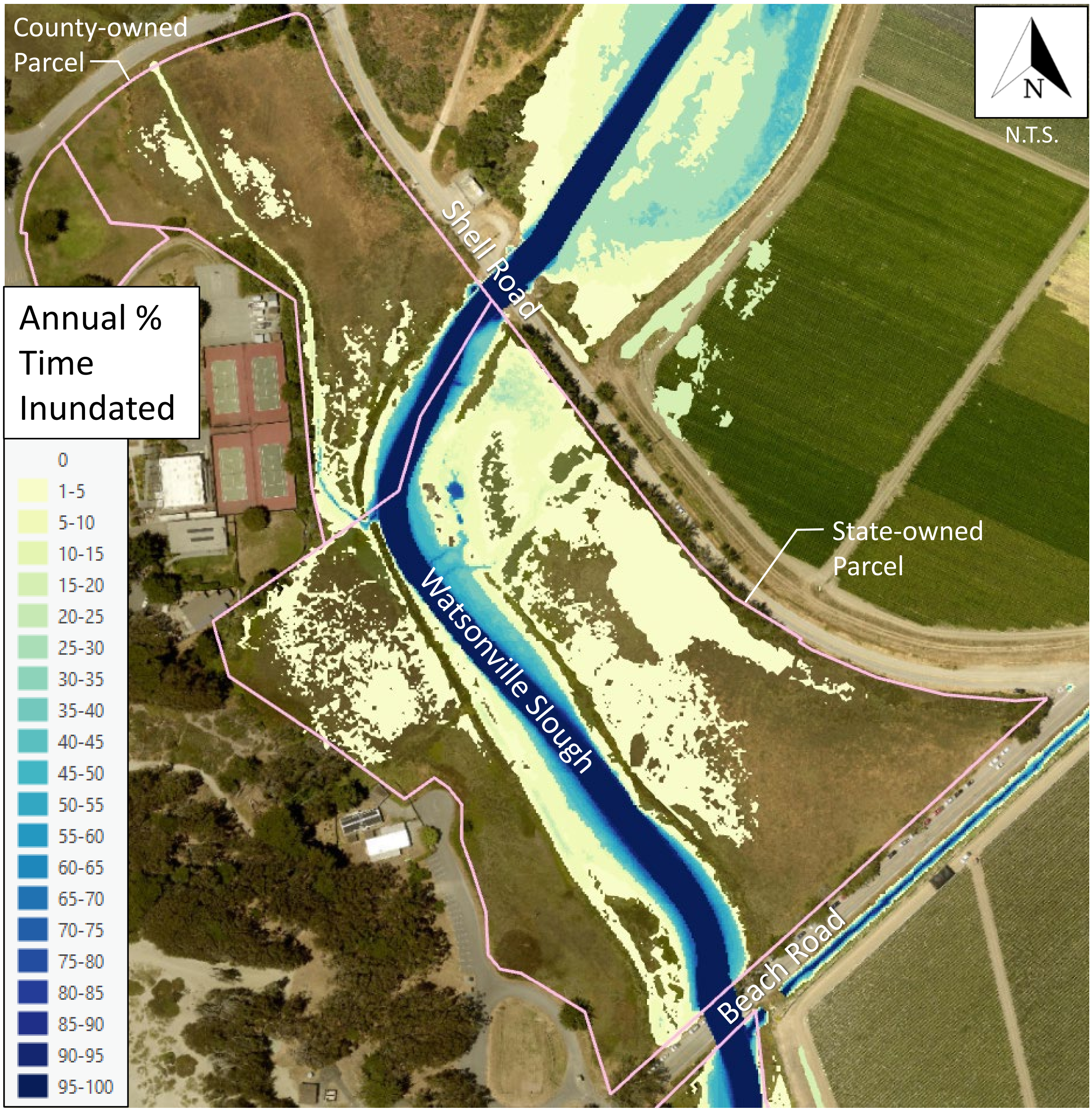


Figure 1: Annual PTI – State and County Parcels; Year 0; No Action

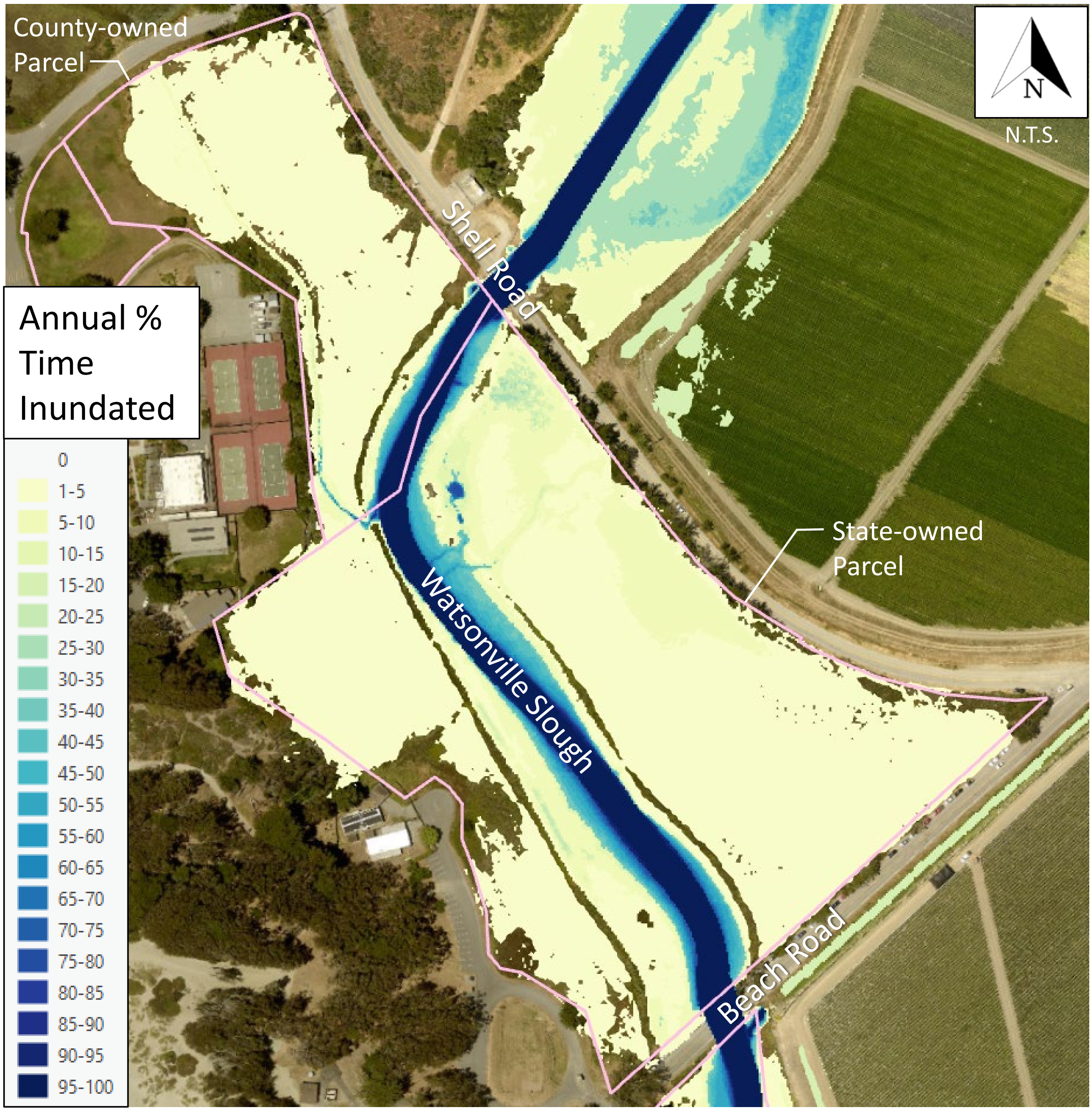


Figure 2: Annual PTI – State and County Parcels; Year 0; Crossing Improvements

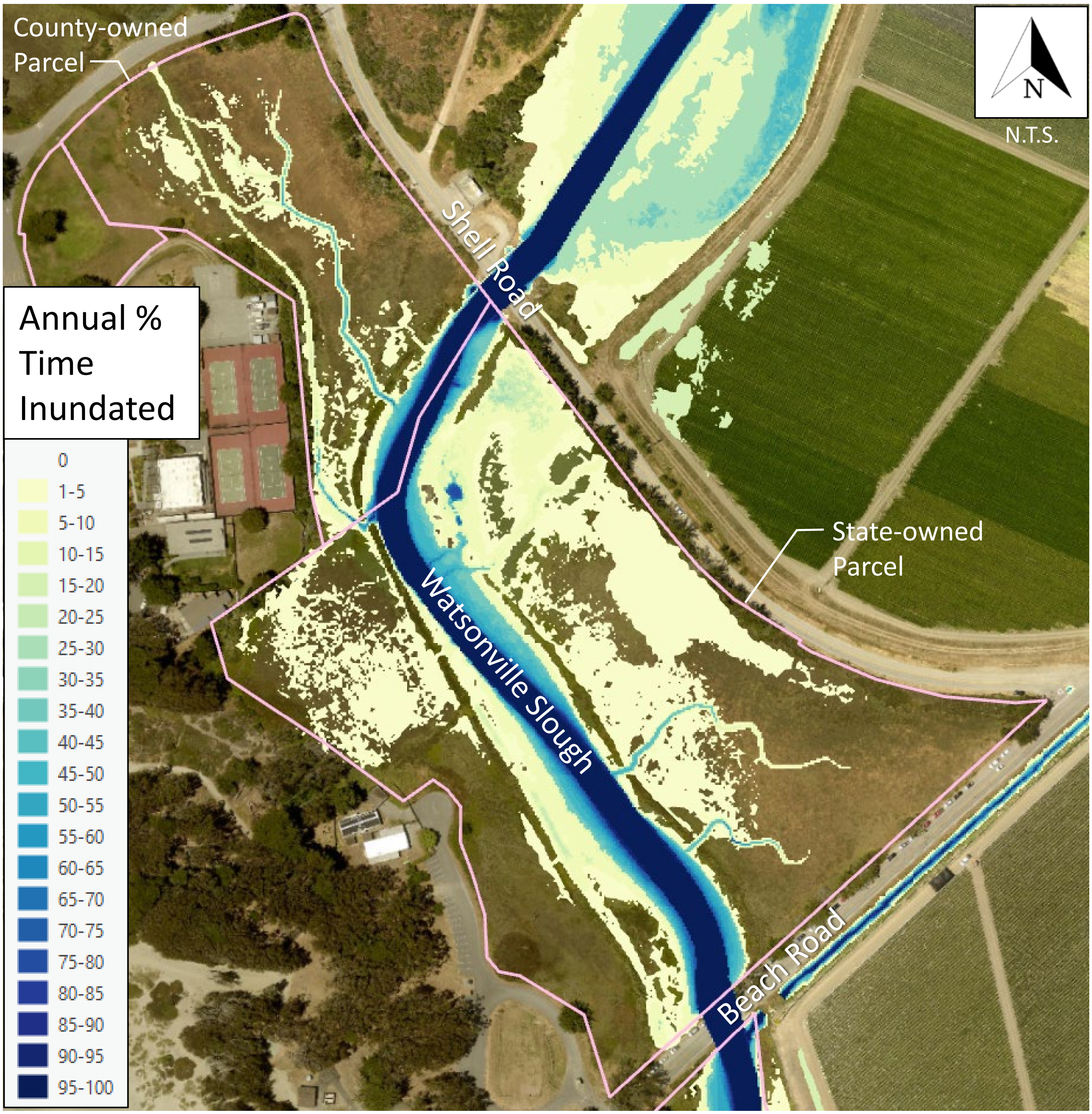


Figure 3: Annual PTI – State and County Parcels; Year 0; Earthwork

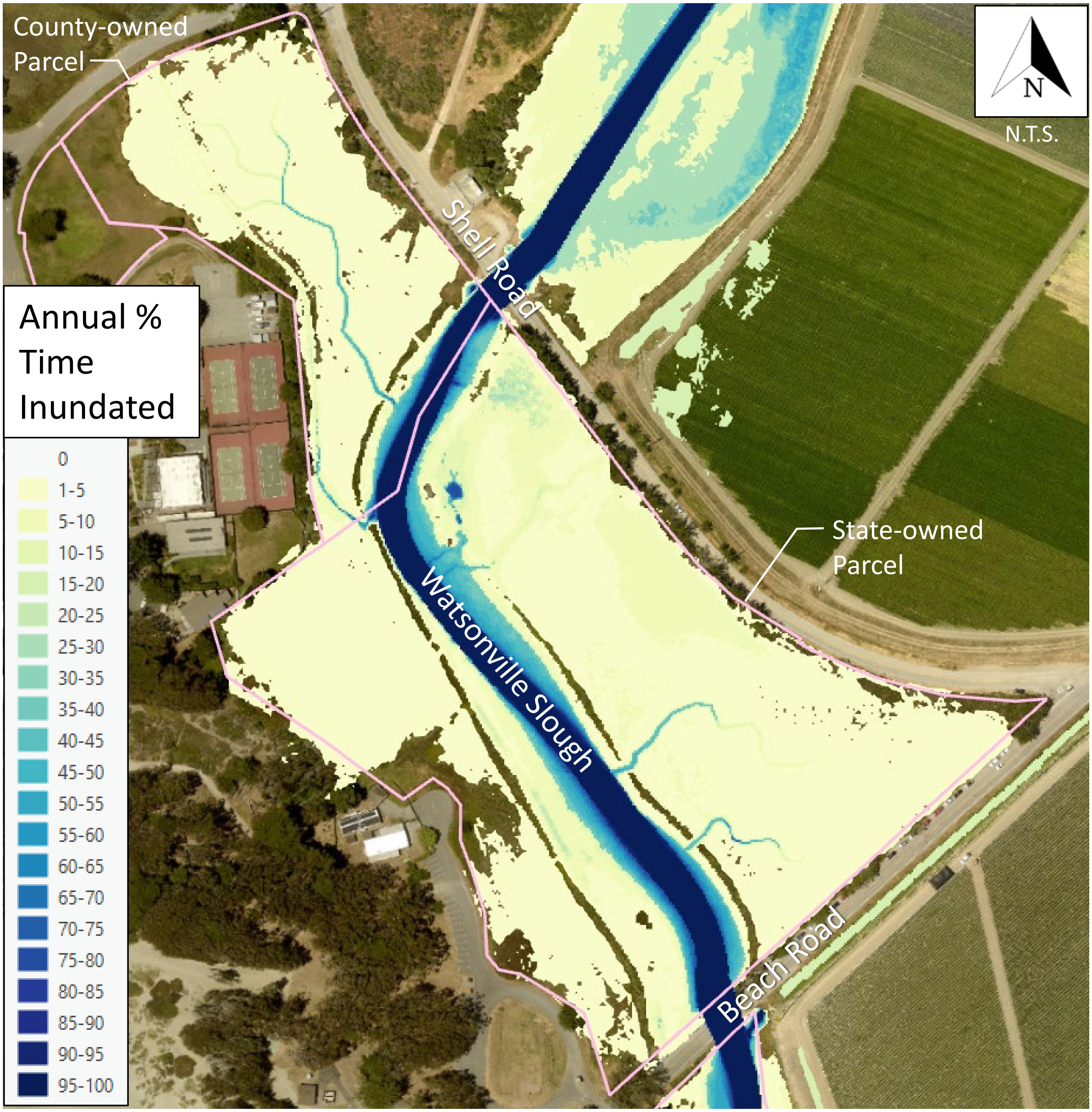


Figure 4: Annual PTI – State and County Parcels; Year 0; Crossing Improvements + Earthwork

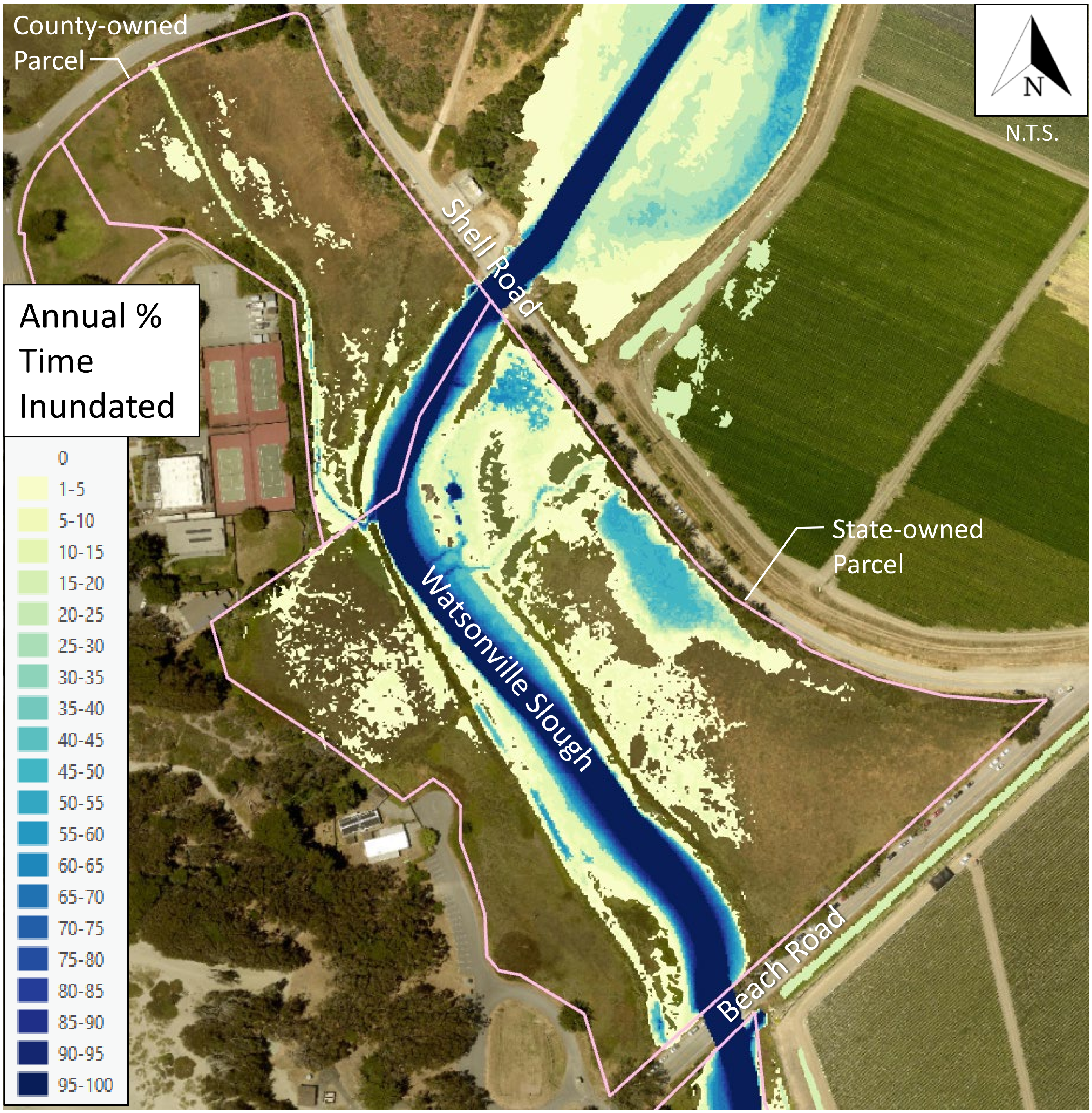


Figure 5: Annual PTI – State and County Parcels; Year 25; No Action

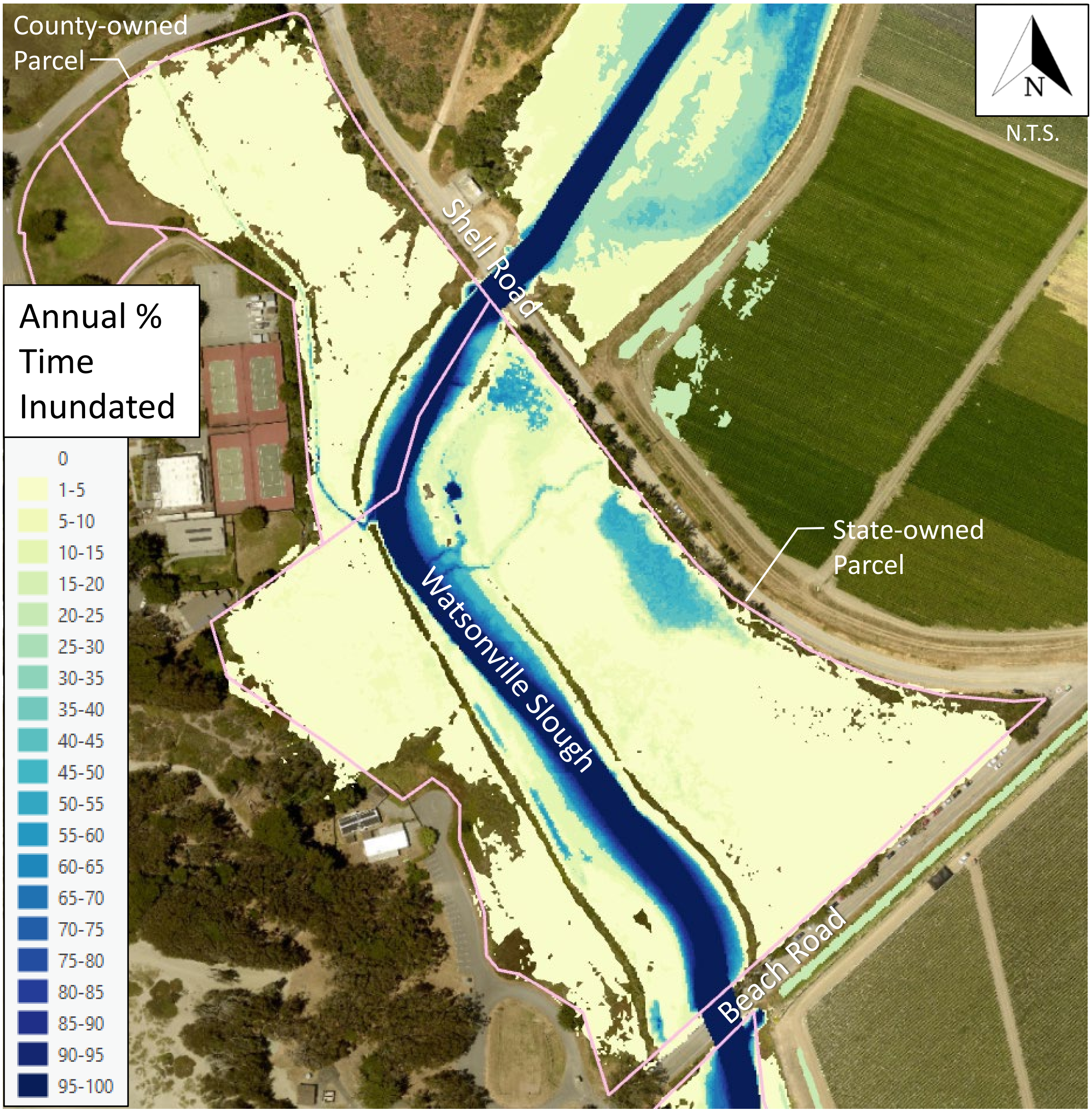


Figure 6: Annual PTI – State and County Parcels; Year 25; Crossing Improvements

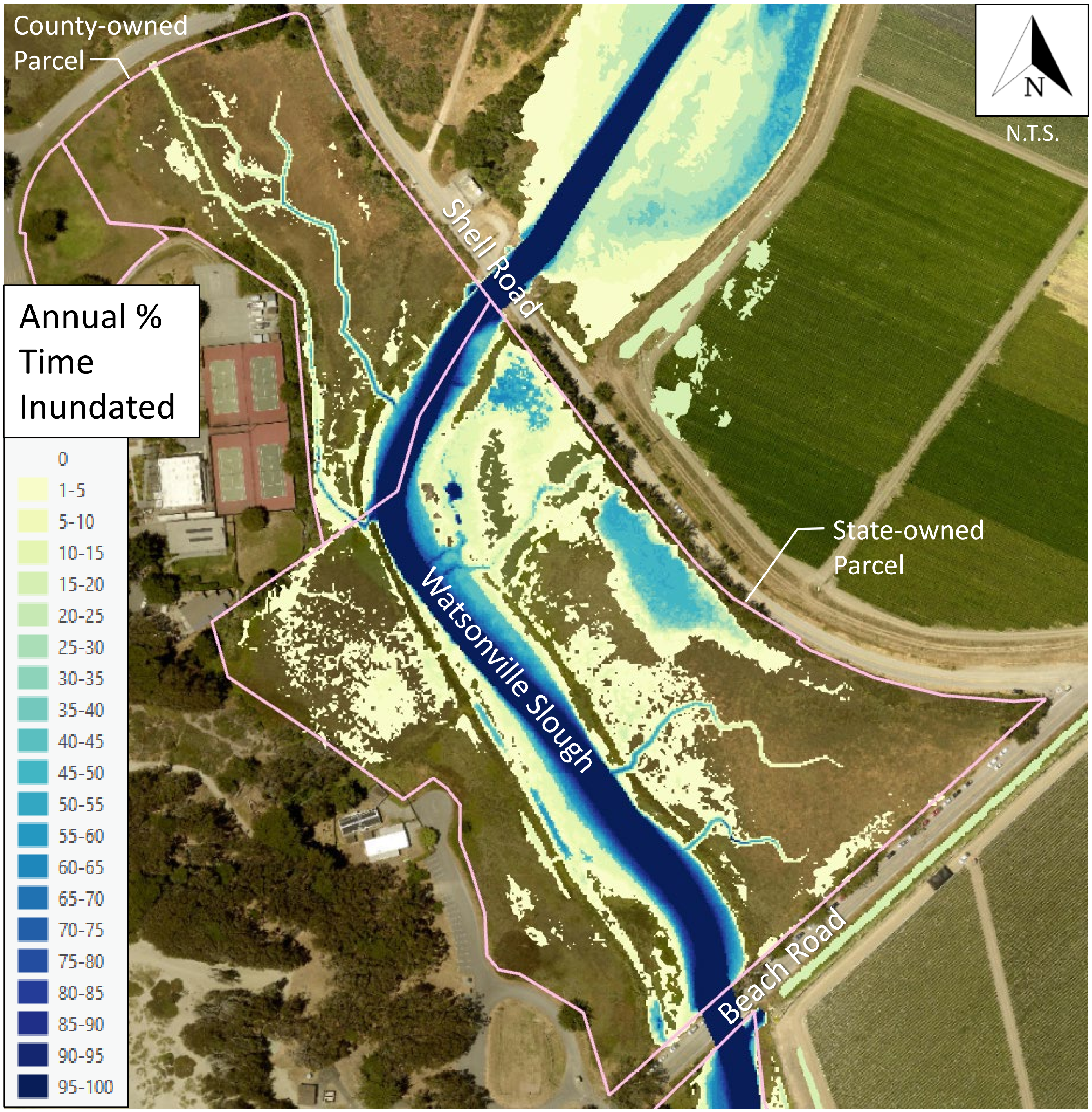


Figure 7: Annual PTI – State and County Parcels; Year 25; Earthwork

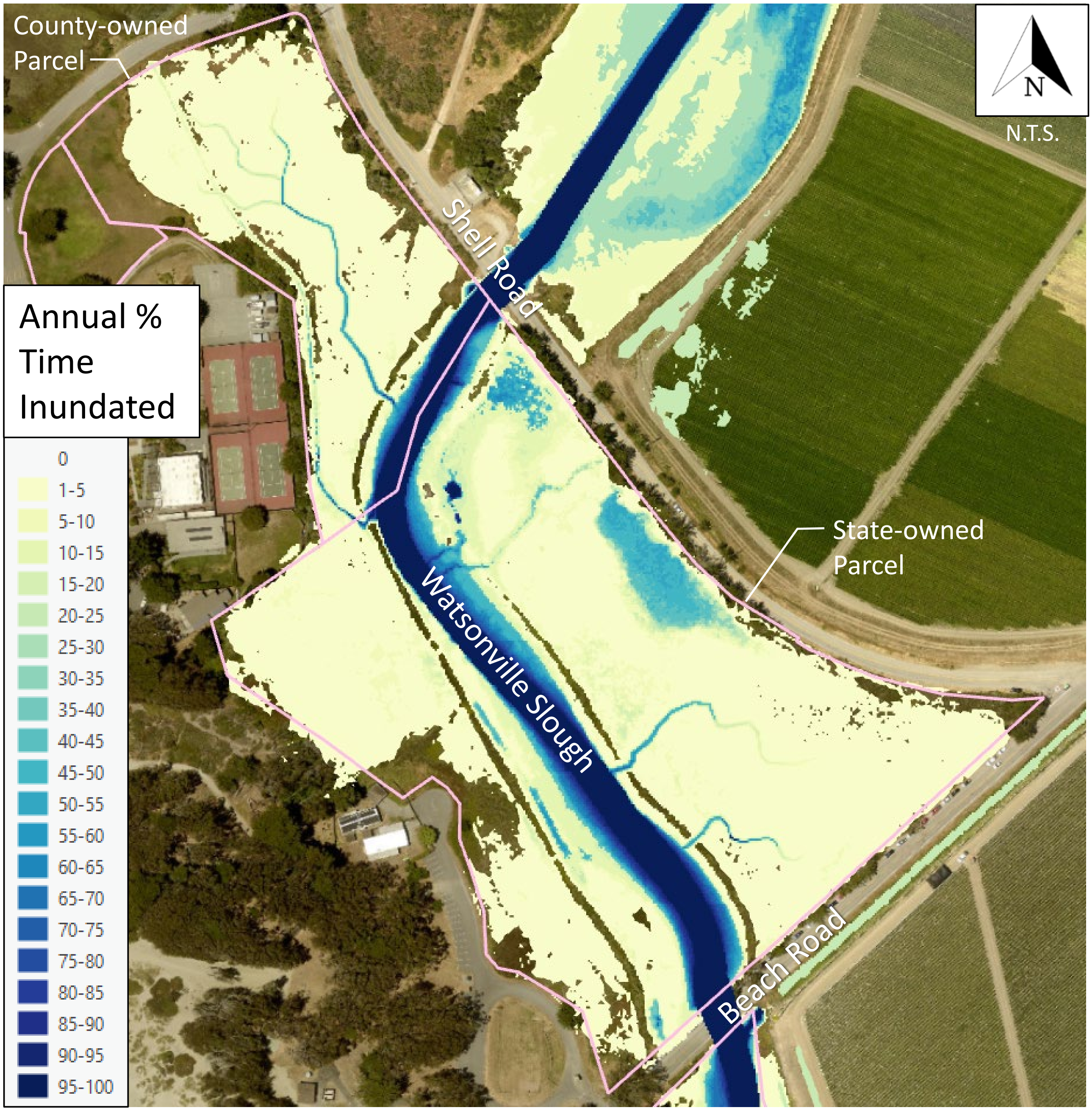


Figure 8: Annual PTI – State and County Parcels; Year 25; Crossing Improvements + Earthwork

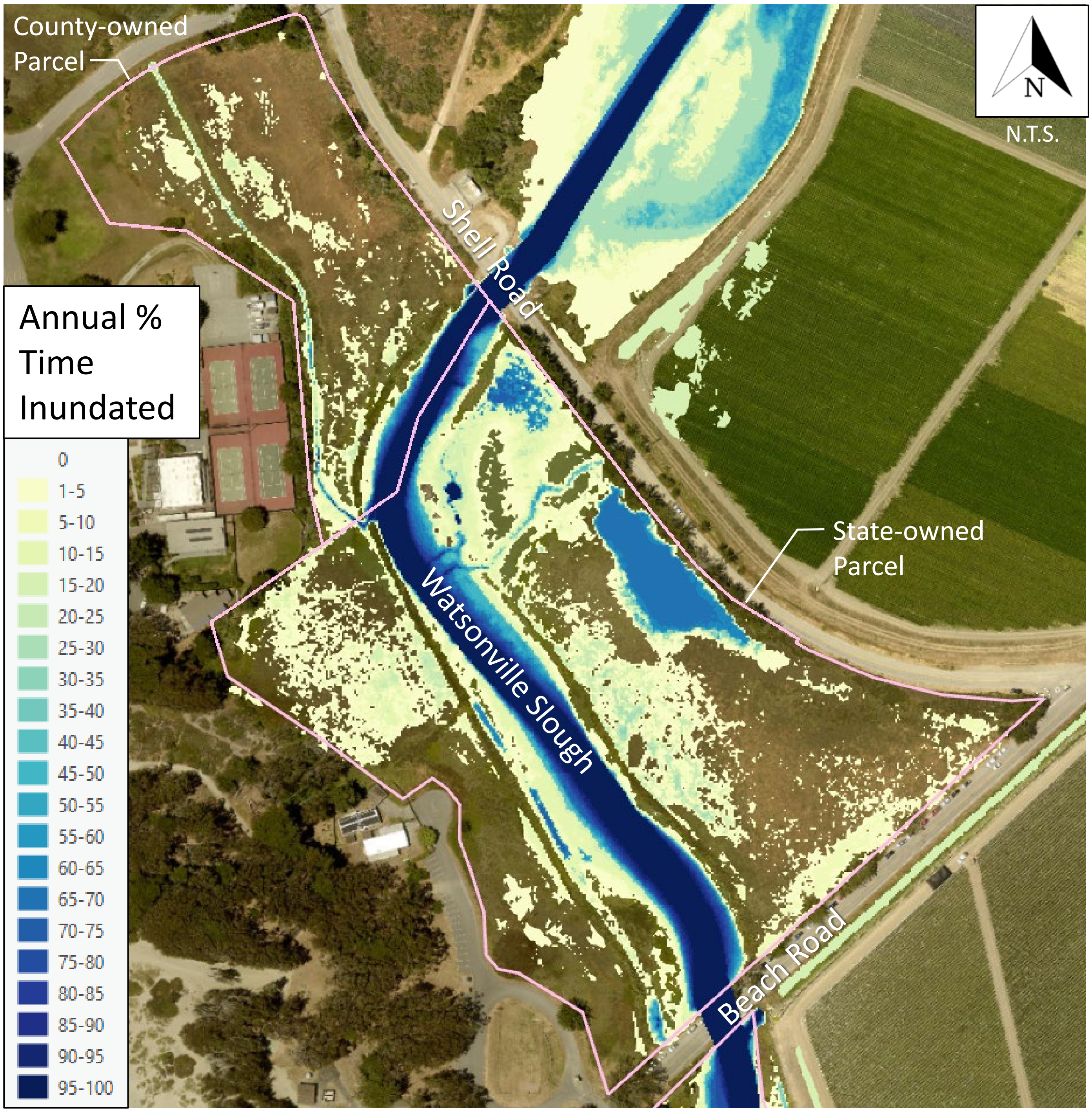


Figure 9: Annual PTI – State and County Parcels; Year 50; No Action

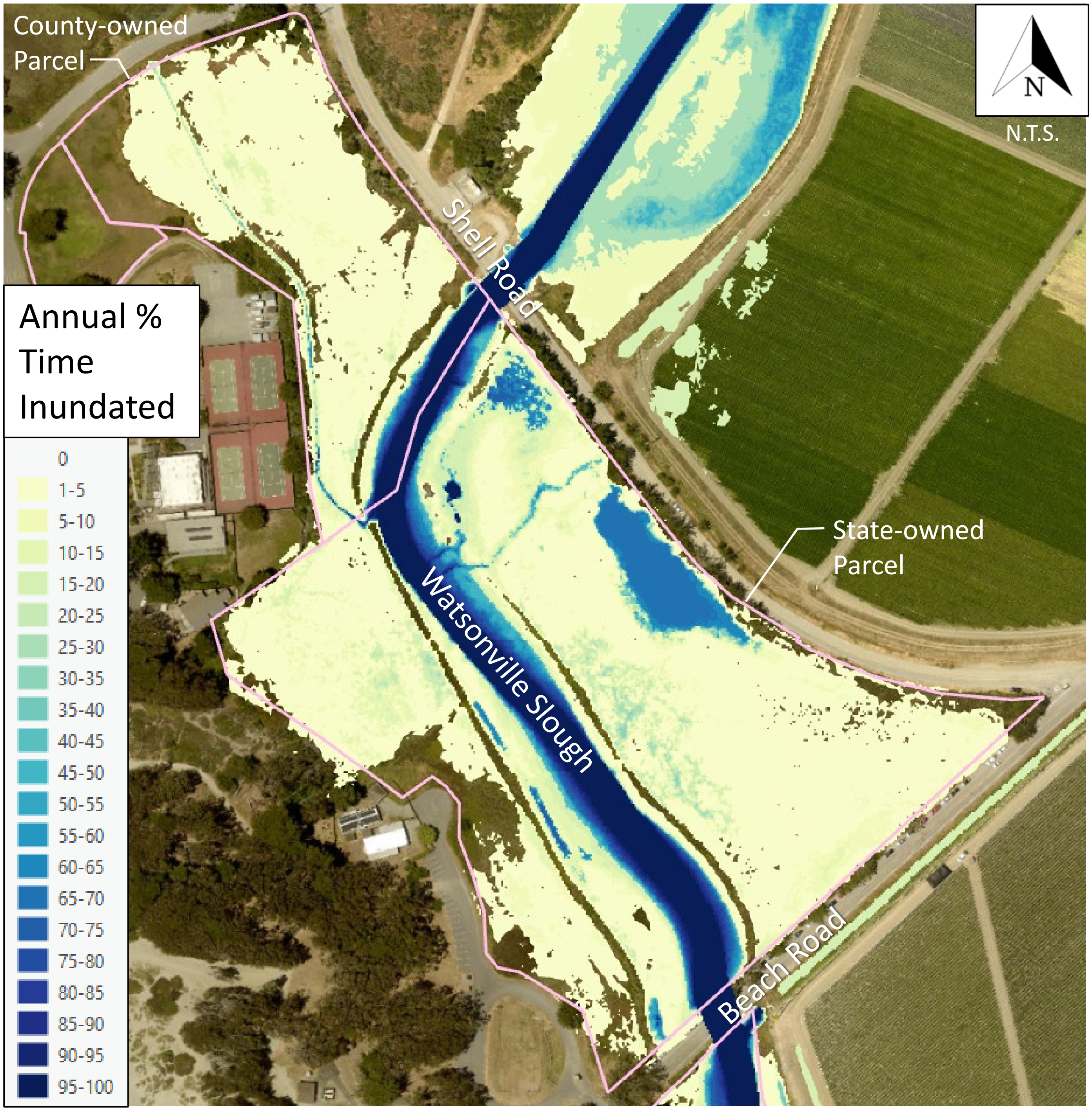


Figure 10: Annual PTI – State and County Parcels; Year 50; Crossing Improvements

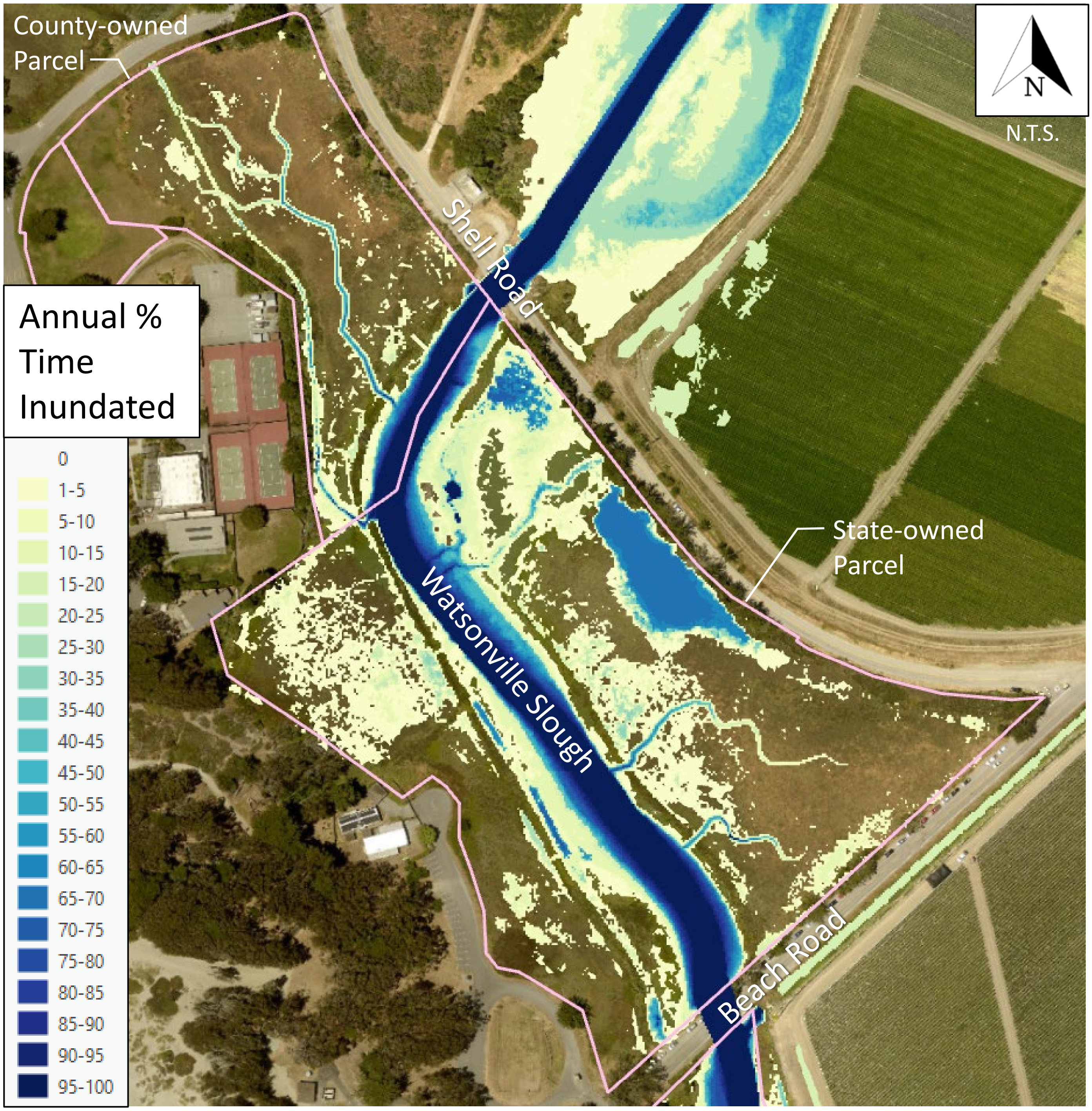


Figure 11: Annual PTI – State and County Parcels; Year 50; Earthwork

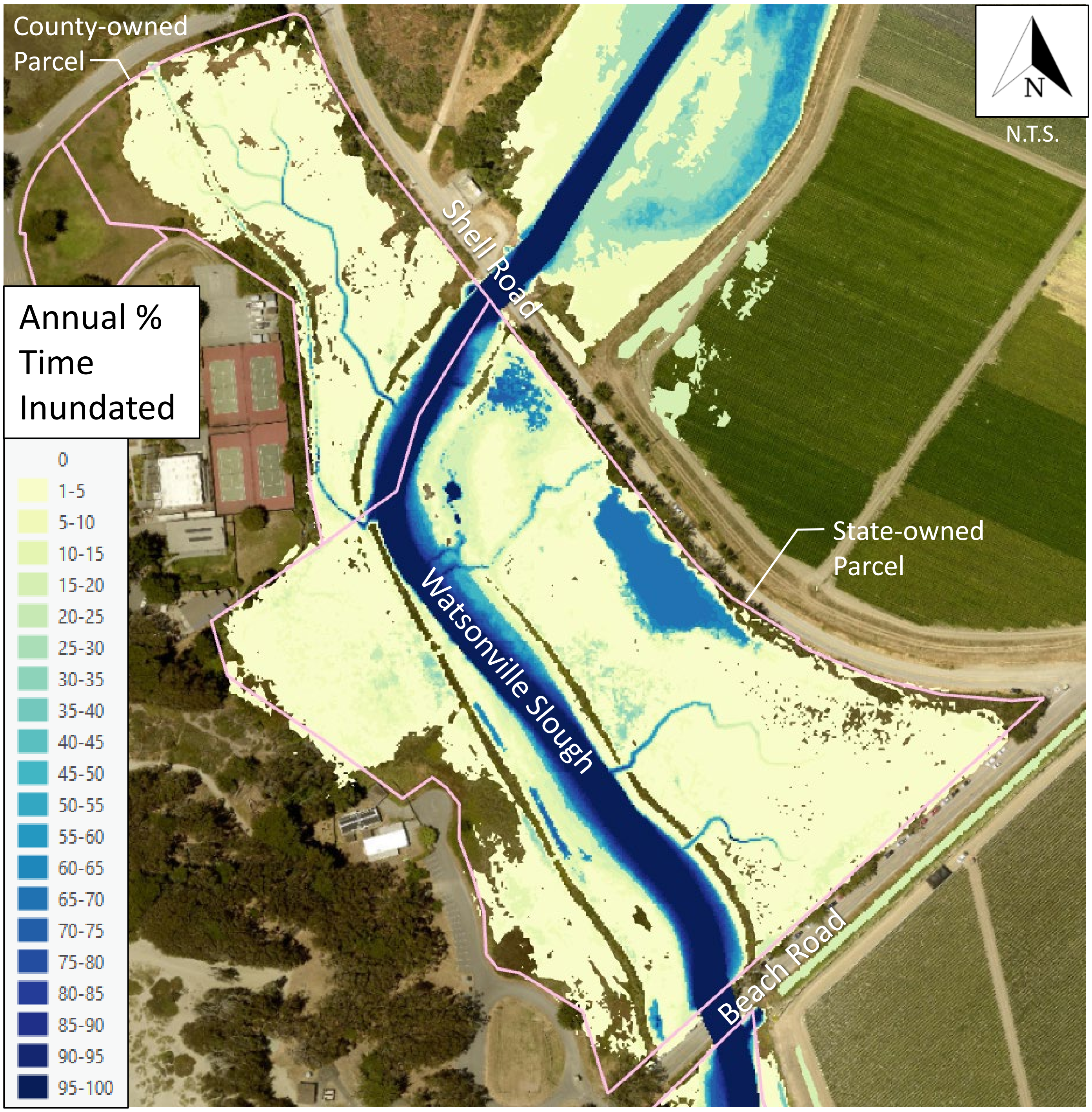


Figure 12: Annual PTI – State and County Parcels; Year 50; Crossing Improvements + Earthwork

Lower Mile,
Upstream Parcel

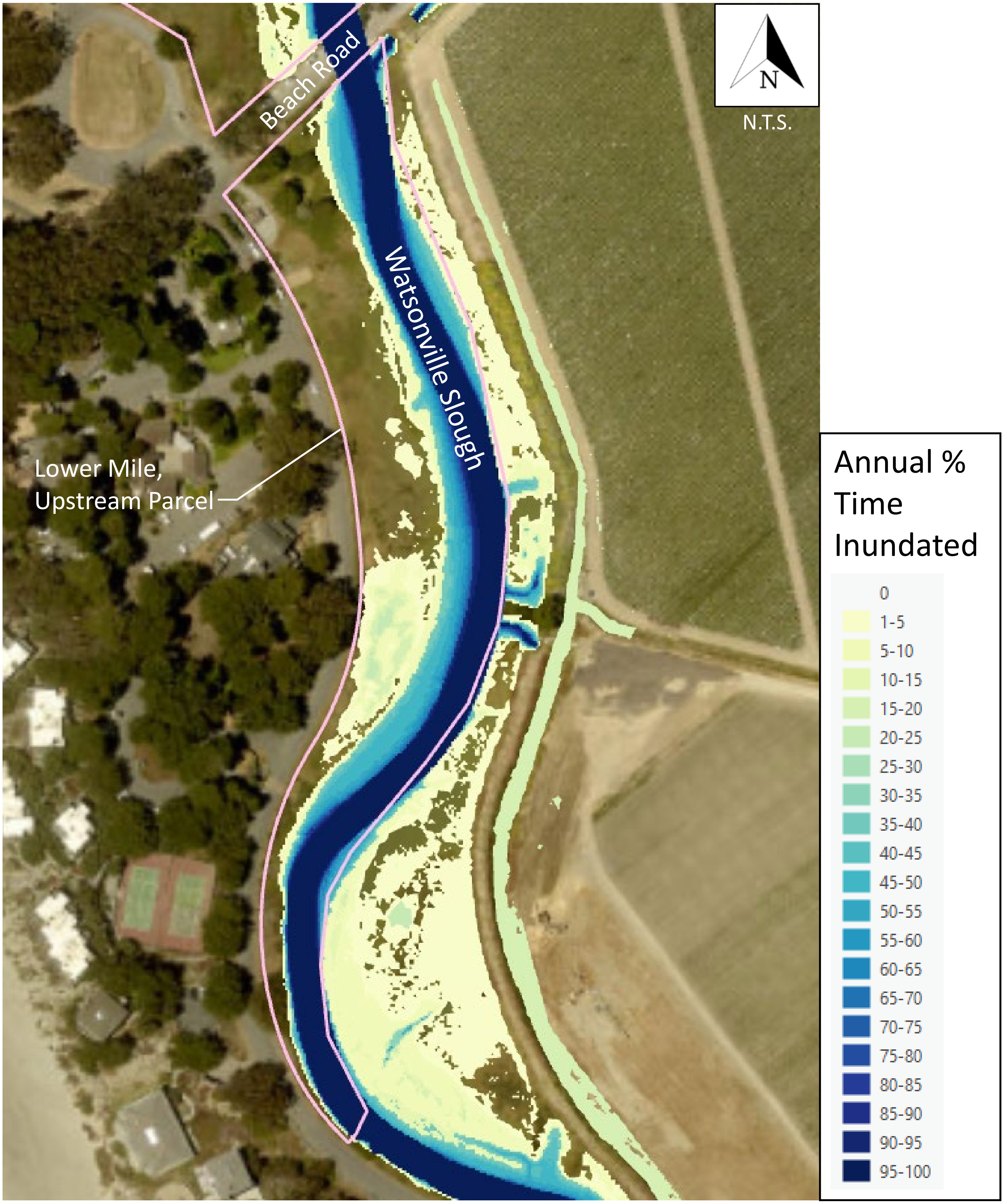


Figure 13: Annual PTI – Lower Mile, Upstream Parcel; Year 0; No Action

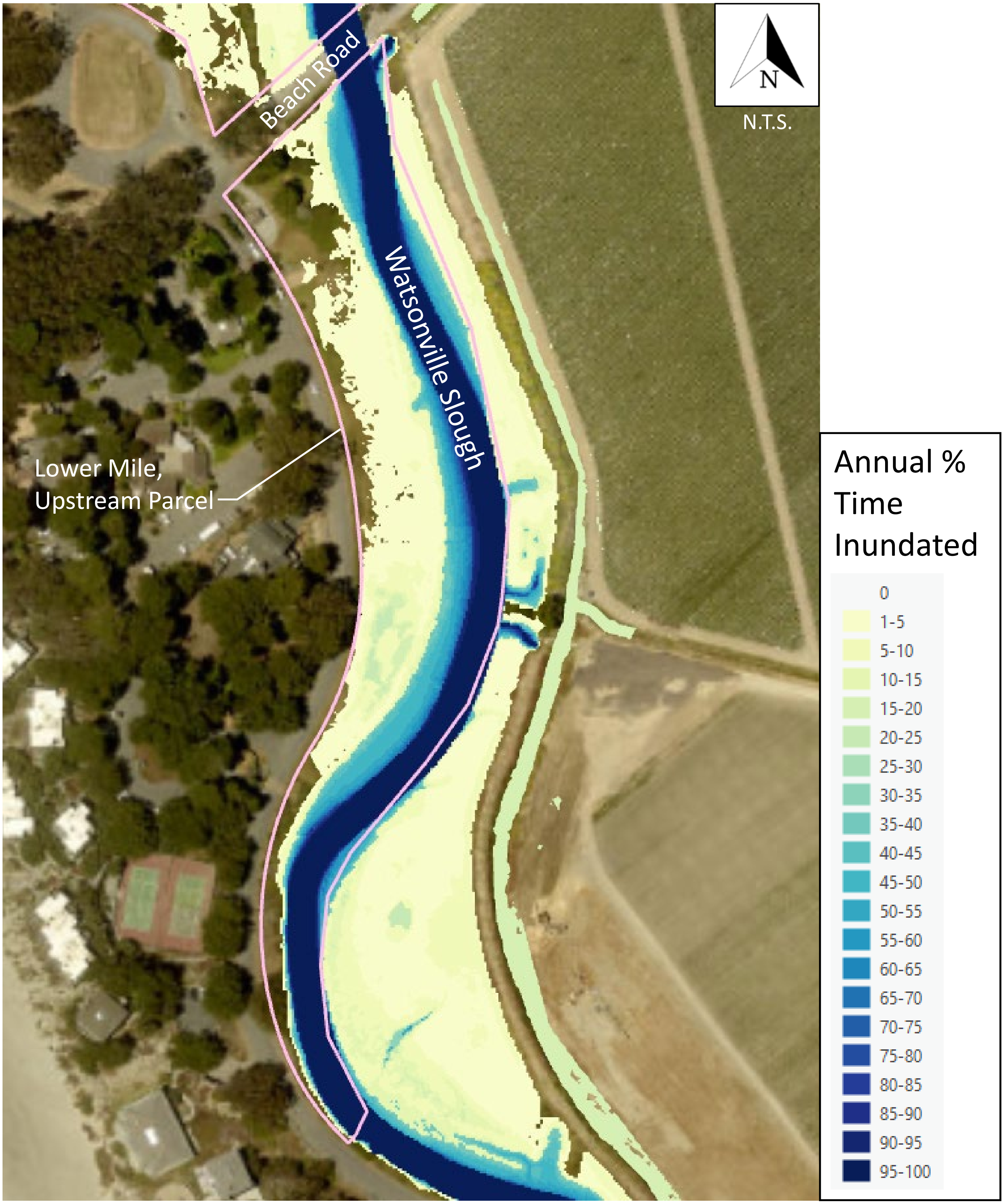


Figure 14: Annual PTI – Lower Mile, Upstream Parcel; Year 0; Crossing Improvements

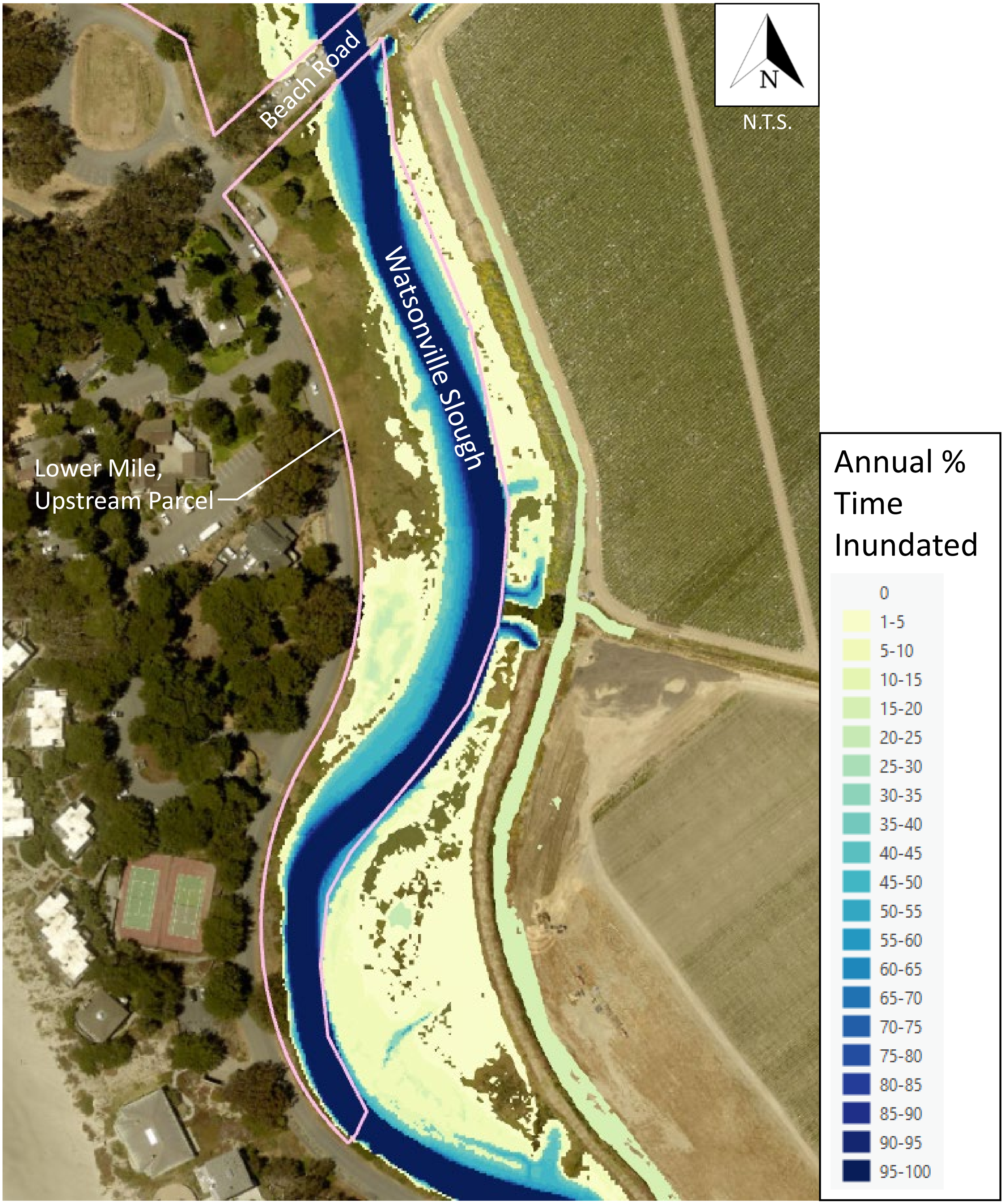


Figure 15: Annual PTI – Lower Mile, Upstream Parcel; Year 0; Earthwork

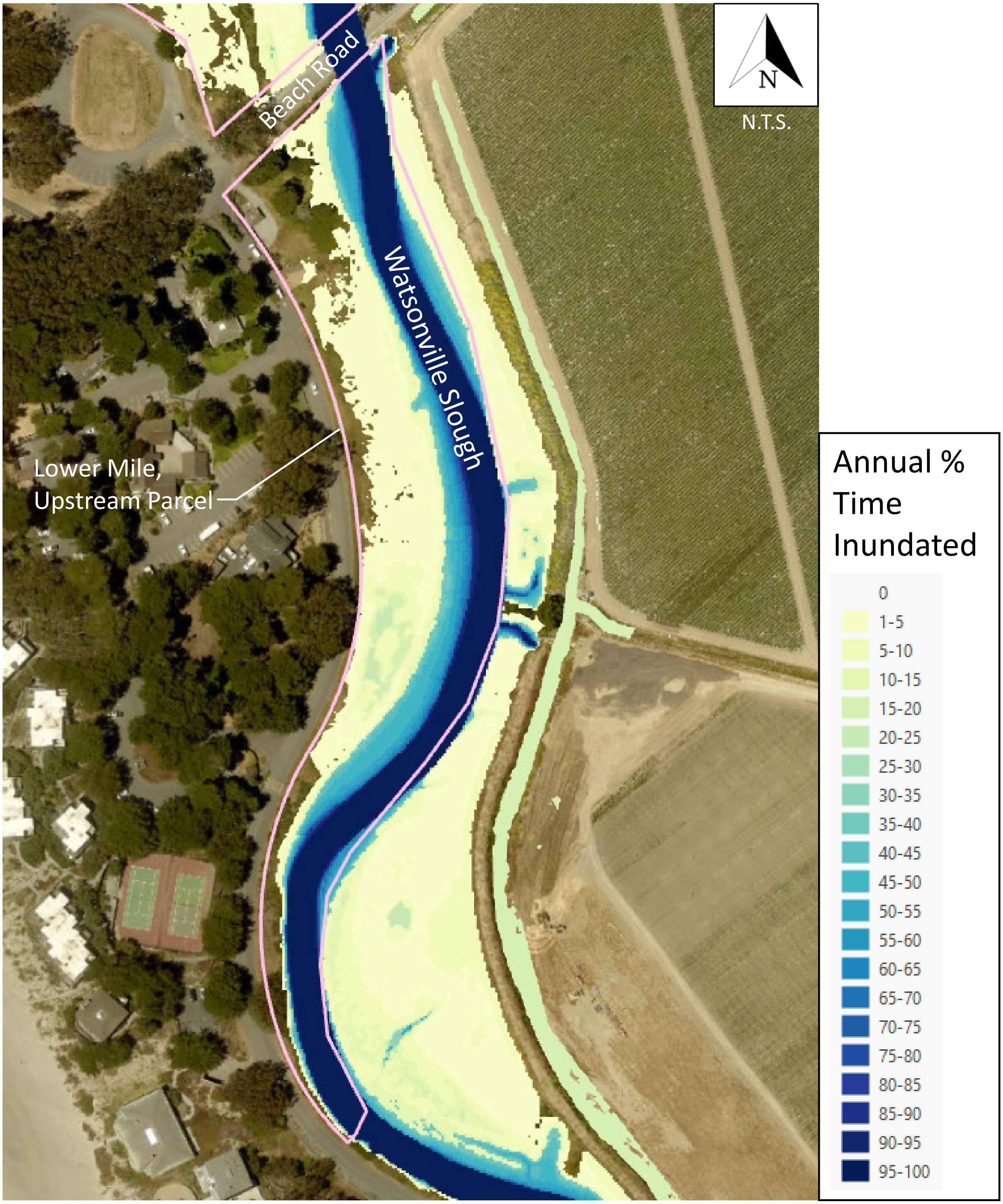


Figure 16: Annual PTI – Lower Mile, Upstream Parcel; Year 0; Crossing Improvements + Earthwork

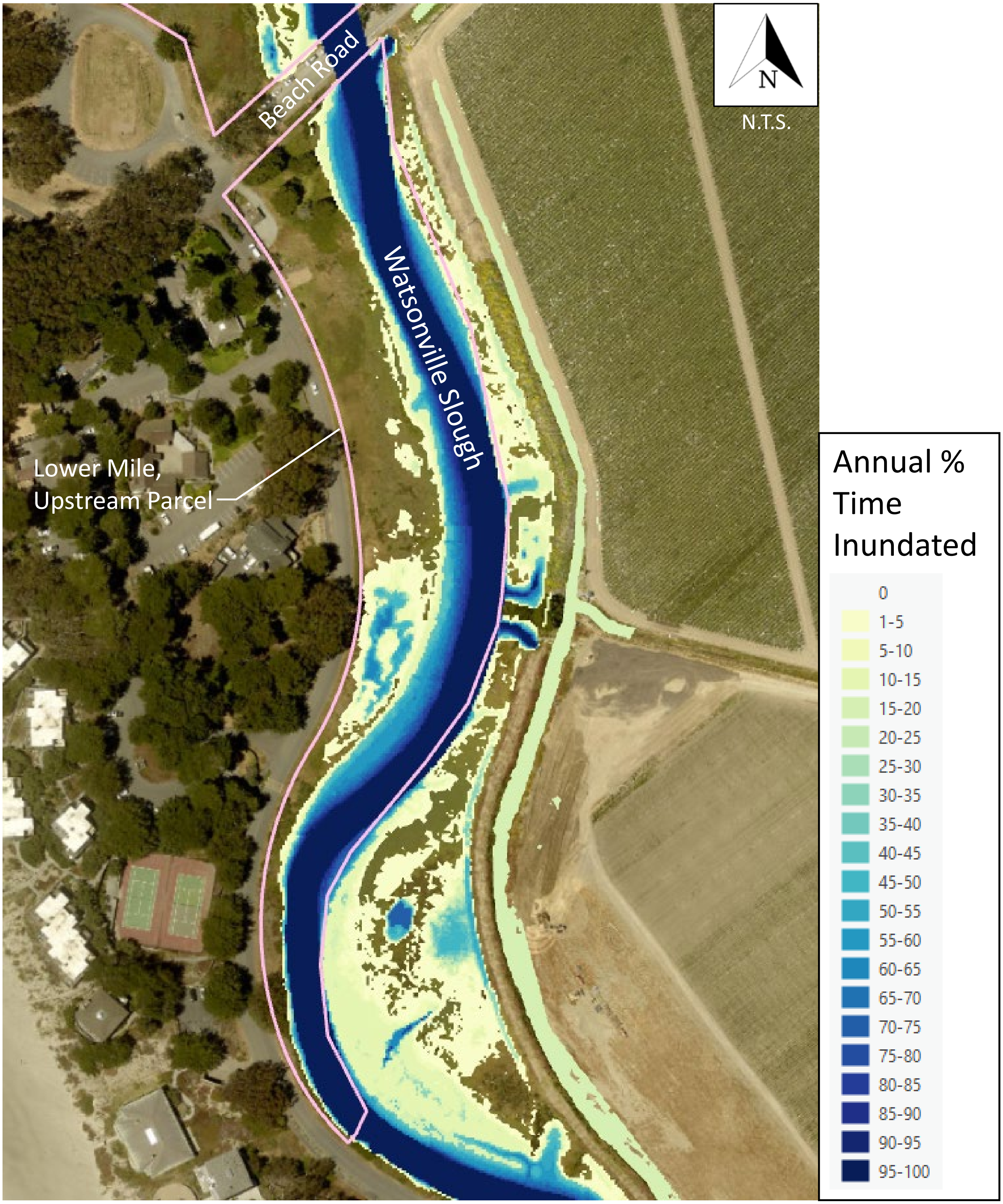


Figure 17: Annual PTI – Lower Mile, Upstream Parcel; Year 25; No Action

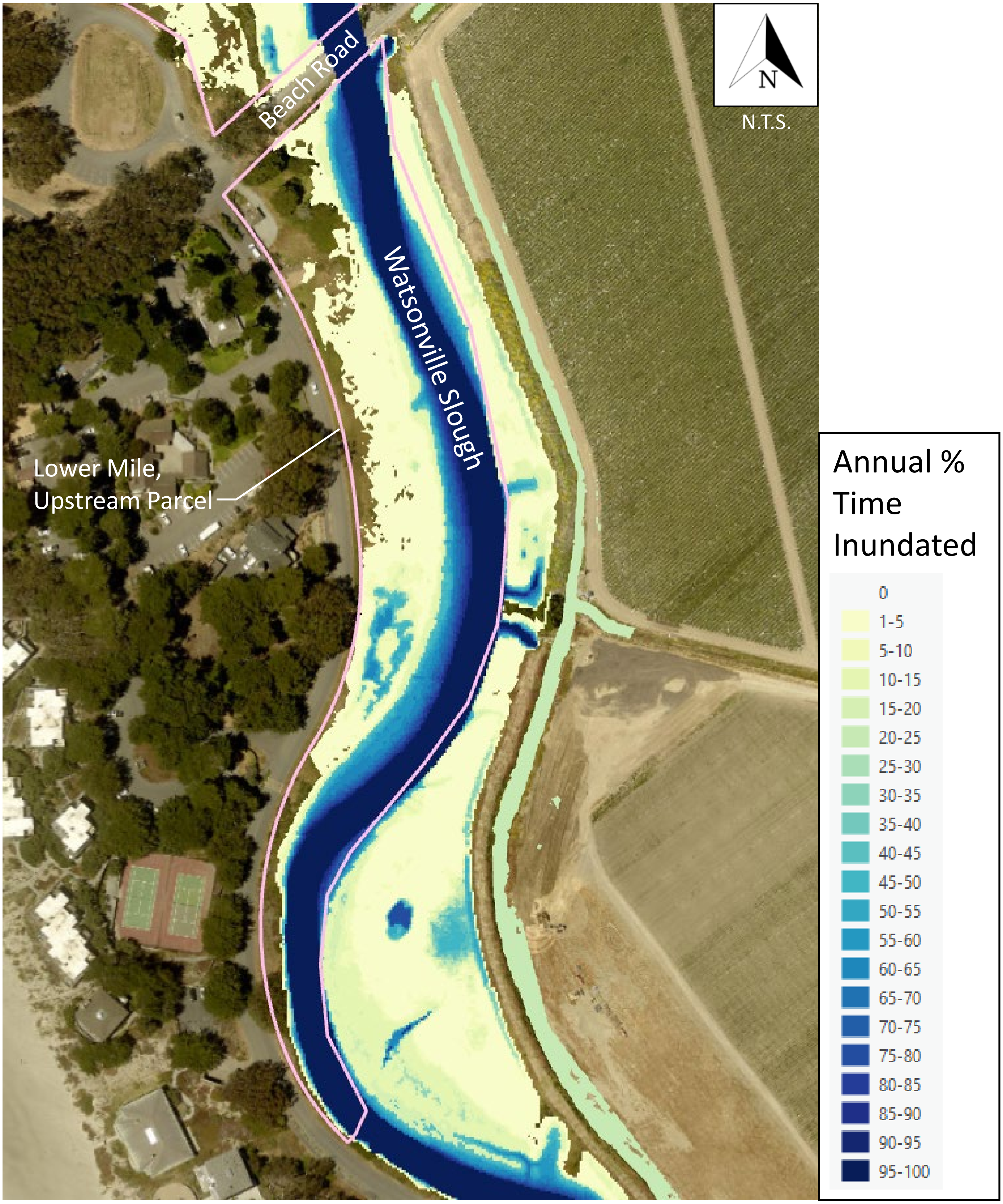


Figure 18: Annual PTI – Lower Mile, Upstream Parcel; Year 25; Crossing Improvements

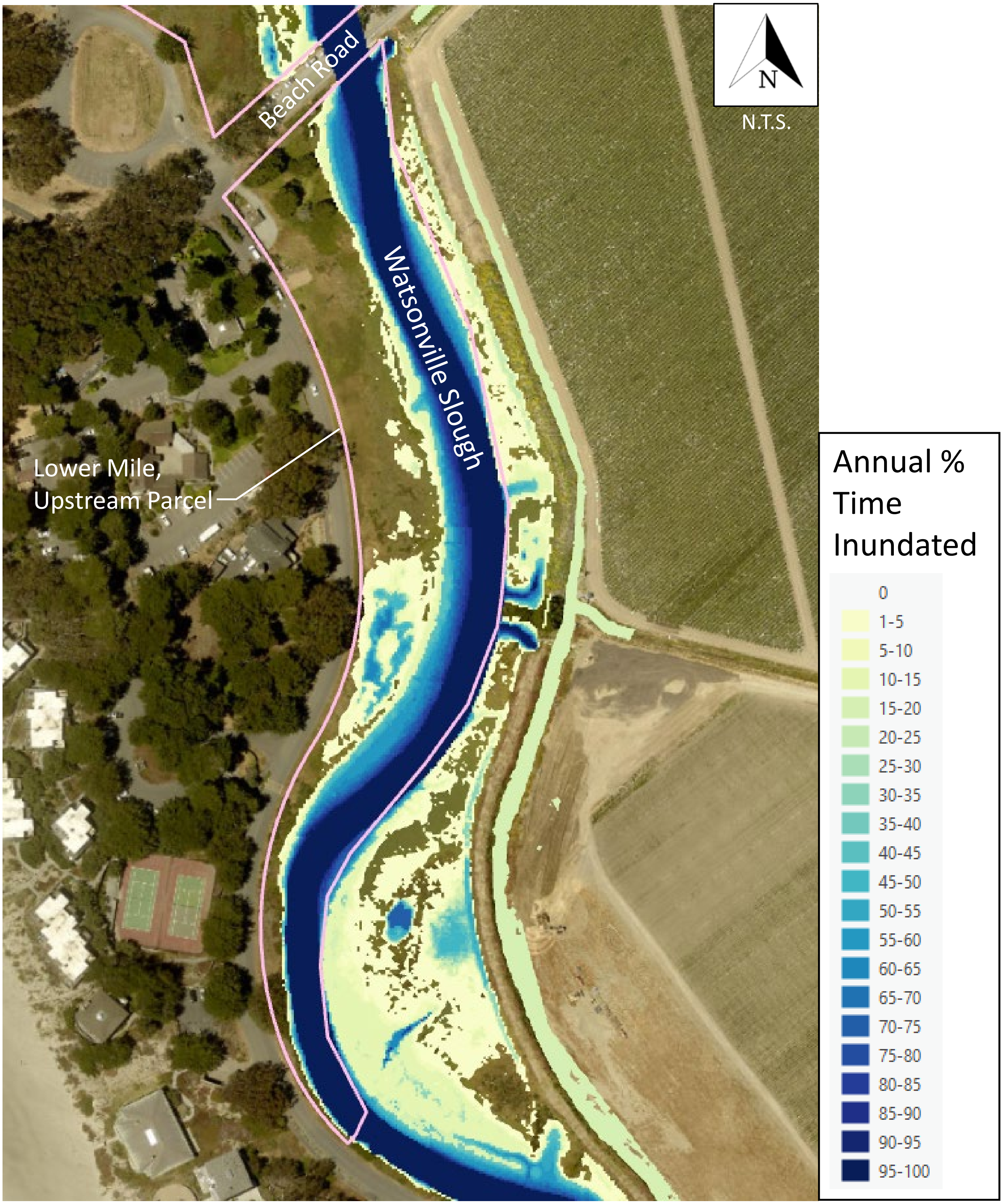


Figure 19: Annual PTI – Lower Mile, Upstream Parcel; Year 25; Earthwork

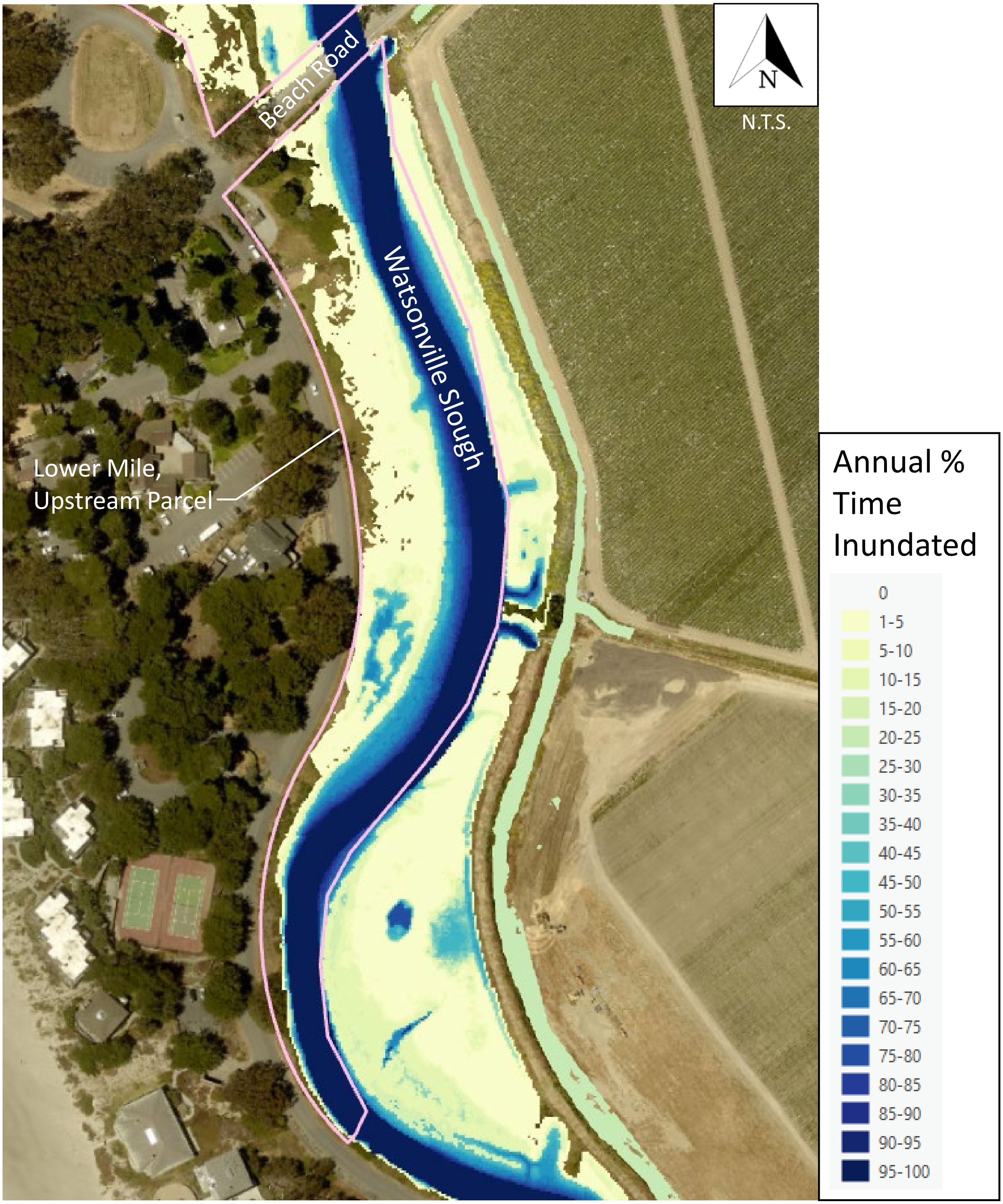


Figure 20: Annual PTI – Lower Mile, Upstream Parcel; Year 25; Crossing Improvements + Earthwork

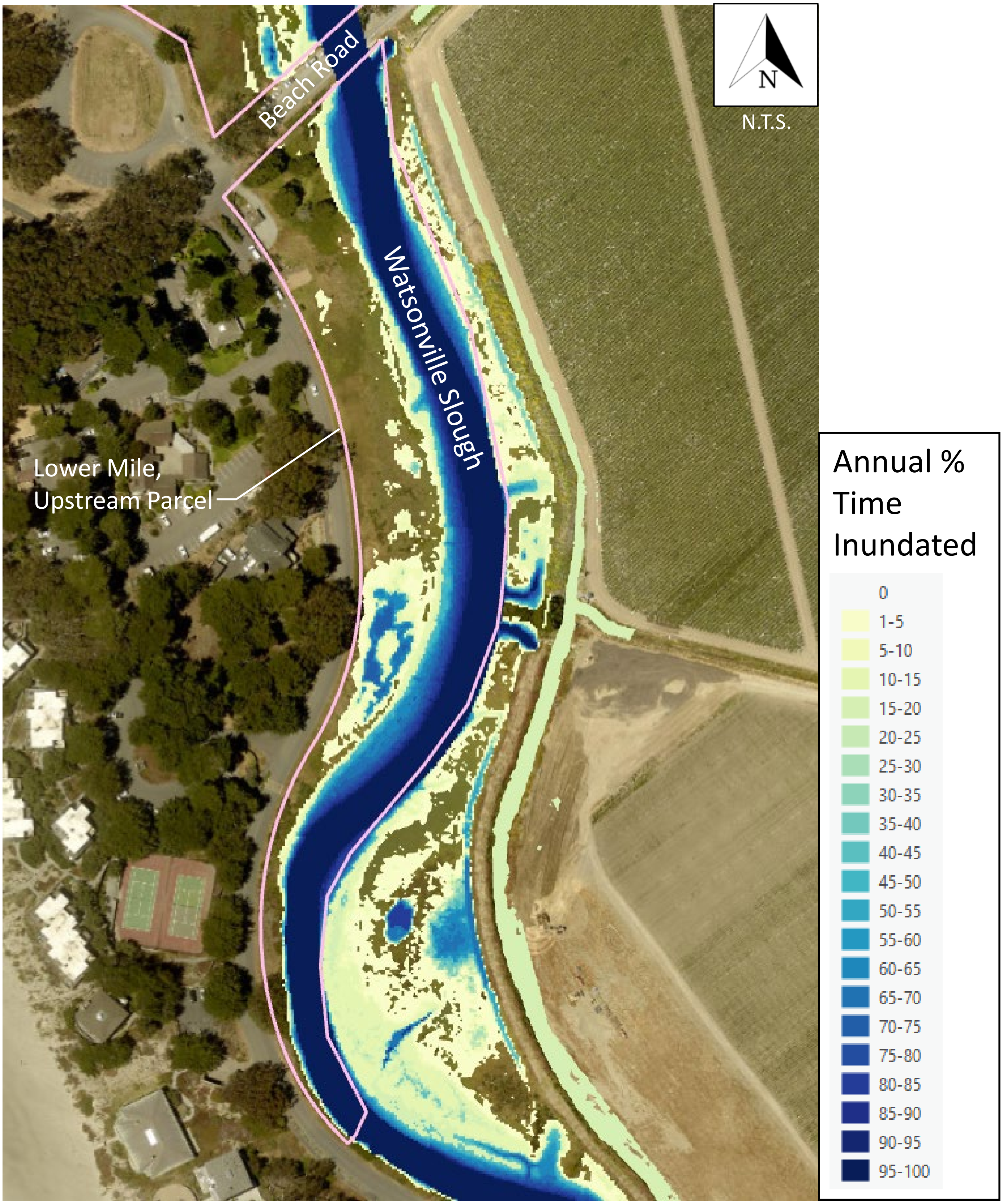


Figure 21: Annual PTI – Lower Mile, Upstream Parcel; Year 50; No Action

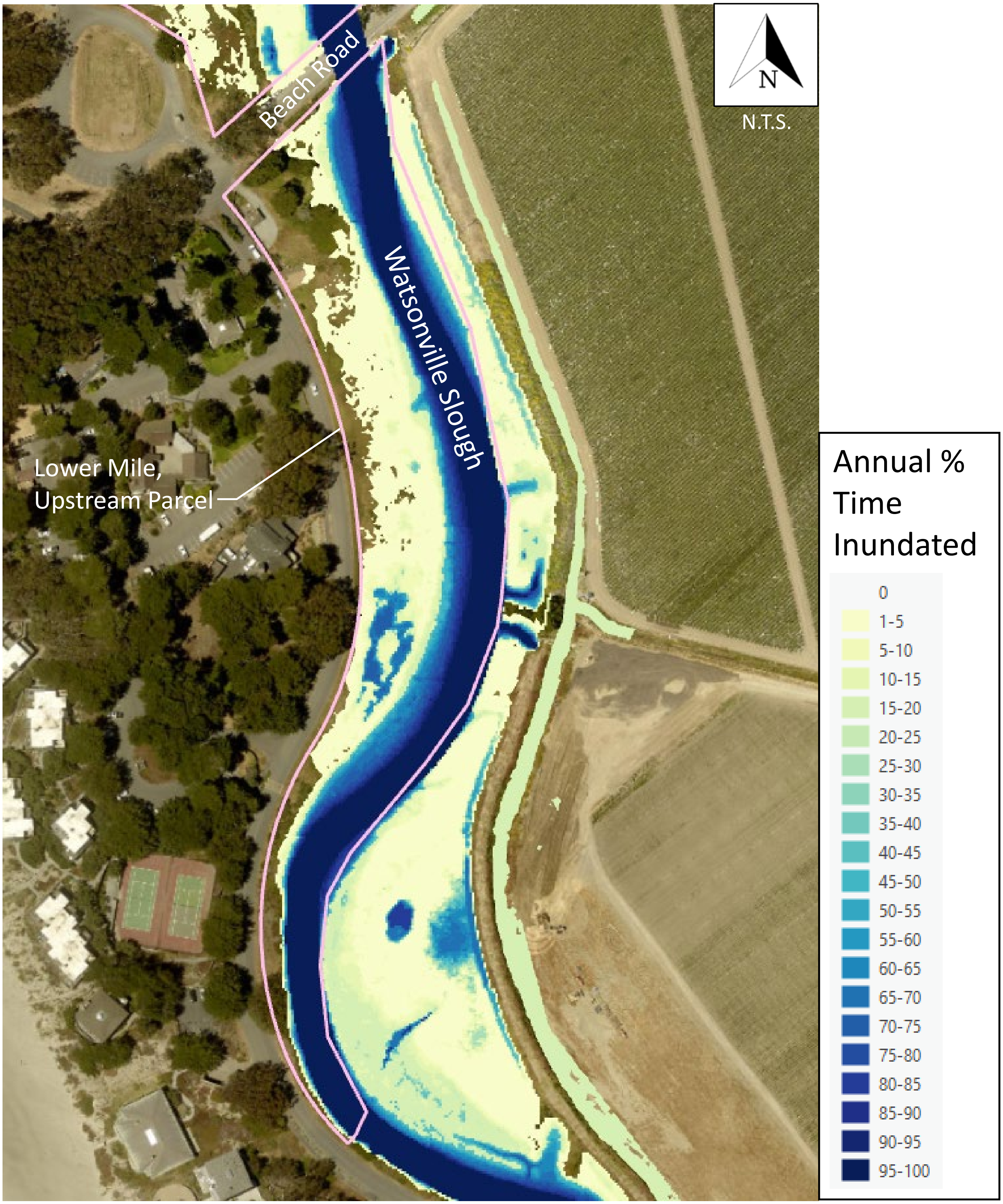


Figure 22: Annual PTI – Lower Mile, Upstream Parcel; Year 50; Crossing Improvements

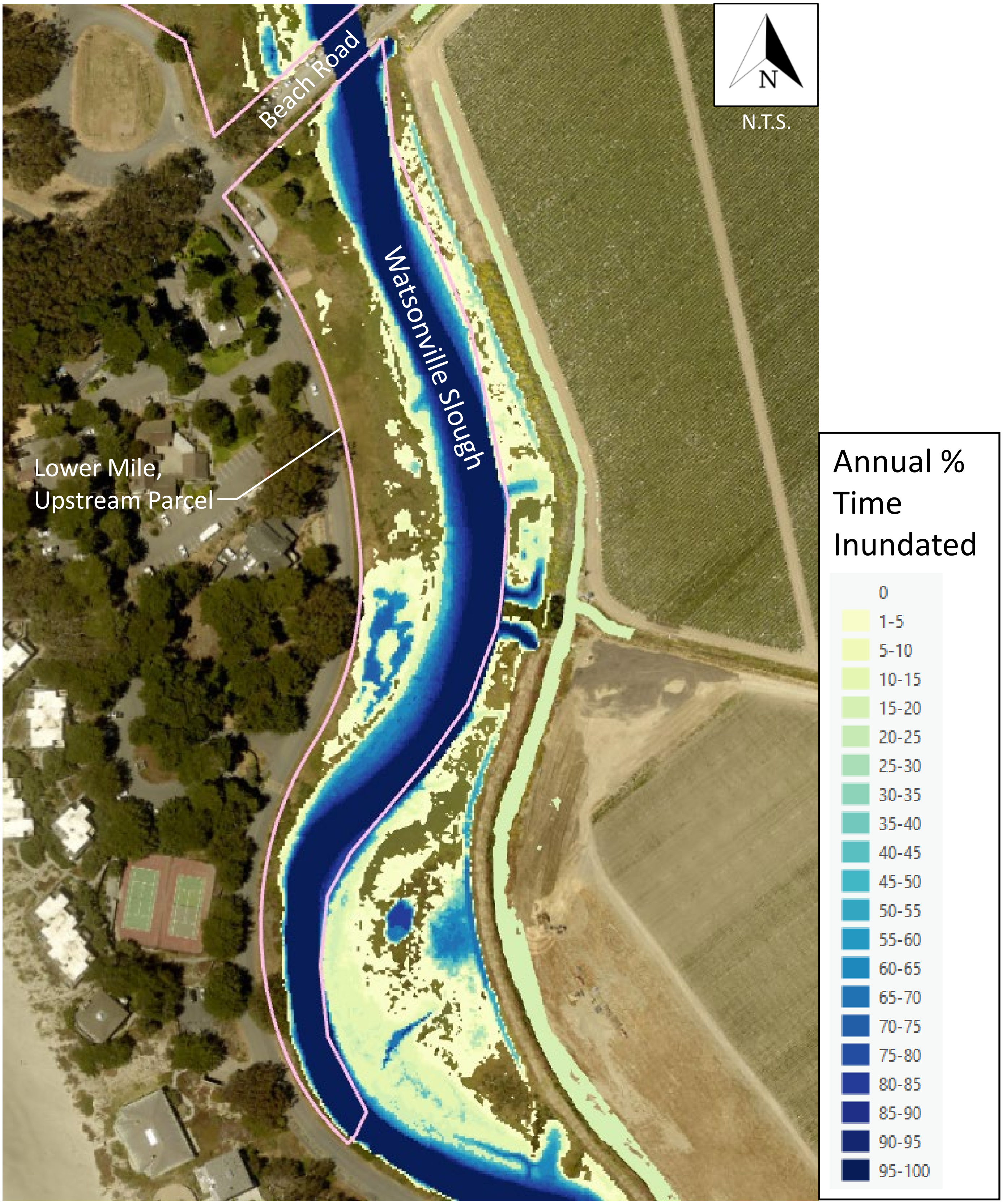


Figure 23: Annual PTI – Lower Mile, Upstream Parcel; Year 50; Earthwork

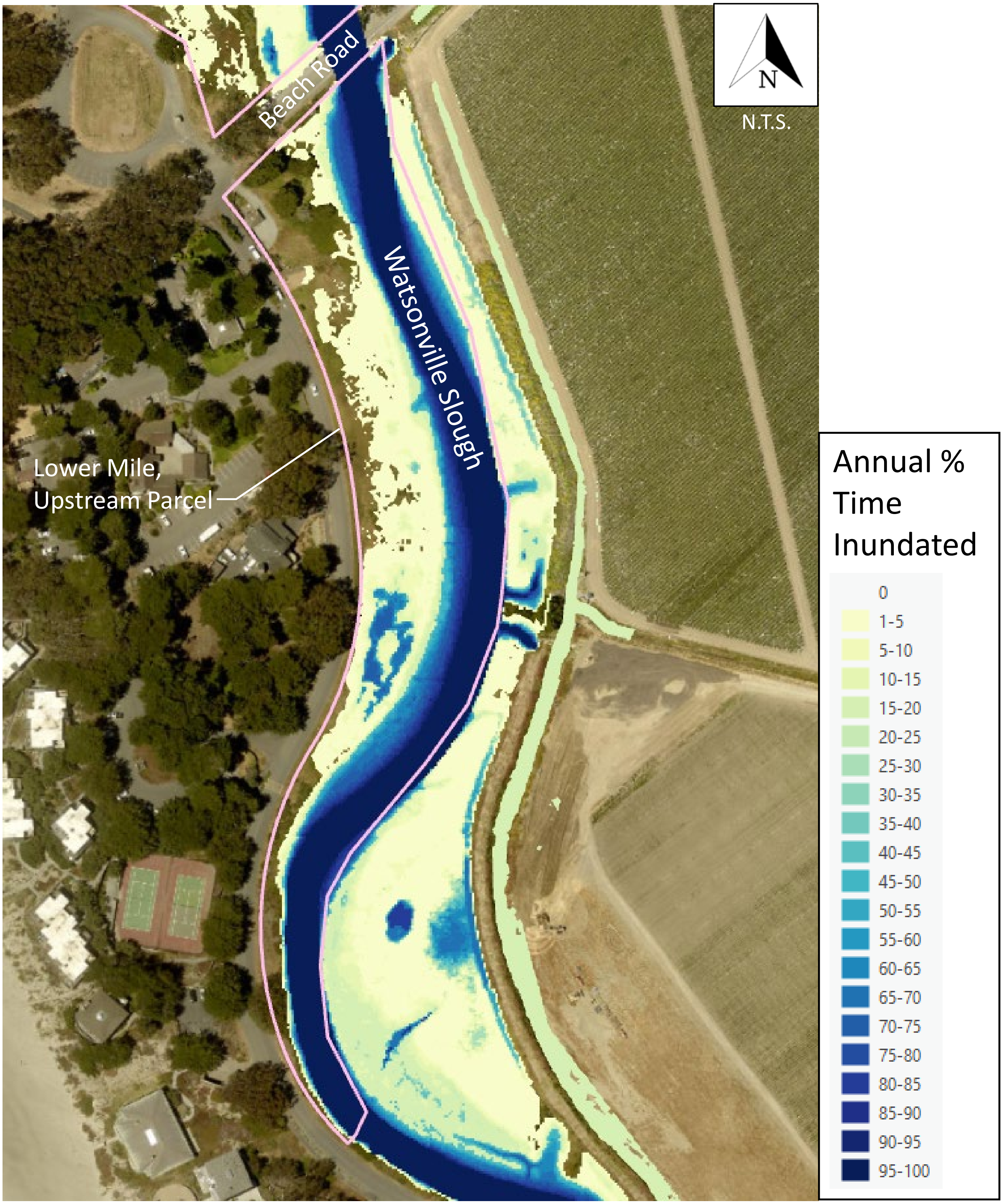


Figure 24: Annual PTI – Lower Mile, Upstream Parcel; Year 50; Crossing Improvements + Earthwork

Lower Mile,
Downstream Parcel

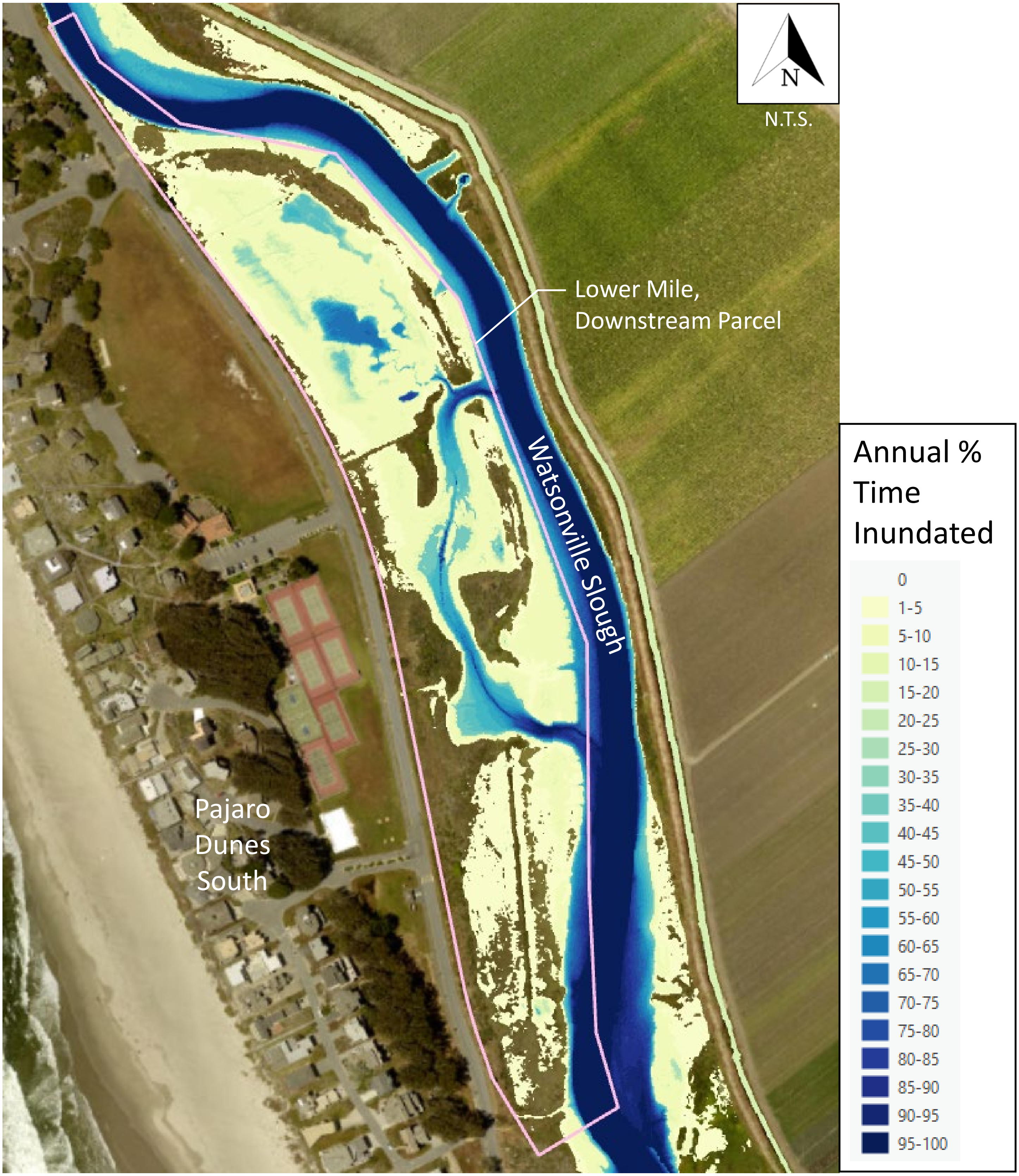


Figure 25: Annual PTI – Lower Mile, Downstream Parcel; Year 0; No Action

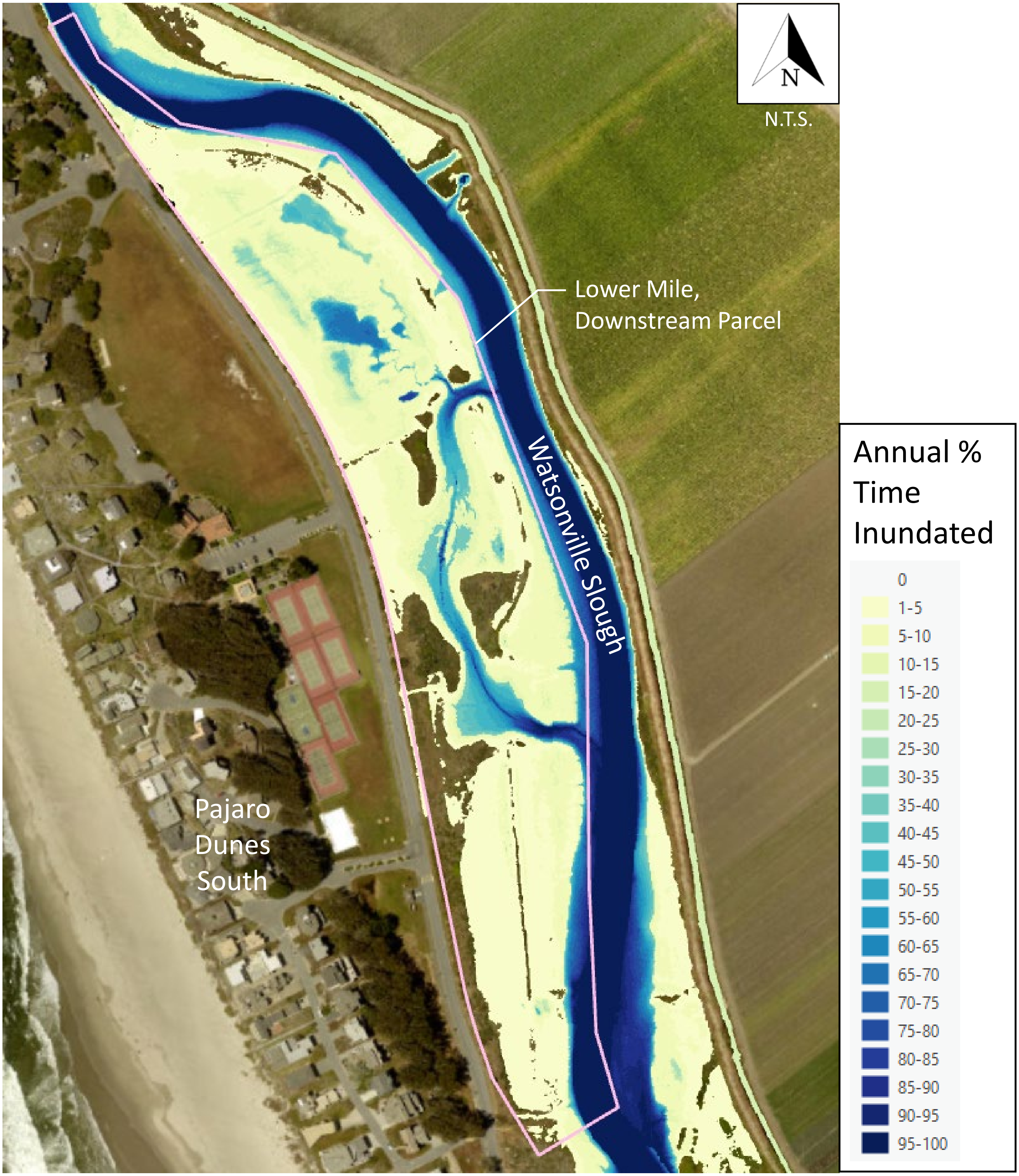


Figure 26: Annual PTI – Lower Mile, Downstream Parcel; Year 0; Crossing Improvements

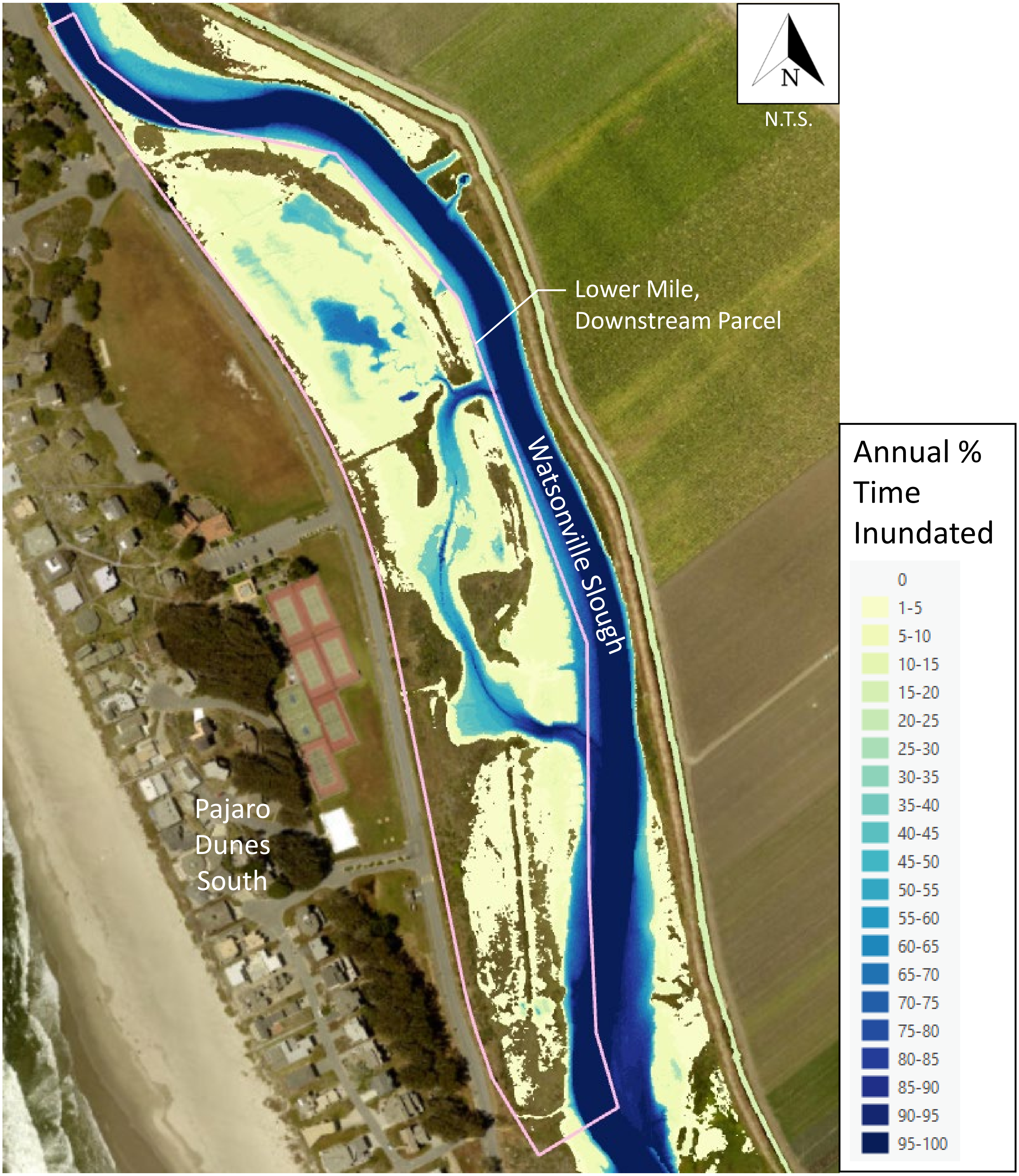


Figure 27: Annual PTI – Lower Mile, Downstream Parcel; Year 0; Earthwork

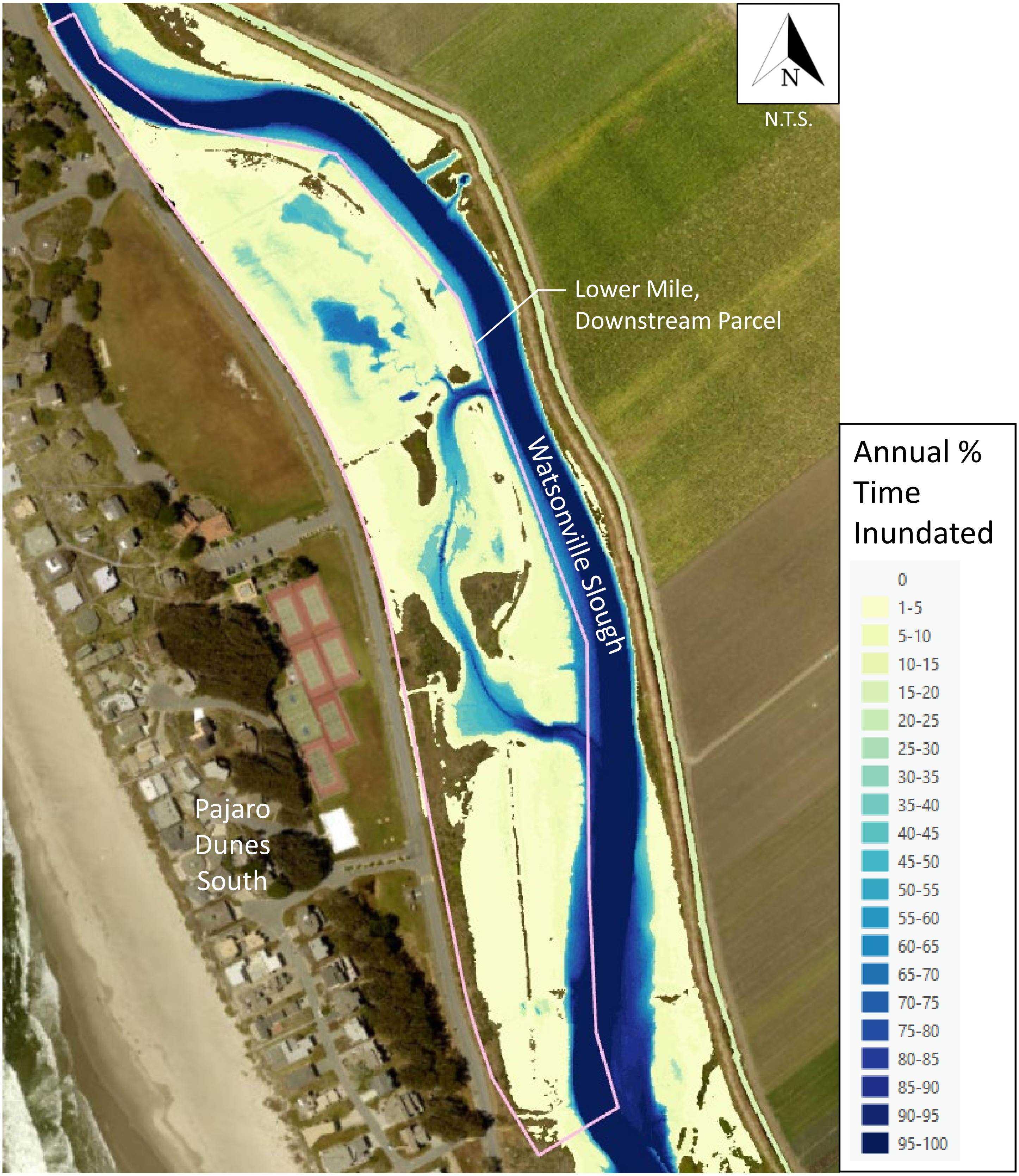


Figure 28: Annual PTI – Lower Mile, Downstream Parcel; Year 0; Crossing Improvements + Earthwork

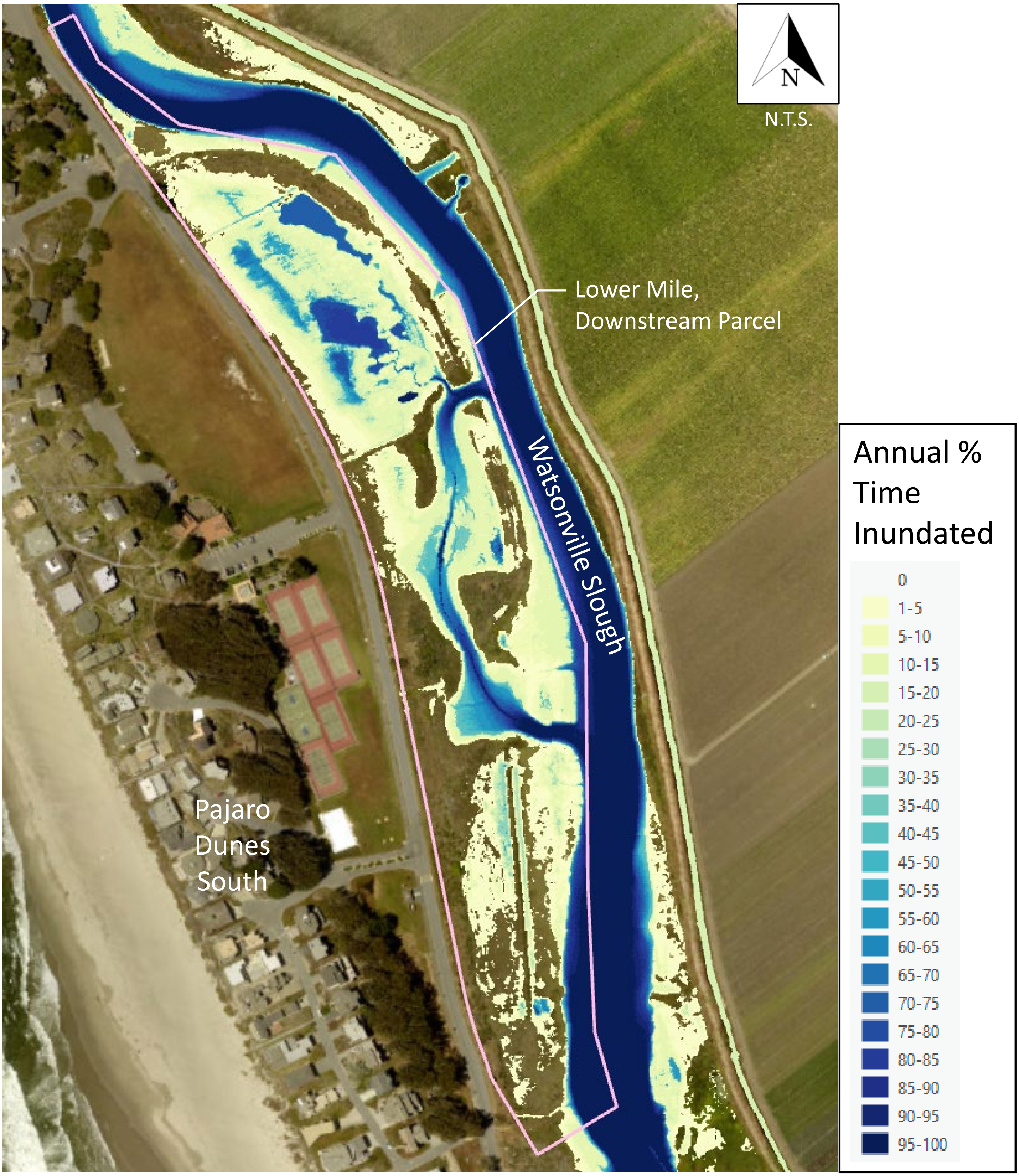


Figure 29: Annual PTI – Lower Mile, Downstream Parcel; Year 25; No Action

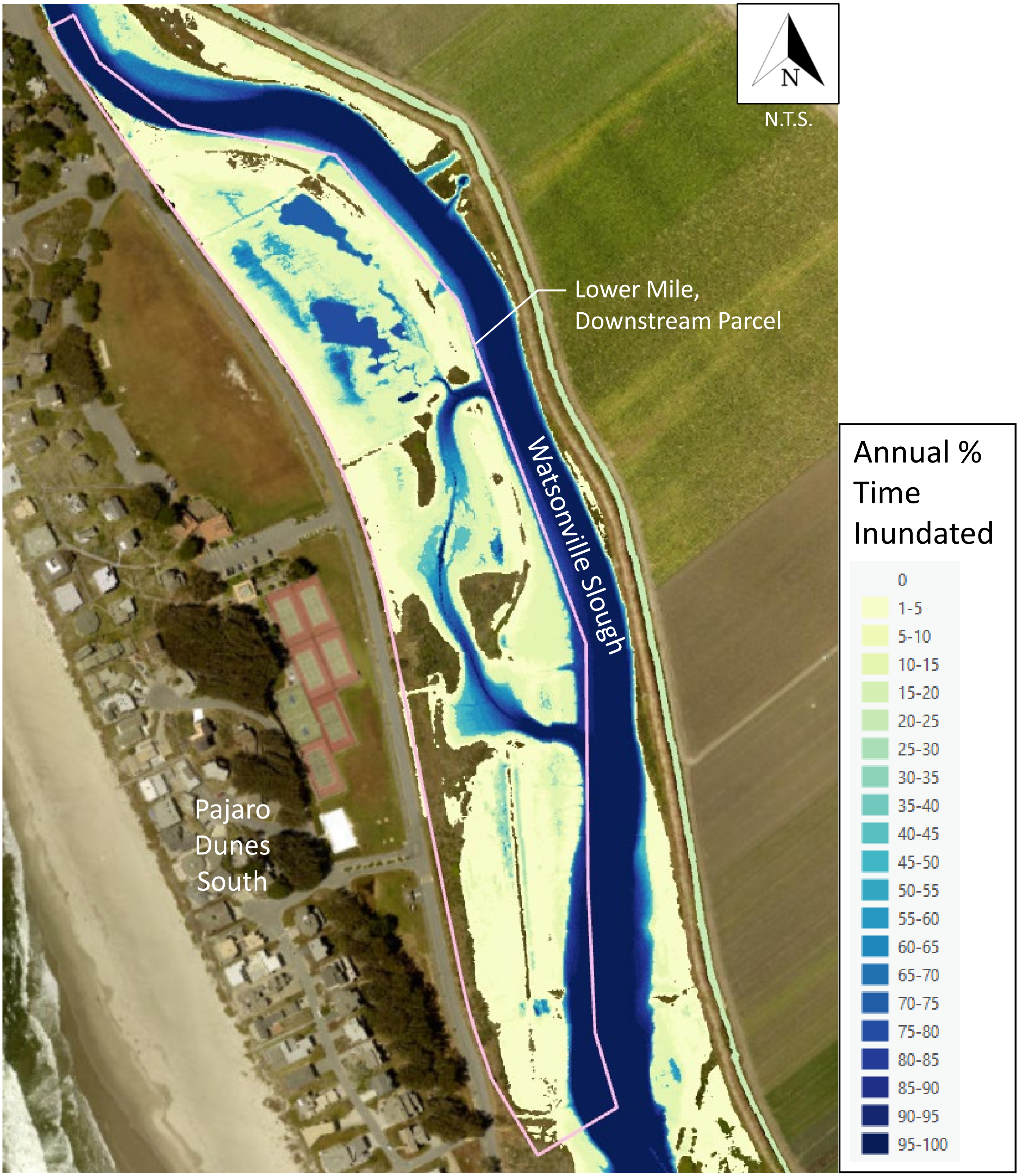


Figure 30: Annual PTI – Lower Mile, Downstream Parcel; Year 25; Crossing Improvements

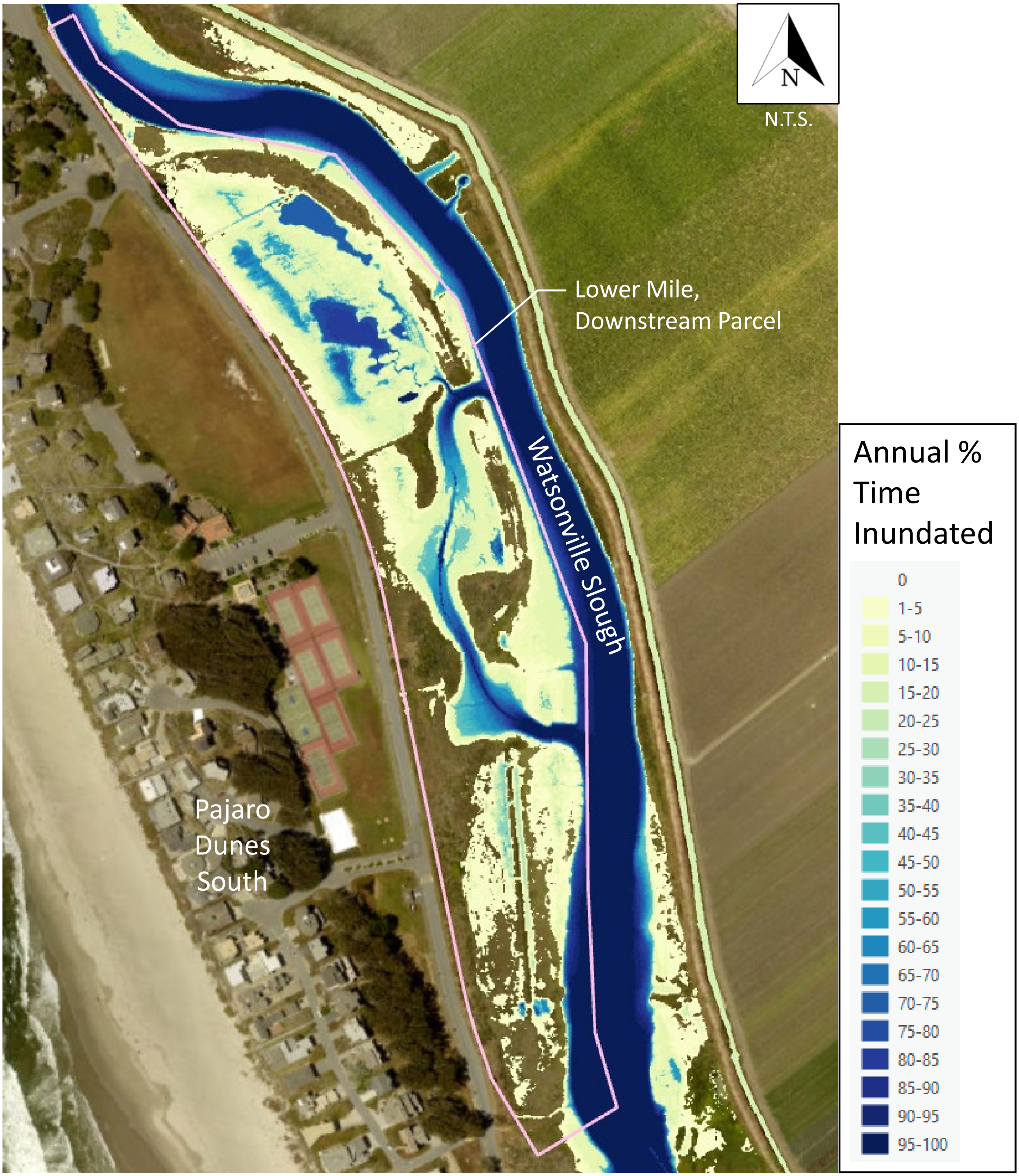


Figure 31: Annual PTI – Lower Mile, Downstream Parcel; Year 25; Earthwork

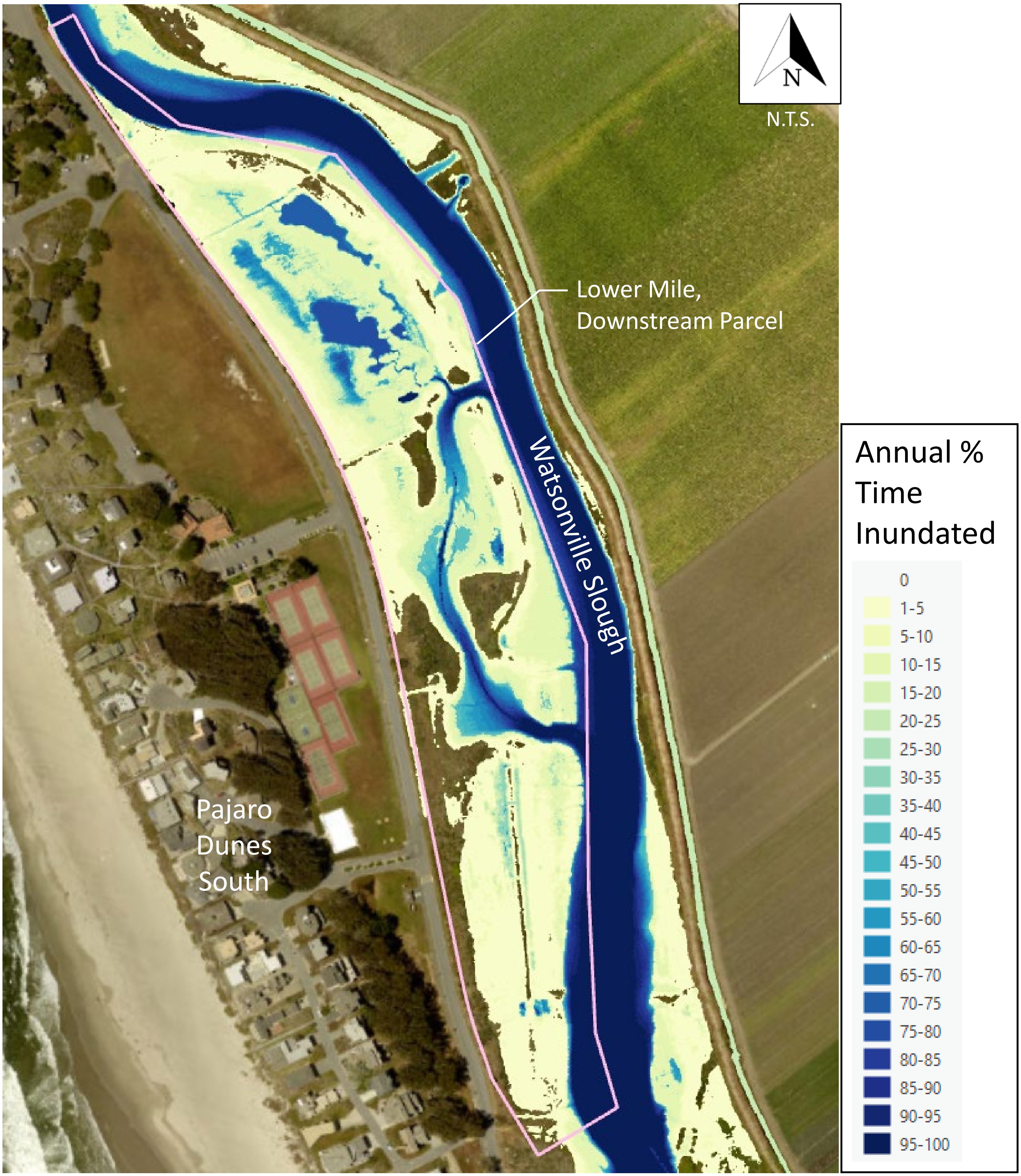


Figure 32: Annual PTI – Lower Mile, Downstream Parcel; Year 25; Crossing Improvements + Earthwork

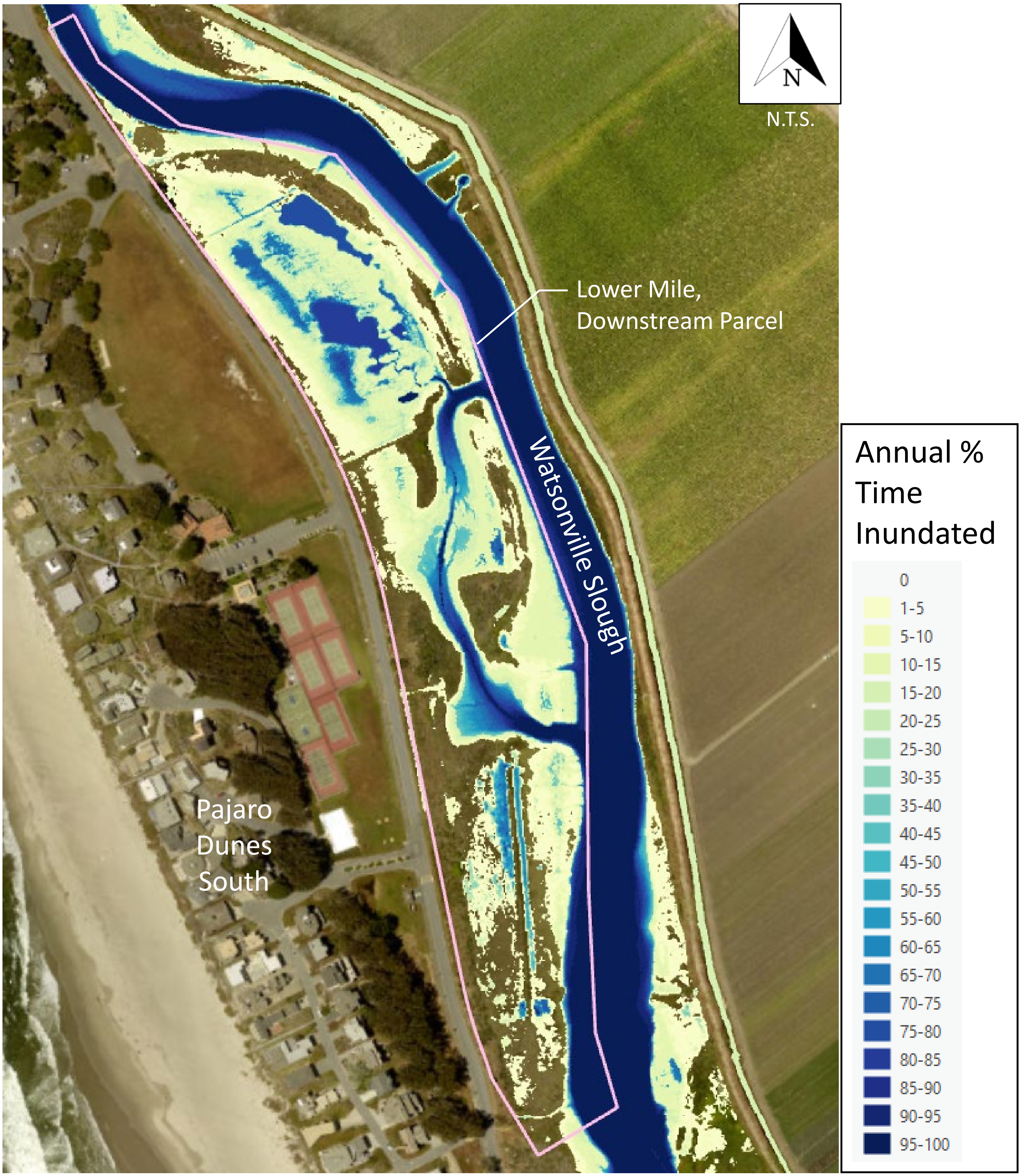


Figure 33: Annual PTI – Lower Mile, Downstream Parcel; Year 50; No Action

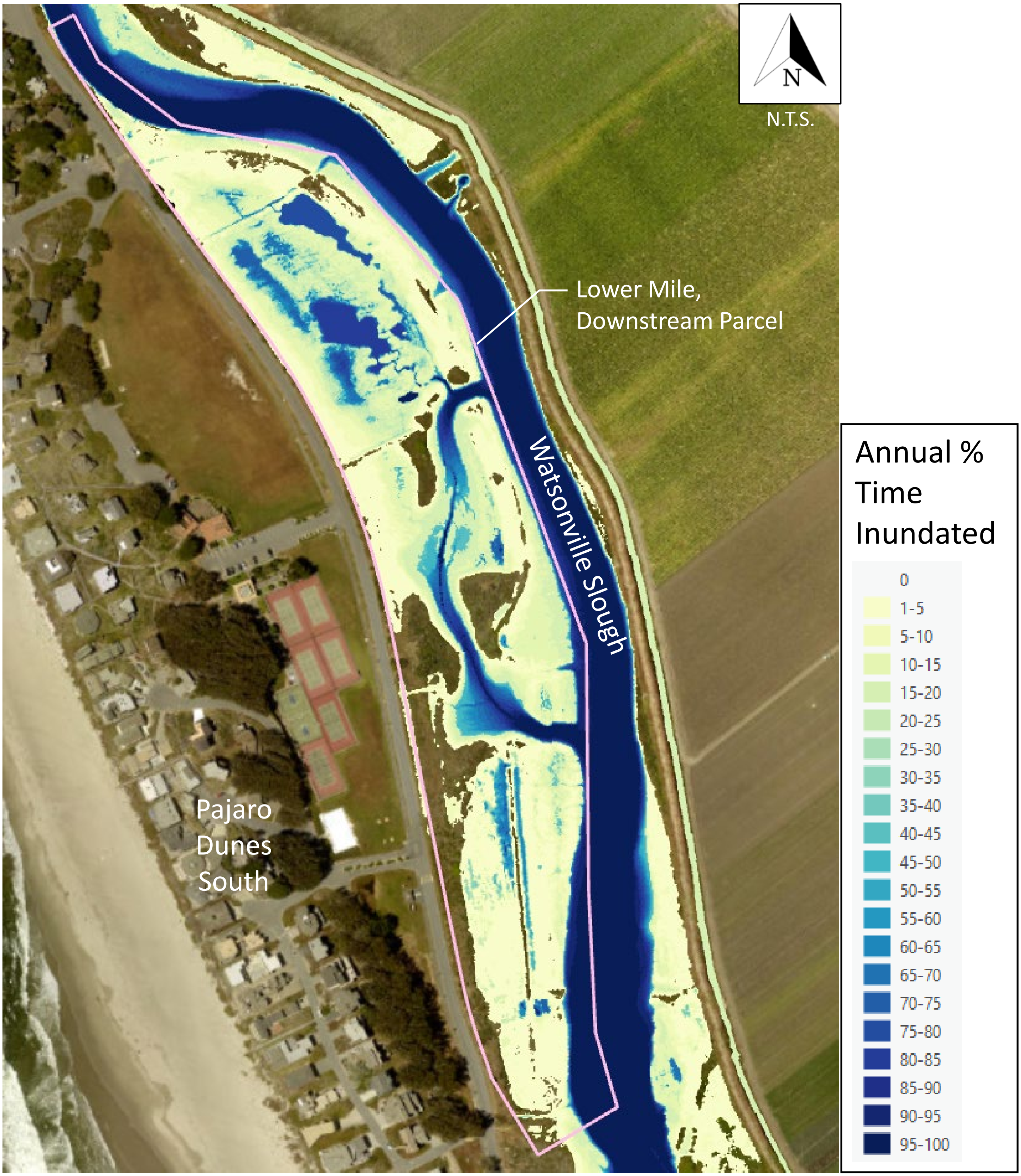


Figure 34: Annual PTI – Lower Mile, Downstream Parcel; Year 50; Crossing Improvements

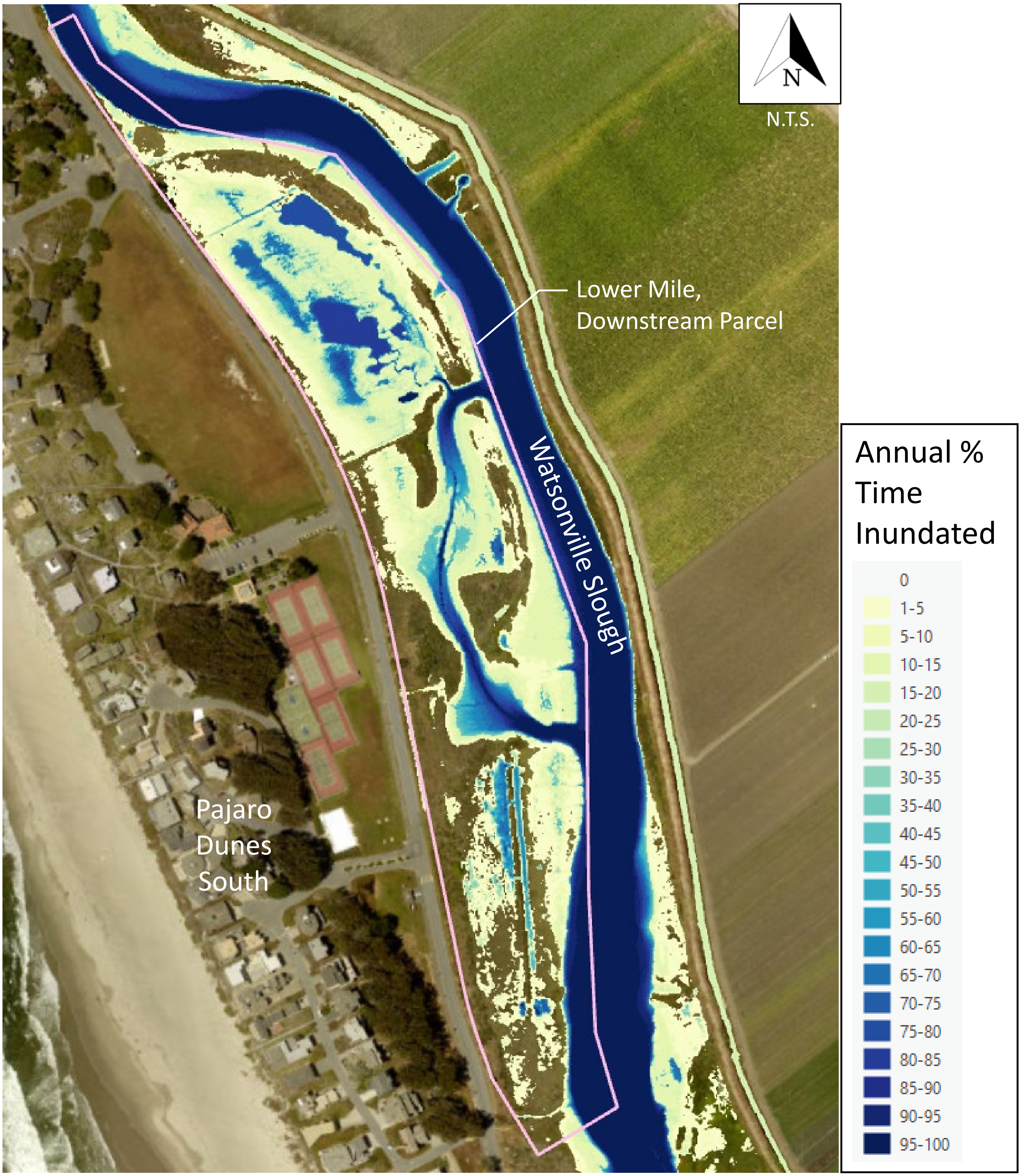


Figure 35: Annual PTI – Lower Mile, Downstream Parcel; Year 50; Earthwork

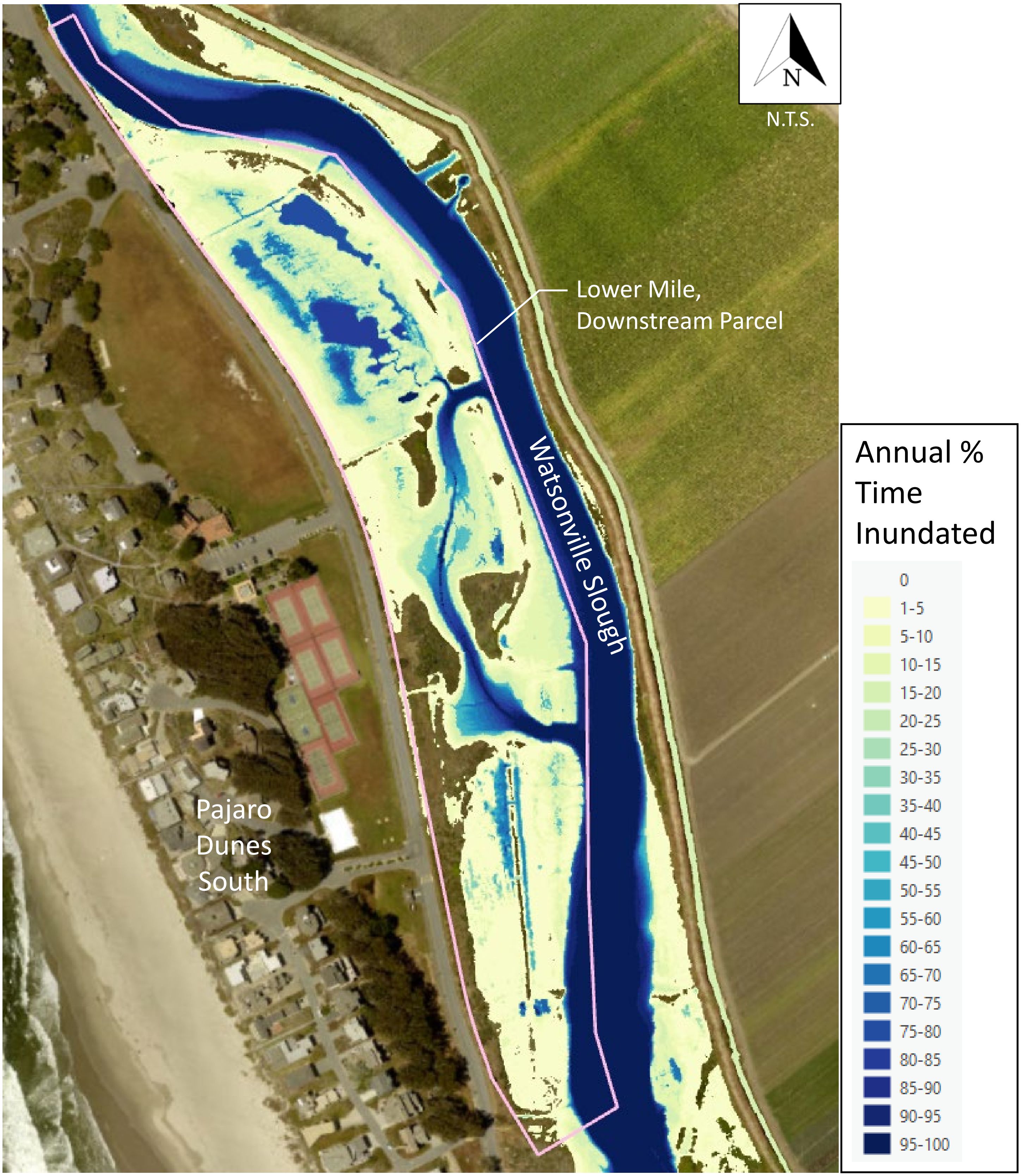


Figure 36: Annual PTI – Lower Mile, Downstream Parcel; Year 50; Crossing Improvements + Earthwork

Attachment D. Lower Watsonville Slough Ecosystem Restoration – Lagoon Response Modeling Memorandum (Environmental Science Associates)

ESA

180 Grand Avenue
Suite 1050
Oakland, CA 94612
510.839.5066 phone
510.839.5825 fax

esassoc.com

memorandum

date	March 31, 2023
to	Tiffany Cheng, PE
cc	Mark Strudley, Phd, PE; Rusty Barker, M.S., PE; Antonella Gentile, CFM
from	Dane Behrens, PhD, P.E.; Environmental Science Associates
subject	Lower Watsonville Slough Ecosystem Restoration – DRAFT Lagoon Response Modeling Memorandum

1. Introduction

This technical memorandum documents the development and results of a hydrologic/geomorphic model of the Pajaro River Lagoon, which encompasses the lower Pajaro River, Watsonville Slough, and their adjacent floodplain areas. The model is a tool for evaluating changes in the mouth behavior of the coastal lagoon in response to future changes in management or climate conditions. It is being developed as a decision-support tool to support the Santa Cruz County Department of Public Works (County) and U.S. Army Corps of Engineers (USACE), in their development of restoration plans for the Watsonville Slough Ecosystem Restoration Project (Project), located in Santa Cruz County, near the town of Watsonville, CA.

This study is being conducted under Section 1135 of the Water Resources Development Act (WRDA) of 1986. Section 1135 projects are part of a larger Continuing Authorities Program (CAP). Work under the CAP authority can include modification to the structures and operations of water resources project constructed by USACE or undertake restoration projects at locations where a USACE project has contributed to environmental degradation. The County is the non-federal sponsor of the Project.

This memorandum is intended to document the potential effects of the project on mouth behavior (timing of opening and closure events, changes in timing needed for managed breaches). Apart from predicting future mouth states of the lagoon the model was also used to annualize HEC-RAS model results from the USACE, for using in estimates of Project habitat benefits.

The sections below provide detail on the major processes that affect the lagoon, describe the development of the lagoon model, and summarize the results for existing and project conditions. A separate report is being prepared for the County that will provide more information, including a more detailed review of model calibration and results.

1.1 Lagoon Mouth Processes in the Pajaro-Watsonville Lagoon

Watsonville Slough is the lowest tributary to the Pajaro River lagoon, and a significant portion of the slough experiences both tidal flows during open lagoon mouth conditions (typically during wetter months), and also backwater effects of trapped water during periods of lagoon mouth closure (caused by wave action and typically occurring during the drier months). The hydrology and water quality of the lower Pajaro River and Watsonville Slough watershed are affected by the beach, which is built by wave-driven sand transport. During low river flows, the beach elevation aggrades by wave action, and trapped inflows can rise to flood stage. Inflows that raise the lagoon levels can come from wave runup overtopping the beach and from watershed runoff. The hydrology of the lagoon during periods of closure is complex, both because of these time-varying freshwater and ocean water inflows, but also because of losses from seepage through the beach berm and evapotranspiration, which can be significant.

Though natural 'breach' events sometimes occur when trapped runoff raises lagoon levels to the height of the beach, the County at times induces breach events as an emergency measure via excavation of a drainage channel across the beach. This action is used to mitigate flooding potential of infrastructure adjacent to the lagoon. The potential for flooding is generally highest when prolonged periods of mouth closure combine with significant runoff, especially in late fall or early winter, and lead to heightened water levels in the lagoon as water collects behind the beach. Flood levels during these events are unlike typical fluvial flood stages, as they are effectively controlled by the beach morphology, which sets the beach elevation necessary for trapped water to overtop.

Both Watsonville Slough and the Pajaro River form segments of the same coastal lagoon (referred to herein as 'the lagoon', or 'the estuary'), though they receive separate freshwater inflows and are often managed as separate entities. The estuarine portion of both segments (i.e. the extent experiencing a water level backup during lagoon mouth closure) provide extremely important intertidal and supratidal marsh complexes, which provide habitat and food web benefits for a host of native species, some listed at that state and federal level. The hydrology of these habitats are closely linked to the behavior of the lagoon mouth, meaning that the any future changes to mouth management will have an influence on the ecology of the lagoon as a whole.

1.2 Modeling Approach

ESA is applying its Quantified Conceptual Model (QCM), developed previously for the site in support of the Pajaro Valley Water Management Agency (PV Water). For this effort, ESA coordinated with the County to develop a series of modeling alternatives that encompass a range of hypothetical future conditions in the lagoon, including changes in lagoon size, future sea-level rise, and changes in the elevation threshold for enacting a managed breach of the lagoon. This work focuses on the latter, which corresponds to the USACE alternative of raising a portion of Beach Road to mitigate future flooding. The USACE also evaluated the effects of enhancing the floodplain within the existing levees along the Last Mile segment of Watsonville Slough. These alternatives are described in more detail in separate reporting provided by USACE.

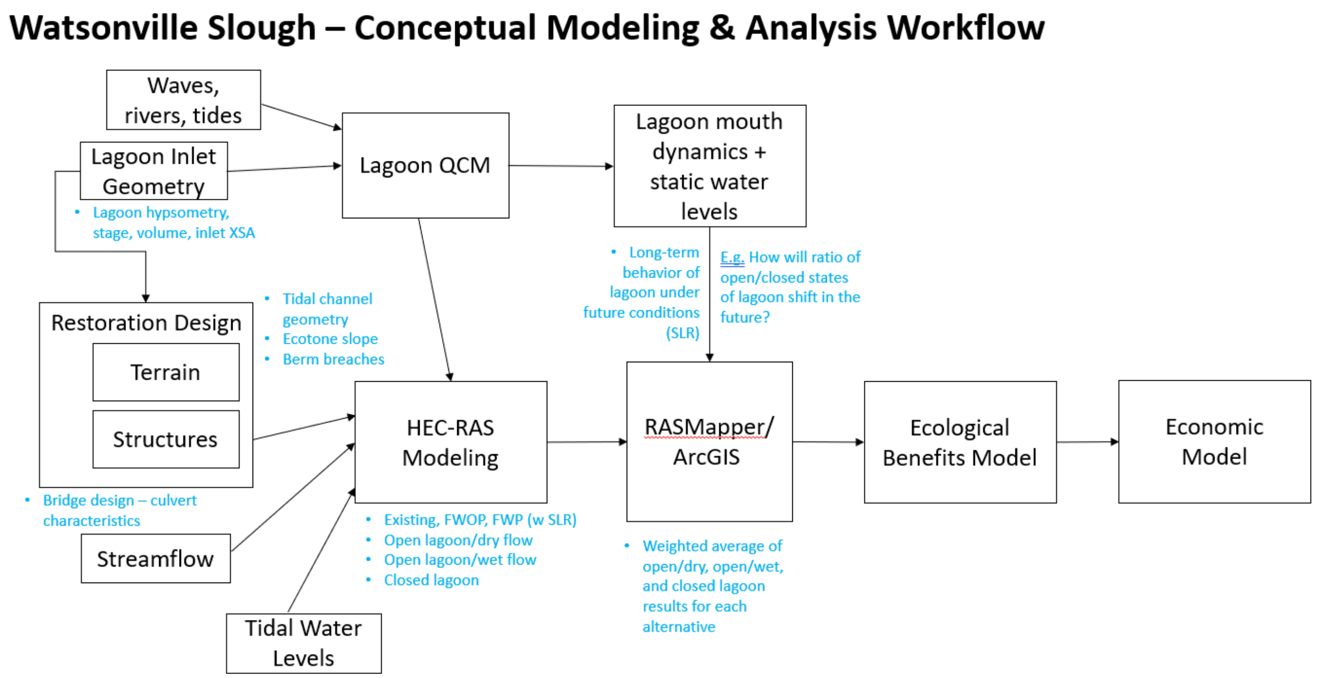
TABLE 1
LAGOON QCM SCENARIOS

#	Scenario ID	Breaching threshold	SLR	Details
1	*Baseline*	8 feet NAVD	0 feet	Baseline simulation of 2008-2021 time period, used for calibrating the model
2	*Project*	9.2 feet NAVD	0 feet	Same as *Baseline* with higher breaching threshold. This represents the Project condition with raised road at Beach Road crossing.
3a	*Baseline with SLR: no sedimentation*	8 feet NAVD	0.5-3 feet	Simulation of the *Baseline* with sea level rise (SLR) added to the boundary ocean tide levels. This is the Future Without Project (FWOP) condition. The lagoon is assumed to experience zero sedimentation, but the beach moves up with SLR. This leads to long-term drowning of the lagoon by higher water levels.
3b	*Baseline with SLR: partial sedimentation*	8 feet NAVD	0.5-3 feet	FWOP, with the assumption that future sedimentation in the lagoon channels and floodplain offsets up to 50% of the increase in water levels with SLR. Actual sedimentation rates are largest in the channels and decrease with elevation on floodplain areas.
3c	*Project: no sedimentation*	9.2 feet NAVD	0.5-3 feet	Same as *Run 3a,* with higher elevation threshold for managed breaches, corresponding to the Project condition.
3d	*Project: partial sedimentation*	9.2 feet NAVD	0.5-3 feet	Same as *Run 3b* with higher elevation threshold for managed breaches, corresponding to the Project condition.

1.3 Application to Watsonville Slough Benefits Quantification

The USACE developed a separate 2D unsteady HEC RAS model to provide the basis for estimating the habitat benefits of the Project. This is gridded model that provides high resolution estimates of water levels, depths, and hydraulic parameters throughout the site. Given the computational cost of this approach, this model was applied to a series of representative open-mouth and closed-mouth simulations covering several months.

The QCM model described in this memorandum only provides average lagoon water levels, but considers the time-varying condition of the lagoon mouth, and its effect on the lagoon hydrology. Since it was run for a 14 year period from 2008 to 2021, overlapping the HEC RAS simulation periods, it was used to provide a basis for translating the HEC RAS results to representative annual conditions. This is described in more detail in separate documents provided by USACE, and summarized in schematically in the Figure 1 below.



SOURCE: USACE

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Figure 1
Schematic of technical approach for the current study, provided by USACE.

2. Model: Existing Conditions

The current QCM approach is an adapted and refined version of earlier approaches for tidal conditions from Crissy Field Lagoon (Battalio et al. 2006) and for fluvial conditions for the Carmel River (Rich and Keller 2013), and builds on lessons learned from both approaches. In recent years, ESA has further developed the QCM as a more complete tool to assess systems with both tidal and fluvial characteristics (Behrens et al. 2015). It is typically used as a decision support tool to better understand impacts of lagoon management and climate change, and has been applied at about twenty sites throughout California since 2012. Most recently near the Project site, the QCM was applied as a decision-support tool at the Pescadero Lagoon (ESA 2020) and the San Lorenzo River (ESA 2023).

2.1 Model Details

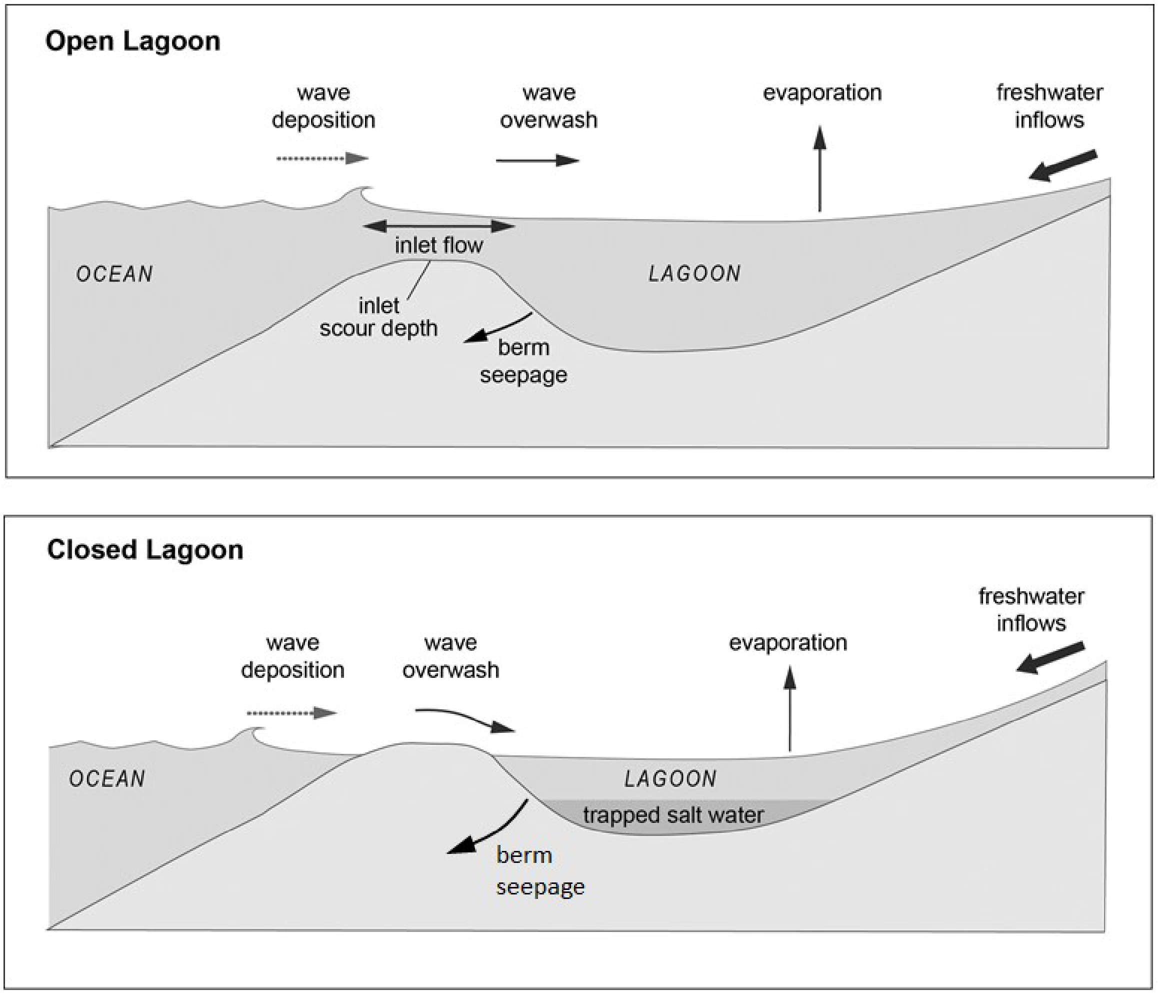
The QCM approach is centered on a water budget for the lagoon, which is coupled with a sediment budget for the lagoon mouth. The model is based on two core concepts:

- All water entering and leaving the lagoon should balance.
- The net erosion/sedimentation of the inlet channel results from a balance of erosive (fluvial and tidal) and constructive/deconstructive coastal (wave) processes.

The model uses time series of nearshore waves and tides, watershed runoff, and evapotranspiration data as boundary conditions. Using these as forcing conditions with information about a lagoon's topography, the model dynamically simulates time series of lagoon water levels, along with inlet, beach, and lagoon state. With each time step, the net inflows or outflows to the system are estimated, along with the net sedimentation or erosion in the mouth. The flow terms vary depending on whether the mouth of the lagoon is open or closed. During closed conditions, inflows include watershed runoff and wave overwash into the lagoon, while outflows include beach berm seepage and evapotranspiration.

Figures 2a and 2b show schematic sketches of the water balance and beach/inlet portions of the QCM. As the model steps forward in time, it continuously transitions the mouth through tidal, perched, and closed conditions. When deposition in the inlet bed exceeds erosion, the bed rises vertically, eventually perching above most tidal elevations and closing. Mouth closure occurs in the model when sediment fills the bed higher than lagoon water levels. Breaching occurs in the model when the lagoon fills from accumulation of either watershed runoff or wave overwash, and water levels overtop the beach berm crest, eroding a new lagoon mouth. The model is trained by adjusting empirical coefficients that control the amount of sediment trapped in the mouth, beach berm growth, and frictional losses in the channel during outflow. Flow terms such as wave overwash and berm seepage are also adjusted to allow variations in lagoon water levels to match observations. For more information on how the model resolves different processes, refer to Behrens et al. (2015).

In the model, managed breach events are initiated whenever the inlet is closed and water levels rise to the prescribed threshold amount. This is implemented by lowering the beach crest to the lagoon water level and allowing it to form a new inlet by flowing over the beach. The model also allows the lagoon to breach naturally if water levels reach the height of the beach crest if it is lower than the prescribed breach elevation.



SOURCE: Behrens et al (2015)

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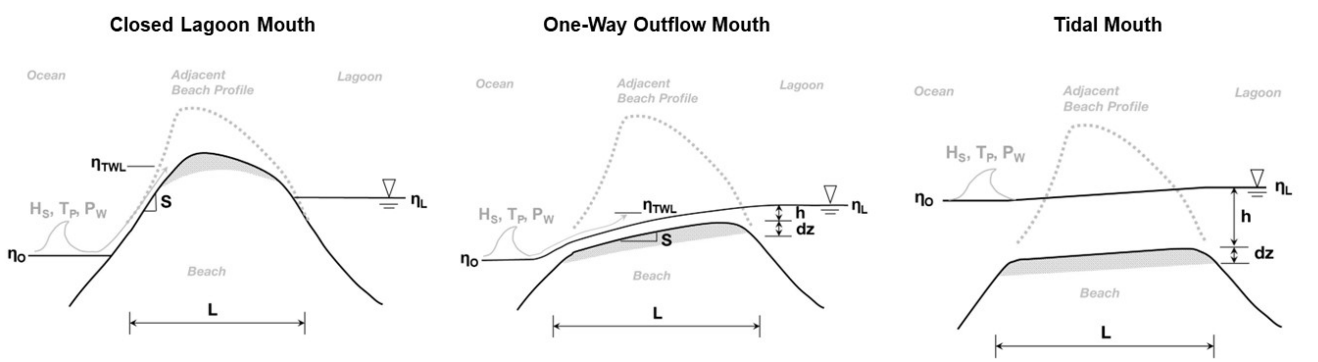
Figure 2a
Schematic of water balance component of the QCM.



SOURCE: Behrens et al (2015)

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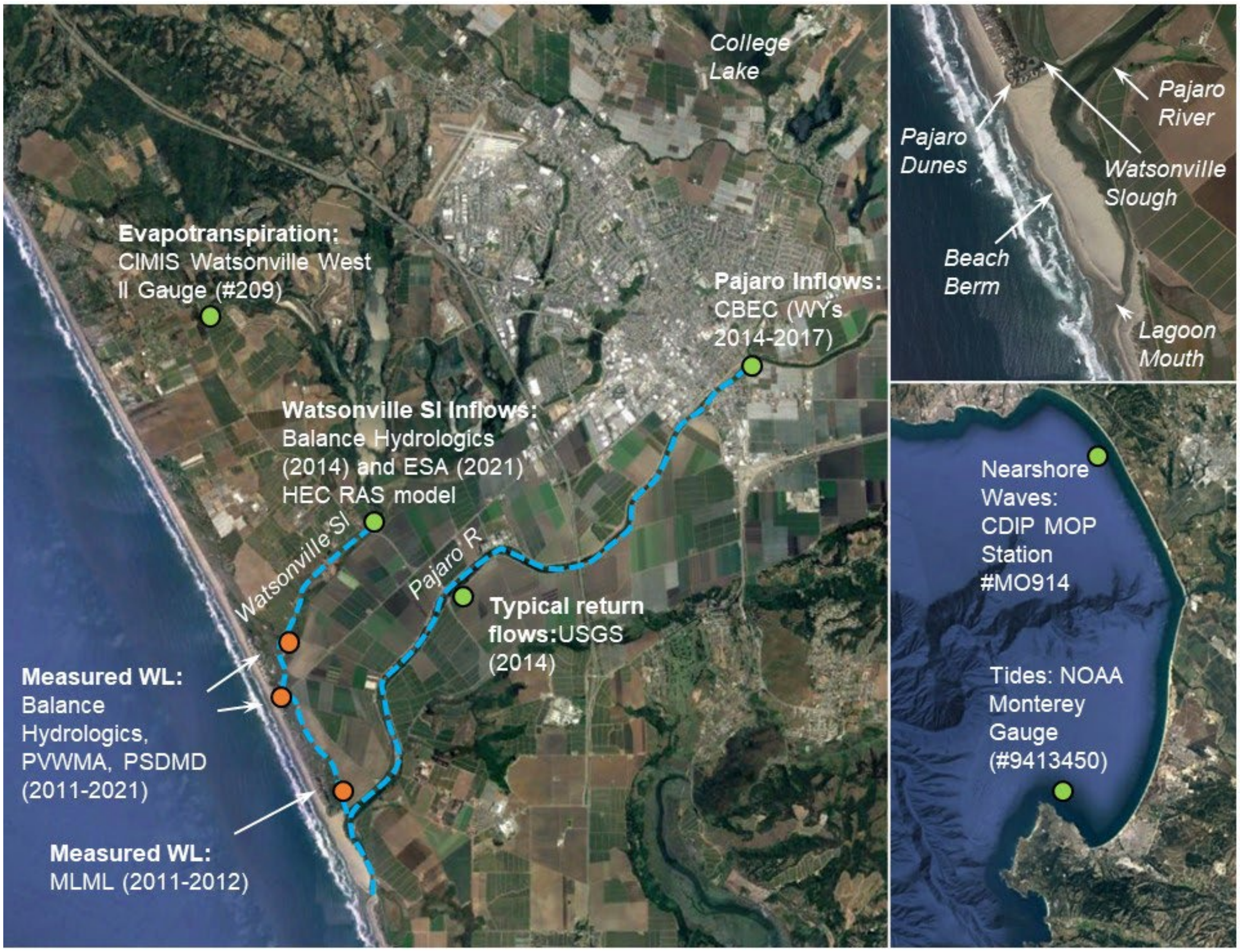
Figure 2b
Schematic of beach/inlet component of the QCM.

2.3 Boundary Conditions

The data sources used to simulate the period from 2008 to 2021 are summarized in Table 2 below and Figure 3. The Pajaro River and Watsonville Slough are treated as separate basins (i.e. interconnected water balances). For the purposes of this study, the 'lagoon' is assumed to include both water bodies, since both experience tides during open-mouth lagoon conditions and water levels inundate both areas when the beach blocks the mouth.

TABLE 2
KEY SOURCES OF DATA

Parameter	Source/Location	Availability
Coastal Influences		
Offshore Wave Measurements	• NDBC Monterey Buoy (#46042)	Directional:1987- present Full spectral:1996- present
Nearshore Wave Estimates	• Coastal Data Information Program (CDIP): Station MO914 • ESA PWA (2014)	2000-present
Ocean Tide Stage	• NOAA Monterey Gauge (#9413450)	1986-present
Beach and Lagoon Mouth		
Inlet Condition (Open/Closed)	• Record of closure and breach events compiled by the County for 2008-2022 • Mouth closure periods also inferred from 2012-2017 from lagoon water level time series	2008-present
Beach/Lagoon topography	• Coastal LiDAR from NOAA and USGS: (2010, 2016) • ESA (2018): topographic survey cross sections of Watsonville Slough • Schaaf & Wheeler (2001): Pajaro River thalweg profile	2001, 2010, 2016, 2018
Lagoon Hydrology		
Pajaro Runoff	• USGS Pajaro R Gauge at Chittenden (#11159000), modified based on recent observations from of flow reductions between Chittenden and Highway 1 crossing • Hanson et al. (2014): estimates of agricultural return flows • cbec (2018): existing and project inflows at confluence of Salsipuedes Creek and Pajaro River (2014-2017 WYs)	1951-present
Watsonville Runoff	• Watsonville Slough flows from 1D HEC RAS developed by Balance Hydrologics (2014) and ESA (2021)	2000-2022
Evapotranspiration	• CIMIS #209 (Watsonville West II)	2007-present
Lagoon Water Level	• Moss Landing Marine Labs: (2011-2012) • Balance Hydrologics: (2011-2013) • PV Water (2018): 2012-2016 • Balance Hydrologics: 2016-2017	2011-2017
Shell Rd pump station flows	• Coordination with County staff	2000-2022
Infrastructure		
Elevations of assets within the floodplain	• ESA (2018)	2018



SOURCE: ESA

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Figure 3
Sources of data used for QCM model input development.

2.4 Key Assumptions and Limitations

The main assumptions include the following:

- For simplicity when comparing existing (baseline) and Project conditions, we assumed that breaching occurs whenever water levels in the lagoon reach 8 feet NAVD88 for the baseline conditions. In reality, breaching sometimes occurs earlier, depending on anticipated timing of forecasted rainfall events, availability of beach topography data, and timing for equipment mobilization. It follows a phased process that involves multiple rounds of agency coordination. Since this model simulates hypothetical changes to the lagoon that may alter its behavior from the Baseline case, we apply the 8 feet NAVD88 threshold for simplicity rather than assuming that historical breach events would necessarily happen at the exact same dates.

- Surveys used to generate the hypsometric (stage vs volume) curve for the lagoon are assumed to be generally representative of 2008-2021 conditions, although sedimentation, flushing during floods, and migration of the lagoon mouth will cause change in the lagoon hypsometry that are not reflected here.
- The slope of the water surface in the lagoon is assumed to be small under most flow conditions (i.e. that the surface can be assumed flat for the purpose of volume calculations). This assumption is not valid during very high fluvial flows, and modeled water levels are expected to be representative of the water level gauge locations (i.e. not farther upstream).
- Gains and losses from interaction between surface flows and the local aquifer are assumed to be small below San Andreas Road on Watsonville Slough and below the confluence with Salsipuedes Creek on the Pajaro River.
- Agricultural return flows reported by Hanson et al. (2014) are added to the lagoon based on an annual average of 2 cubic ft per second (cfs) based on a reported value of 1,400 Acre-feet.
- The lagoon model is split into three water balance areas: Watsonville Slough upstream of the Shell Road pump station, Watsonville Slough Lower Mile, and Pajaro River. The exchange between the upper and lower Watsonville Slough areas is dictated by pump station discharges, based on coordination between ESA and County staff.
- Since water levels were only collected on Watsonville Slough, they are presumed to be representative of lagoon conditions only during mid- to high-tides in the lagoon and during typical closed-lagoon conditions (when water ponds behind the beach and inundates both the slough and river). However, these data do not show low water levels that may occur in the Pajaro side of the lagoon at low tide. This is because the bed of Watsonville Slough is higher than the bed of the Pajaro River, and thus the gauges located in the slough show a truncated version of low tides during open-mouth lagoon conditions.
- For simplicity, the beach is shape is assumed to be constant across the simulation period. This affects estimates of seepage losses, and inlet length (and thus friction losses). In reality, the beach undergoes the seasonal and interannual changes that influence its shape continuously.
- At this phase in the model development, short-term alterations to the pump station outflows at the Shell Rd crossing were not considered, although these are known to have varied recently (pers. comm. R. Barker). This influences the estimated inflow to the lagoon and thus the predicted water levels. This should be refined in the future.

2.5 Calibration

Model calibration involves adjustment of correlation coefficients that relate wave conditions to deposition in the mouth, and relate inlet currents and shear stresses to erosion of the inlet bed. The process also considers other factors that influence the lagoon hydrology in the model. Once freshwater inflows to the lagoon are known, other important terms that complete the water balance such as occasional wave overtopping flow rates (e.g. Laudier et al. 2011) or beach seepage losses (e.g. Rich and Keller 2013) can be adjusted using correlation coefficients, to allow the water level time series in the lagoon to be modeled accurately during periods of mouth closure. Calibration coefficients are generally adjusted at several scales:

- **Short-term:** At the scale of days to months, the coefficients that affect bed deposition and erosion are adjusted to match the level of tidal muting that occurs in the lagoon during typical wet and dry periods. This is a natural process that occurs when the bed of the lagoon becomes high enough that it limits the exchange of a portion of tides between the lagoon and ocean (Williams and Stacey 2016). In general, the shape of the tides in the lagoon differ from ocean tides in response to the bed elevation and friction losses in the mouth.

- **Long-term:** At the scale of multiple years (in the case of this study, the period from 2008 to 2021), the same coefficients are adjusted to allow the water level statistics to match with observations. This includes monthly-averaged water levels in the lagoon and water level exceedance estimates. At this time scale, the seasonal closure pattern is also compared between model and observations. The prediction of closure events in the model is sensitive to friction losses in the mouth, and to the ease with which waves can deposit sediment.

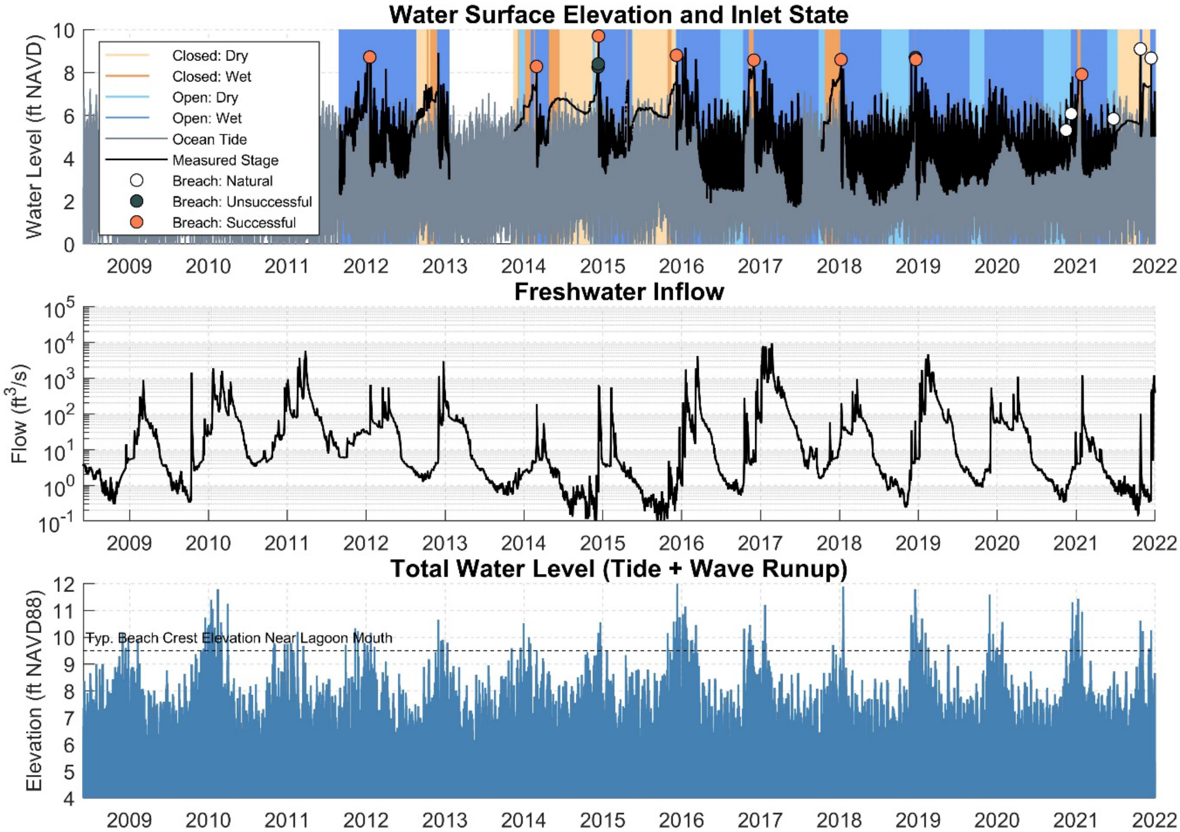
3. Observations: Existing Conditions

The model period from 2008 to 2021 covers a range of hydrologic extremes. It includes a number of relatively wet years (water years 2010, 2011, 2017, 2019), and drought years (water years 2014-2015, 2020-2021). It also included periods of powerful ocean wave conditions, which contribute both to mouth behavior and the hydrology of the lagoon (via wave overtopping). Figure 4 shows a time series of observed lagoon water levels, compared with combined streamflow to the lagoon and estimates of total water level on the beach from combined tides and wave runup. The latter is a useful indicator for when major wave overtopping into the lagoon is most likely to occur. Figure 4 also indicates when natural or managed breach events were known to have occurred.

In general, the mouth tends to experience more and longer closure events in dry years, with closures lasting for many months. During the few winter storm events in these years, the mouth remains open for several months, before closing due to wave action in early spring. In especially dry years, low base flows are eventually overmatched by beach seepage and evaporative losses, visible as seasonal low points in water levels in early fall. Whether or not rain is present in the fall, lagoon water levels typically increase in response to wave overtopping events, especially in the months from September to November.

In the wetter water years, higher winter flows scoured a deeper mouth, allowing the lagoon to remain open to tides for substantially longer periods of time. Powerful waves, such as during the El Niño winter of 2015-2016, can at times partially block outflows from the lagoon, leading to high water levels in the open lagoon.

After mouth closure in both dry and wet years, waves continue to cause the beach to grow through the dry season. The available coastal LiDAR suggests that areas of the beach that are distant from the location of the mouth can grow to 10-14 feet NAVD88. Recurrent breaching of the mouth creates an seasonal low point in the beach that is slowly rebuilt every year, but this area does not grow to the height of northern portions of the beach that are less frequently disturbed. Because of this, the mouth is sometimes able to breach naturally at low elevations (less than 8 feet NAVD88), whereas under natural conditions the elevation threshold for natural breaching might higher.



SOURCE: data sources listed in Table 1

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Figure 4
Comparison of (top) observed water levels in Watsonville Slough and nearby ocean tides, (middle) combined streamflow to the lagoon, and (bottom) Total water level on the beach.

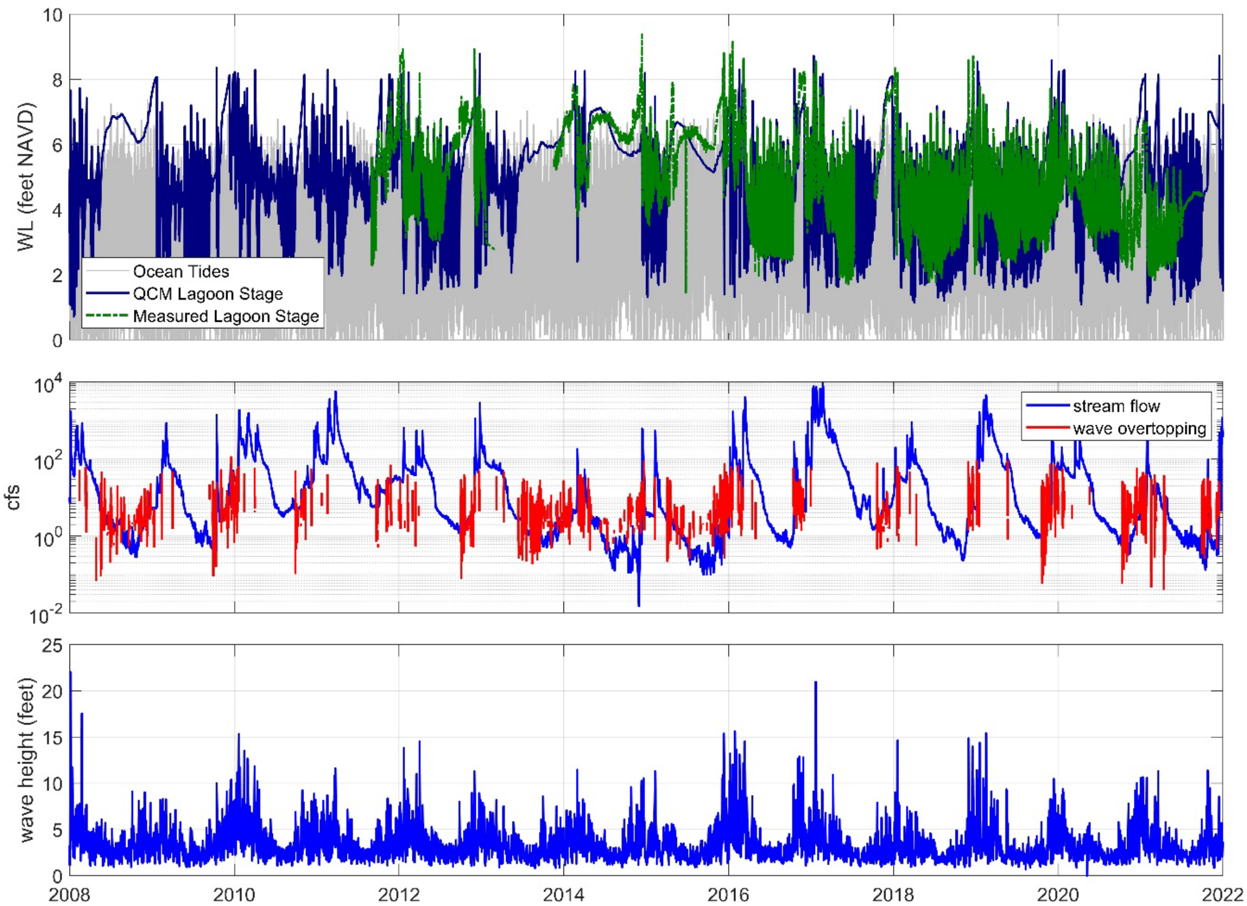
4. Model: Existing Conditions

The model calibration presented in this section corresponds to the *Baseline* scenario in Table 1. Figure 5 shows model predictions of the lagoon water levels compared to measured water levels, where additional information of the streamflow as well as calculated overtopping rates and nearshore wave power are also presented.

Overall, the model compares well against the available data, although further refinement is possible as more data are collected. During relatively wet conditions, the model reproduces the observed deep scouring of the mouth and periods of strong tidal communication between the lagoon and the ocean. The model also approximates the progressive shallowing of the mouth (cutting off low tides in the lagoon) prior to seasonal closure events, capturing the transitional weeks of muted tides that lead up to closure events in most years.

Overall, the timing of seasonal closure events were typically approximated to within about 1-2 weeks of the observed dates for most years, and the monthly likelihood of closure over the simulation period was well captured (Figure 6). However, in 2020 and 2021 the model had more difficulty in capturing the initiation the seasonal event (underpredicting closure in 2020, and overpredicting in 2021). This could potentially be a result of our assumptions about the shape of the beach in the model (which remained constant in the model through the simulation period, but was known to vary in size from year to year). Short-lived (less than one week duration) closure events that occurred in winter or spring prior to final seasonal closure were sometimes not captured by the model, or were predicted in error, which is expected given the simplicity of the model and complexity of lagoon mouth morphology on the open coast. Future refinements that consider interannual changes in the beach shape could improve these results further.

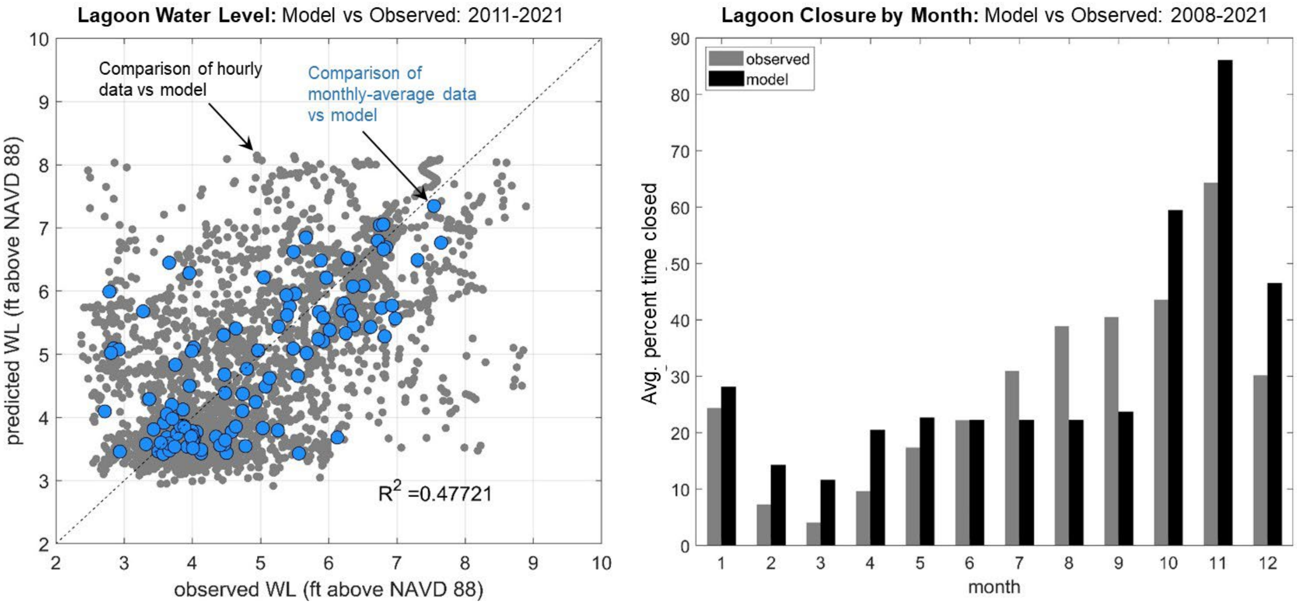
Water levels in the lagoon during mouth closure events were typically captured to within one foot of observations, as well as monthly-average water levels are across the entire 2008-2021 time period (Figure 6, left panel). When comparing hourly water levels, errors can be larger. This is because it is difficult to accurately predict every closure event, and the difference between closed- and open-mouth water levels is large. The model is intended to accurately match seasonal changes in water levels and mouth behavior over long periods of time, rather than at the hourly scale.



SOURCE: Coastal Ecosystem Resiliency Project – Lower Watsonville Slough: D202000443.00

see Table 1 for data sources

Figure 5
QCM-data comparisons for '*Baseline*' scenario. Top: QCM calculations of lagoon water levels compared to the observations of lagoon water level and ocean tides. Middle: Observations of streamflow with model estimates of wave overtopping rates. Bottom: Observations of nearshore wave heights.



see Table 1 for data sources

Figure 6

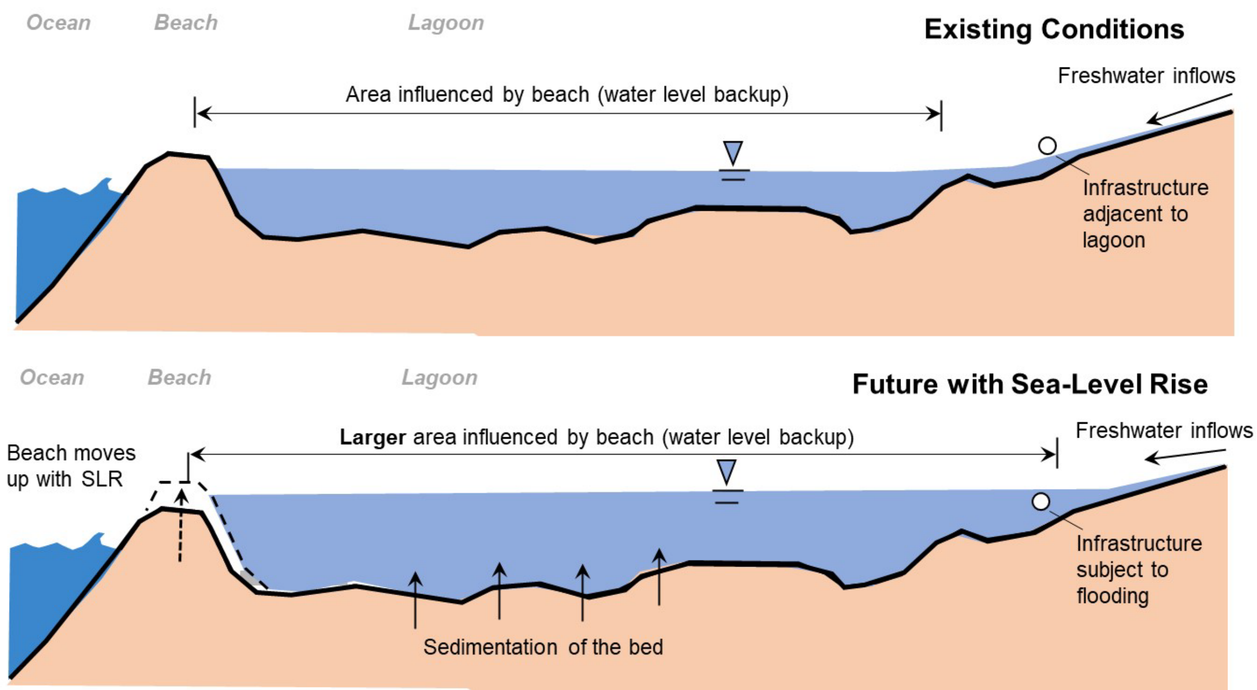
(left) Comparison of modeled and observed water levels in the lagoon and (right) comparison of modeled and observed % time of inlet closure by month of the year.

3. Model: Future Conditions

With sea-level rise, the beach fronting the lagoon is expected to increase in elevation. This is because the wave processes that form the beach will still be present, but will be lifted to higher elevations by the tides. The beach is expected to move landward over time, but would otherwise still be supplied with sediment from the watershed and adjacent segments of the coast. While the beach rises at pace with sea-level rise, infrastructure around the lagoon would be fixed in elevation, leading to a higher vulnerability for flooding (e.g. ESA PWA 2014). This is demonstrated in schematic form on Figure 7 below.

Some level of sedimentation is expected to occur within the lagoon channels and adjacent marsh areas. This means that sea-level rise is would not simply drown the lagoon over time. However, the rate of sedimentation is highly variable depending on sediment supply from the watershed, mouth condition, and frequency of inundation (Thorne et al. 2021). The maximum allowable water level in the lagoon before manual breaching is required is a critical component of the future behavior of the lagoon. If this elevation is fixed, higher water levels in the lagoon with sea-level rise would require more frequent breaching to prevent flooding of infrastructure.

This section discusses the difference between modeled outcomes for the future condition with and without the Project, and with consideration for future sedimentation.



SOURCE: ESA

Figure 7
Schematic of lagoon response to sea-level rise.

3.1 Change in Seasonal Closure

Existing Sea Levels

- **Delay in breach events with Project:** Raising the breach threshold with the Project has the effect of prolonging closure events in the model simulations. For many of the closure events from 2008 to 2021, the delay was on the order of several days, with an average of about 4 days (Table 3). The actual breach delay for specific events is heavily dependent on the combined freshwater inflow into the lagoon at the time of the breach. For events with combined inflows above 500 cfs, the delay was on the order of hours. For inflows from 100 to 500 cfs, the delay was on the order of several days. For inflows of less than 100 cfs, the delay could extend for several weeks.

Sea-Level Rise

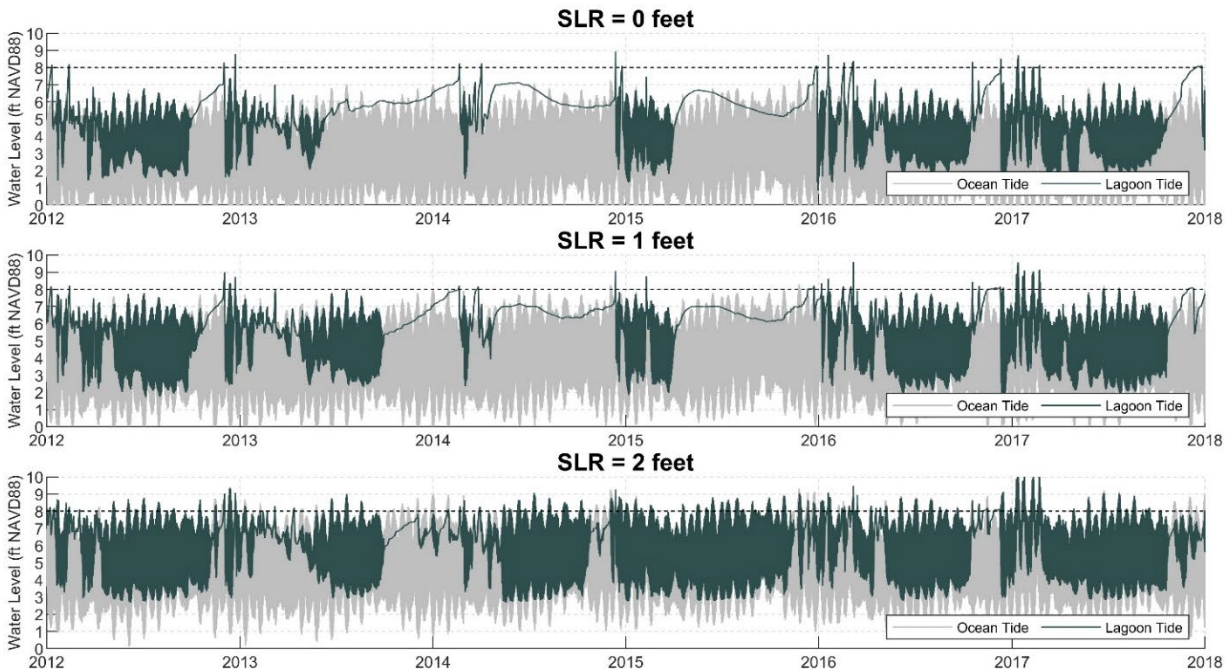
- **Delay in closure:** With sea-level rise, the timing of closure events becomes increasingly delayed in the model simulations, both with- and without the Project. As the lagoon progressively drowns with rising sea levels, the volume of water entering and leaving the inlet with each tide (the tidal prism) increases. This larger volume leads to higher velocities, which have more capacity to remove sediment deposited by waves in the inlet bed. The delay in closure increases progressively with sea-level rise, as summarized in Table 3.

- **Earlier breach events without Project**: For the baseline scenarios (Scenarios 3a and 3b), maintaining the existing breach threshold into the future shortens closure events with sea-level rise. This is because higher ocean tide levels generally led to higher water levels in the lagoon at the time of closure events, so it took less time for lagoon water levels to rise to the level of the breach threshold. The shift toward earlier breaches increased progressively with sea-level rise, as summarized in Table 3.

- **Less severe change in breach events with Project:** For Project scenarios (Scenarios 3c and 3d), sea-level rise also led to earlier breach events, but the effect was less strong. This is because raising the breach threshold allowed for more space to store trapped freshwater flows during closure.

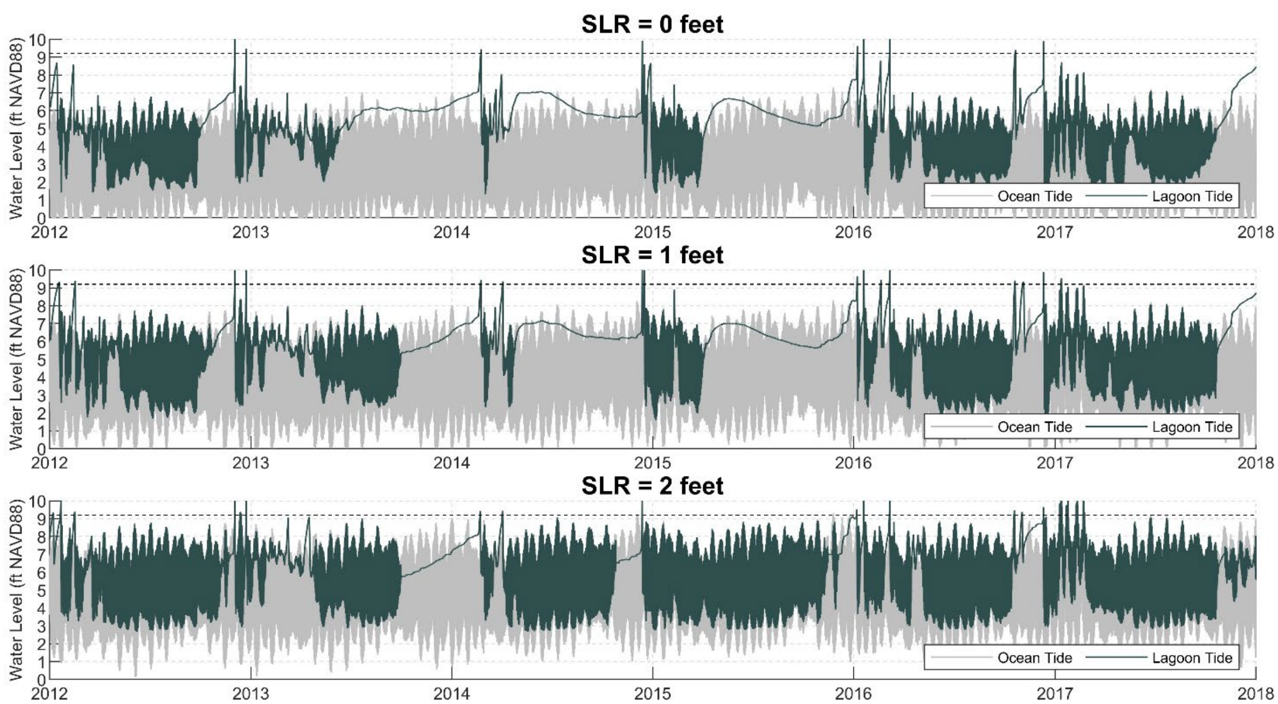
- **Overall shift toward less closure with sea-level rise:** Taken together, the delayed closure events and earlier breaches were predicted to lead to more open-inlet conditions in the future. This shift is illustrated for a subset of the time series in Figures 8 and 9. The Project generally delayed this shift for intermediate amounts of sea-level rise. The difference is most pronounced for about 2 feet of sea-level rise. This is visualized differently in Figure 10, which compares the total percent of time that the inlet was closed from 2008-2021 in the model as a function of sea-level rise. Under existing conditions, the inlet was closed about 30-35 percent of the time both with- and without Project. For 2 feet of sea-level rise, the inlet is closed about twice as often with the Project compared to the baseline.

- **Sensitivity to sedimentation:** Including sedimentation in the lagoon channels and floodplains had only a minor effect on the trends described above. This is illustrated in Figure 10 and Table 3.



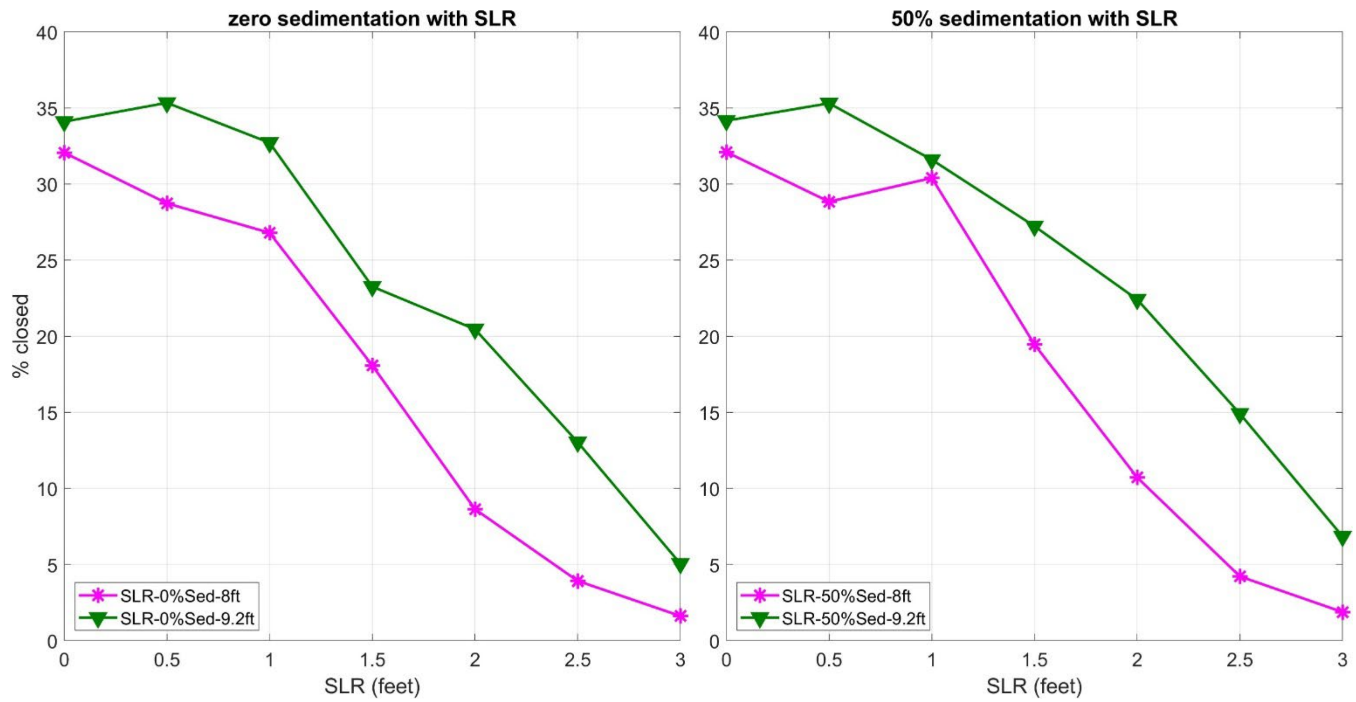
SOURCE: ESA

Figure 8
Comparison of modeled lagoon water levels for baseline conditions and sea-level rise of 0 to 2 feet, for a subset of the model period.



see Table 1 for data sources

Figure 9
Comparison of modeled lagoon water levels for Project conditions and sea-level rise of 0 to 2 feet, for a subset of the model period



SOURCE: ESA

Figure 10
Comparison of predicted percent time of mouth closure from 2008 to 2021 for With- and Without-Project conditions for (left) no future sedimentation in the lagoon and (right) sedimentation equal to 50% of sea-level rise.

TABLE 3
CHANGES IN MOUTH CLOSURE BEHAVIOR WITH PROJECT

Scenario ID	Average no. of days closed per year (2008-2021)	Number of Events per year with lagoon WL reaching breach threshold (2008-2021)[1]	Average no. of closures per year (2008-2021)	Avg. Change in date of closure relative to Baseline (days)	Avg change in date of breach relative to Baseline (days)
Baseline	117	1.8	11.4	--	--
Project	124	1.0	11.1	0	+3.9

[1] Defined here as the number of events in the model with water level reaching the breach threshold for 2 or more days, regardless of season.

3.2 Change in Number of High Water Level Events

Existing Sea Levels

- **Reduction in number of high water level events:** with the Project, the model predicts a reduction in the number of high water level events (i.e. water level reaching 8 feet NAVD88 for Baseline and 9.2 feet NAVD88 for Project conditions) over the period from 2008 to 2021 (Figure 11). In a few cases this was because a series of short closure events combined into single, longer closure event as a result of the higher breach threshold. Otherwise, the reduction was largely a result of the lagoon breaching naturally before water levels could reach the assumed threshold of 9.2 feet NAVD88.

Sea-Level Rise

- **Reduction in number of high WL events:** For intermediate levels of sea-level rise, the Project continued to reduce the number of events with water levels reaching the breach threshold relative to the baseline scenario. Figure 11 compares the two cases as a function of sea-level rise. For higher amounts of sea-level rise, both cases are predicted to have fewer of these events, which is due to the conversion of the lagoon to more open-inlet conditions for higher sea-level rise amounts (described above). For more than 2 feet of sea-level rise, the Baseline case has fewer events, which is because there are fewer closure events for this scenario (i.e. the lagoon converts to tidal conditions, as described above).

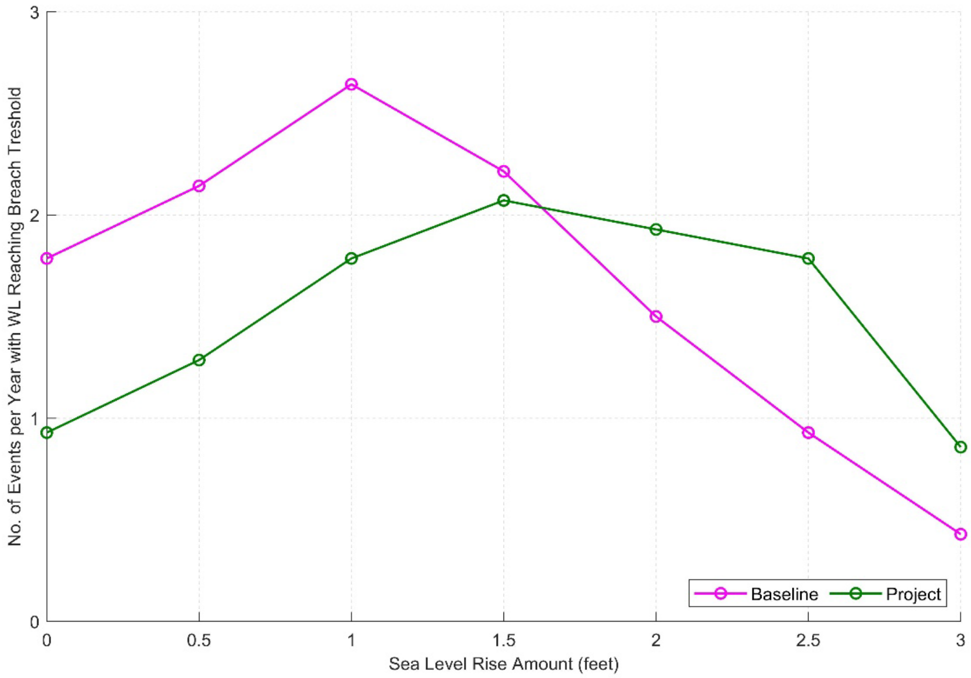
3.3 Change in Water Levels

Existing Sea Levels

- **Slight increase in water levels, but similar seasonal pattern:** The Project primarily delays breach events, with the delay lasting from as little as hours to as long as weeks in most cases. This delay in breaching allows for higher water levels to occur more often (up to 9.2 feet NAVD88), which is visible in a slightly higher peak in the water level frequency distributions shown in the left panel of Figure 12. These distribution curves represent the frequency that each water level is expected to be observed in the lagoon. The fact that water levels are higher than ocean tides in this distribution is a result of the mouth closure allowing for higher levels than open-mouth tidal conditions for much of the period from 2008 to 2021. Apart from slightly higher water levels during closure, the distribution of water levels was not predicted to change substantially between with- and baseline conditions.

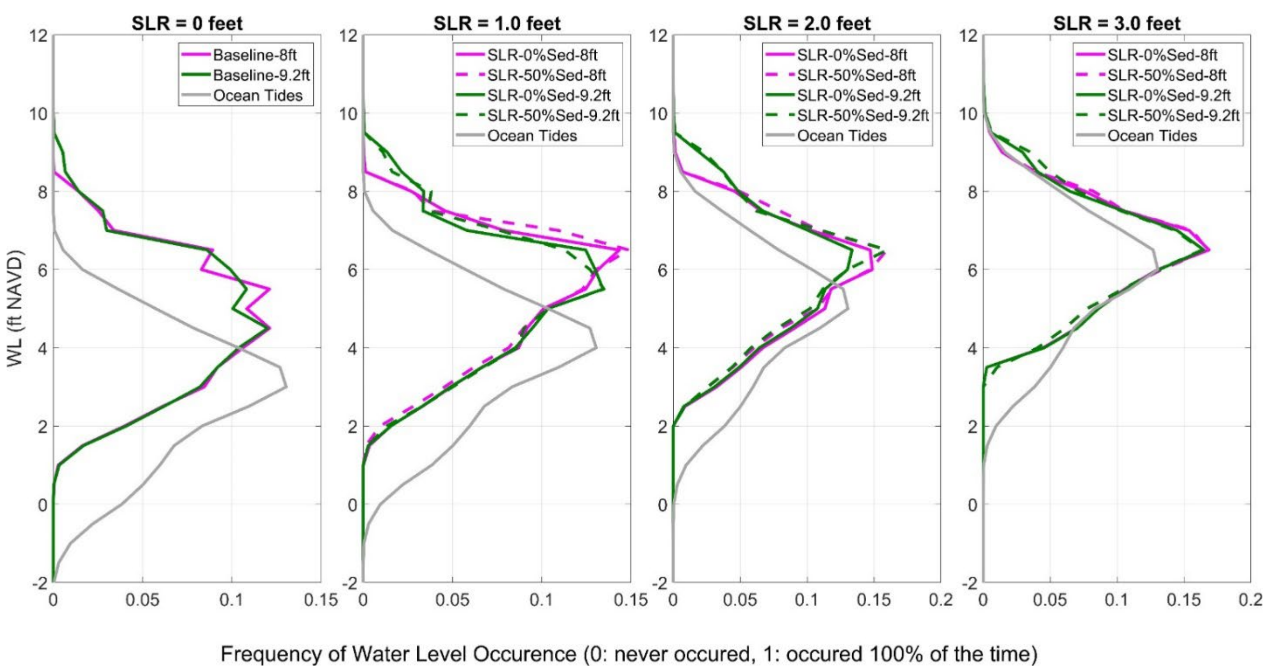
Sea-Level Rise

- **Gradual conversion to more ocean-tidal water level ranges.** With sea-level rise, as closure events become more infrequent, the distribution of water levels in the lagoon begin to match the distribution of ocean tides more closely in the model (Figure 12). Coupled with the rising tide levels, this implies that pickleweed marsh areas adjacent to the channels could become overtopped more frequently if they do not experience enough sedimentation to keep pace.



SOURCE: ESA

Figure 11
Predicted change in number of events per year with water level reaching breach threshold, with and without Project.



SOURCE: ESA

Figure 12
Frequency of modeled lagoon water levels for With and Without-Project conditions, lagoon sedimentation, and 0 to 3 feet of sea-level rise.

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San Francisco District

DRAFT

Appendix B-2

Civil Design

Watsonville Slough CAP 1135 Ecosystem Restoration Project
Santa Cruz County, California

July 2025

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List of Abbreviations and Acronyms

AASHTO - American Association of State Highway and Transportation Officials

AC-asbestos concrete or asphalt concrete

AMD – Adaptive Management Plan

CALTRANS – California Department of Transportation

CDFW – California Department of Fish and Wildlife

CFS or cfs – Cubic Feet per Second

CY – Cubic Yard

D- Diameter

FRM – Flood Risk Management

H – Horizontal

ICW – Inspection of Completed Works

LF – Linear Feet

LB – Pound

LS – Lump Sum

LERRD – Lands, Easements, Relocations, Rights-of-way, and Disposal Area

MHHW (mean higher high water), MHW (mean high water), MLW (mean low water), MLLW (mean lower low water)

NAD – North American Datum of 1983 (NAD 83)

NAVD – North American Vertical Datum of 1988 (NAVD 88)

NED – National Economic Development

NOAA – National Oceanographic …

NMFS – National

O&M – Operation and Maintenance

PC - precast

PDT – Project Delivery Team

PED – Preconstruction Engineering and Design

PV Water – Pajaro Valley Water Management Agency

QTY – Quantity

RW – Retaining Wall

SF – Square Feet

STA – Station

TSP – Tentatively Selected Plan

USACE – U.S. Army Corps of Engineers

V – Vertical

W – Wide

WSE - water surface elevation

Project-Specific References (all by USACE San Francisco District, unless noted otherwise)

- Watsonville Slough Watershed Report, January 2003
- Watsonville Slough Watershed Technical Appendices, January 2003
- Watsonville Slough Section 1135 Aquatic Ecosystem Restoration, Draft Integrated Feasibility Report and Environmental Assessment, Oct 2021
- HH&C Appendix, this report
- Geotechnical Appendix, this report

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1. Introduction

The USACE San Francisco District (USACE) is working together with Pajaro Storm Drain Maintenance District (County or Local Sponsor) on the Watsonville Slough Aquatic Ecosystem Restoration Feasibility Study (Study), under the Continuing Authorities Program (CAP) Authority 1135. This document is an appendix to the main project report and summarizes the civil engineering design work and analyses including: anticipated construction methods, challenges, and considerations for project alternatives. Additionally, construction phasing and quantities have been provided to the Cost Estimating section and will be presented in their appendix. The appendix content and format comply with USACE Engineering Regulation (ER) 1110-2-1150, Engineering and Design for Civil Works Projects.

1.1 Project Site Background and History

The project site is located at Lower Watsonville Slough in Santa Cruz County, a tributary to the Pajaro River, near where the Pajaro River discharges to the Pacific Ocean (Figure 1). The City of Watsonville is located approximately four (4) miles northeast of the study area. The Watsonville Slough watershed encompasses about 20 square miles while the Pajaro River watershed encompasses more than 1,300 square miles. Both watersheds are located on the central coast of California. Watsonville Slough is hydrologically connected to the Pajaro River as a tributary and during backwater events (lagoon closures).

The study area is bordered on the inland side by extensive farmland, while the Pajaro Dunes (residential communities) and Palm Beach State Park are located immediately on the seaward side (Figure 2). West Beach Road is the primary roadway access to the park and communities. About a quarter of a mile upstream of the West Beach Road crossing, Pajaro Valley Water Management Agency (PV Water) operates a pump station with tide gates at the Shell Road crossing. The tide gates prevent Lower Watsonville Slough from flowing back upstream. Santa Cruz County maintains a mechanical breaching regime at the Pajaro River lagoon mouth (to ocean) in order to manage local flood risk to low-lying agricultural lands, assets, and properties. Such breaching truncates the natural hydrology of the marsh.

Figure 1 Project Location and Vicinity Map

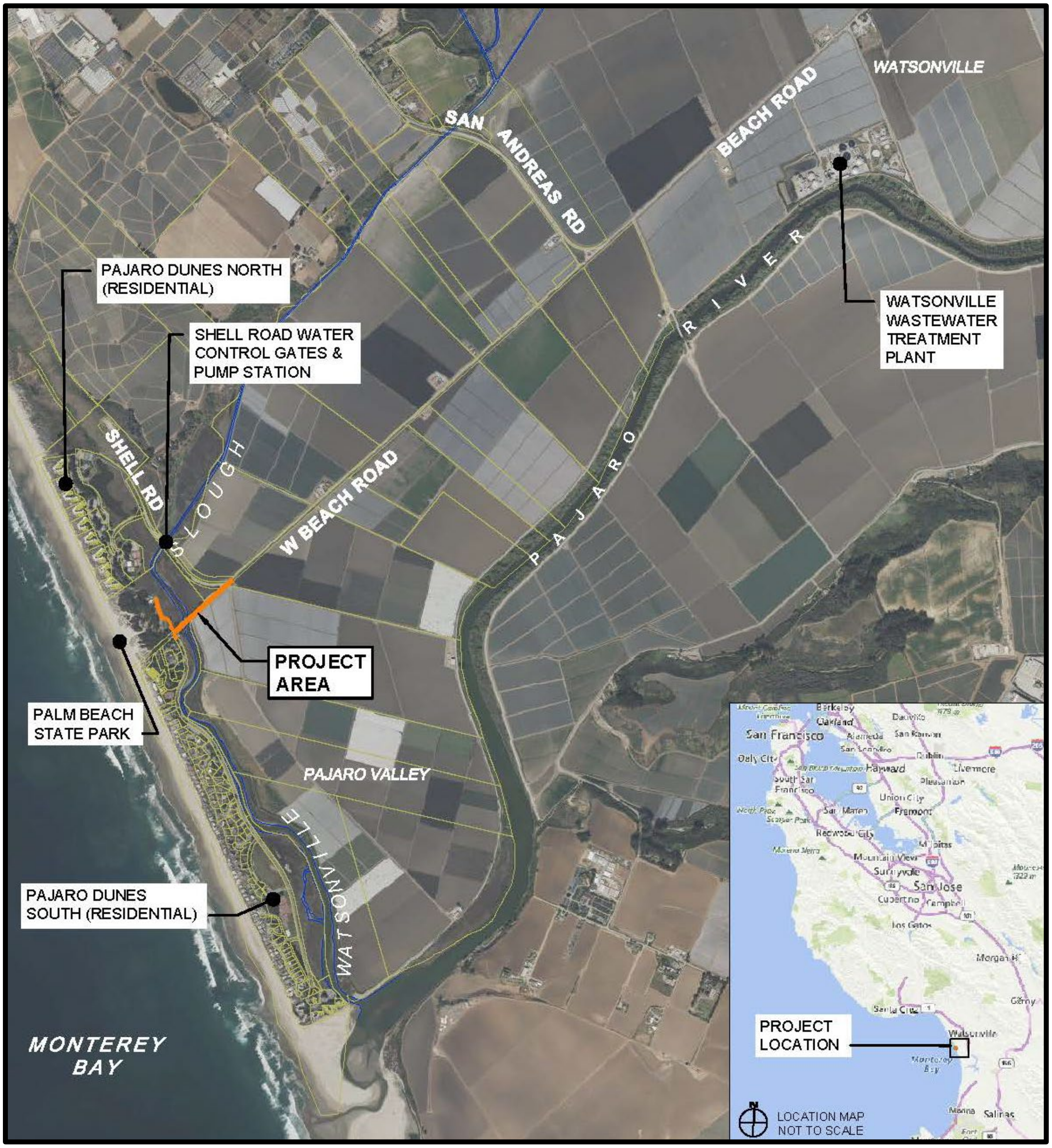
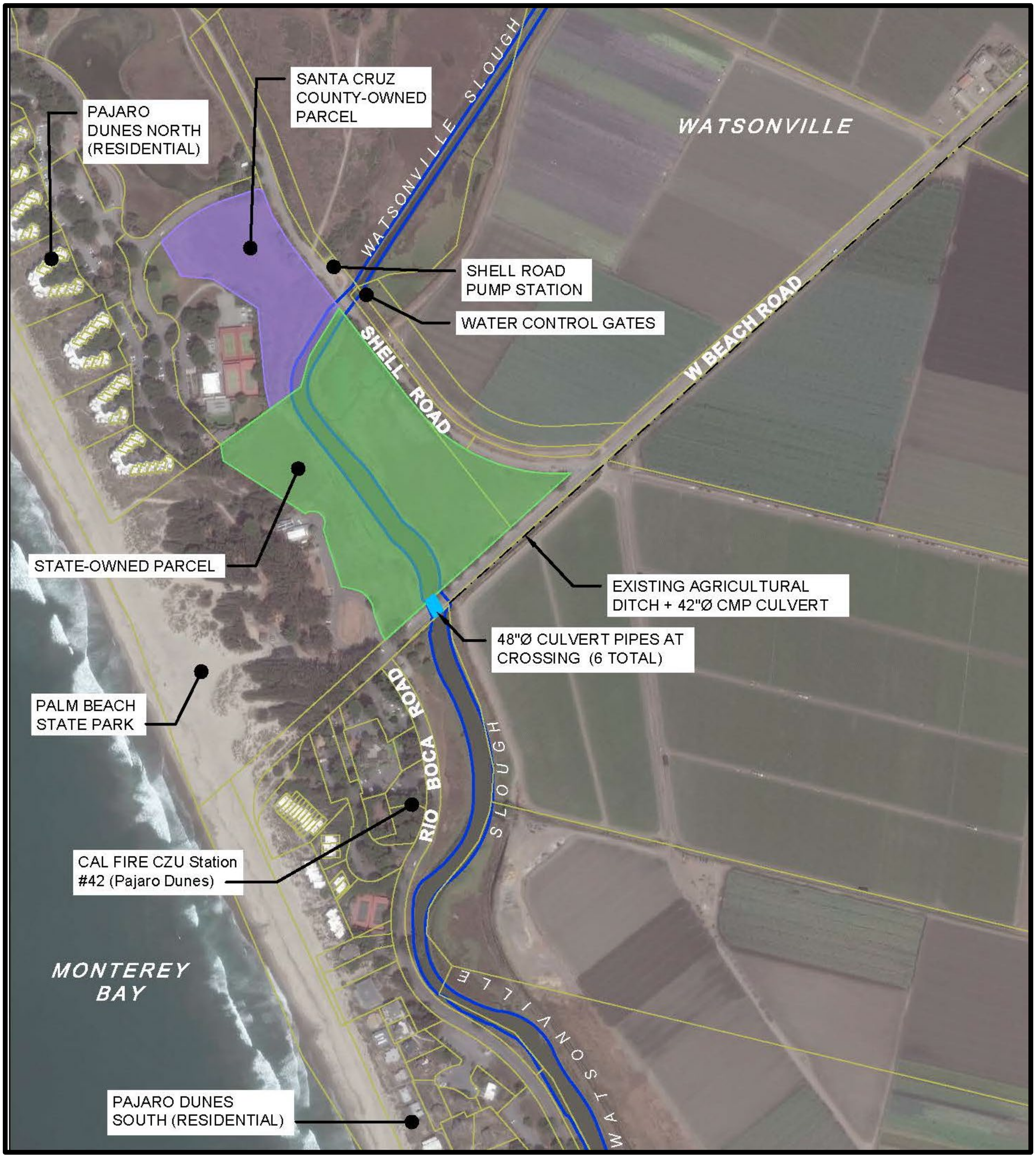


Figure 2 Existing Site Plan



1.2 Civil Design Criteria

This appendix focuses on presenting key design elements and civil/construction engineering considerations for the project alternatives developed. Project goals and objectives are noted in the Main Report. Based on the project goals and objectives, the following design criteria were selected as primary to Civil Design:

- Hydraulic Conveyance: USACE H&H Section to size future culvert at West Beach Road crossing to convey future typical and minimum design flow
- Fish-Friendly Passage: Design future culvert (to replace 6 existing pipe culverts) to support improved fish passage under West Beach Road and within the expected construction window between 15 June and 31 October (dry season).
- Roadway Elevation: Raise roadway elevation of West Beach Road 9.2' NAVD88 to avoid flooding/interrupted access in/out of Pajaro Dunes Community
- Slough Culvert Live Loading: AASHTO HL93 for truck loading
- South Ditch Culvert: Remove and replace existing 42-inch CMP culvert with a new culvert with tidal flap gate or similar
- Turbidity: Avoid elevated turbidity and localized impacts to fisheries and aquatic resources during construction including de-watering and diversion activities
- Emergency Access: Maintain emergency access (e.g. fire trucks, emergency vehicles) in/out of the Pajaro Dunes Community and to Fire House (Cal Fire CZU #42, Pajaro Dunes) with suitable passage through construction site at West Beach Road

2. Summary of Existing Conditions

The study area focuses on Lower Watsonville Slough, specifically the estuarine portion of the Slough downstream of the Shell Road pump station. West Beach Road is the primary access in and out of the Pajaro Dunes Community and Palm Beach SP, both adjacent to the Pacific Ocean. Based on discussions with the Local Sponsor and community members, West Beach Road is impacted by flooding during backwatering events from lagoon closures, which affects emergency access out of the area and road quality (e.g. formation of potholes, erosion). The reader is referred to the Hydrology, Hydraulics & Climate Appendix for more information related to hydrologic data gathered for this Project.

There are six (6) 48-inch diameter precast concrete culvert pipes underneath the West Beach Road crossing (Figure 3). It is unknown if the pipes are asbestos concrete or not, which would affect their removal procedure; the Corps asked the County if any information on material composition of the pipes and is waiting for a response. Both ends of the pipe culverts were found to have concrete slab debris located at the culvert inlets and outlets, which will need to be removed as part of the project. The concrete slab debris may have been installed for erosion protection and were estimated for location, size, and extents during a June 2023 site visit. Rock slope protection (some grouted) lines both the upstream and downstream banks of West Beach Road in the vicinity of the culverts.

West Beach roadway also has both a buried water main and sewage main indicated although their locations have not been verified by pot-holing; a buried natural gas pipeline(s) also serves the area and appears to run both under the roadway and in the adjacent slough. The buried pipelines will need to be temporarily relocated during construction (and kept operational).

No new topographic survey work was performed for this study. However, the County did provide ground survey data of the pipe culvert inverts and nearby features from the Pajaro Dunes and Lagoon Flood Vulnerability Assessment[1]. Field photos and preliminary probing show the presence of sedimentation and roadway debris at both ends of the culverts, potentially impeding flow. A (tidal) agricultural drainage ditch is located on the east side of the culverts and parallel to West Beach Road, draining the agricultural fields to the south. This ditch has a 42-inch CMP pipe culvert under the south roadway slope with an outfall into the slough (Figure 4). The outfall previously had a flap gate that possibly prevented tidal water from entering the ditch, however tides are now present.

[1] Environmental Science Associates (ESA). 27 November 2018. Technical Memorandum: Pajaro Dunes and Lagoon Flood Vulnerability Assessment.

Figure 3 Photo looking upstream (N) at existing six (6) 48-inch diameter precast concrete culverts under West Beach Road

Figure 4 Photo taken from Slough channel, looking NE at the agricultural ditch outlet with existing 42" culvert and headwall.

3. Design Elements

This section summarizes the design elements of the Crossing Improvements alternative, which is the Tentatively Selected Plan (TSP) for the study (Figure 5).

3.1 Roadway Design

Approximately 1300 linear feet of roadway at Beach Road, from east of Rio Boca Road (entrance to Sunset or Palm Beach SP) to Shell Road, will be raised to elevation 9.2 ft NAVD88. The existing roadway will be removed with the AC paving brought off-site and recycled. The road will be built up with new base material as noted further herein and in Geotechnical appendix. New bituminous paving (about 24 feet in width) will replace in-kind the existing roadway at the higher elevation noted with new gravel shoulders installed.

Presently, vehicles park on shoulders along the (mainly north) side of the road on West Beach Road when visiting the beach due to a relatively small parking lot at the State Beach. A goal of the project is to maintain and improve roadway shoulder parking along the northern side of West Beach Road. Additionally, there is an option to raise the existing roadways at the far western side of the site, at paved roadway into the State Beach as well as at the northern entrance to Rio Boca Road, to mitigate localized flooding.

3.2 Culvert Sizing and Specifications

Note that the limited nature of work required for this report will propose a single culvert replacement option of (1) 32-foot span PC concrete culvert in order to meet the minimum requirement of NMFS staff based on preliminary discussions. A single, open-bottom culvert was selected for preliminary design/discussion with permit agencies for at least the following reasons: long-term durability and limited maintenance; time needed to install; option to use PC concrete foundation for speed of installation; provides option to replace roadway with limited depth of cover. An open-bottom culvert or PC box culvert with invert set below the stream bed would both allow for aquatic species passage and help maintain in-stream and floodplain habitat. During the Design and Implementation (D&I) phase, culverts of varying types, configurations, and alignments as well as a possible multiple culvert solution for increased conveyance may be considered. Scour design considerations will also be included in the culvert design. Additionally, the culvert will be designed with soil-retaining components known as head, tail, and wingwalls. See the HH&C appendix for applicable hydraulic design parameters.

The new culvert will perform as a bridge with durability a concern. As noted previously, durability (as well as the high quality of materials and installation) make precast concrete a desired material choice for culverts of this size. Additionally, precast is desirable for its ability to accept road traffic immediately after installation, even if the bridge may be installed in phases. This bridge will have minimal soil (known as “cover”) above the top of culvert sections and will be designed to carry direct wheel loading if needed to pass traffic over the culvert yet before the new roadway is installed. The design live loading will be AASHTO HL93 which is the updated loading for highway lanes, superseding the long-standing HS20 (circa 1944). HL93 loading is also called “design tandem” truck loading.

Figure 5 Tentatively Selected Plan (TSP)

4. Construction

This section describes preliminary construction means, methods and considerations for implementing the TSP. The major components for construction of the TSP include:

- Cofferdam Installation & Dewatering (Section 4.1)
- Culvert Replacement (Section 4.2)
- Roadway Raise, incl. Paving (Section 4.3)

Given the need to maintain emergency access in/out of Pajaro Dunes during construction, two potential construction methods are described for the culvert replacement. It is possible that contractors may propose different construction methods, although the constraints at the site significantly limit the possible paths forward. A major goal of offering a minimum of 2 construction options is to explore a range of environmental impacts that will be needed to perform the work and to include as much leeway in the compliance documents.

-Option 1: Bisecting West Beach Road and replacement of the existing six (6) culvert ½ at a time (keeping 1 lane of West Beach Road open at all times) and

-Option 2: Construction of a temporary roadway(or similar passage) through the Slough and replacement of existing culverts all at once. Section 4.2 provides greater detail on construction methods, traffic control/considerations and other aspects of the two culvert replacement methods.

Figures 6 and 7 show the proposed components of Options 1 and 2 for the TSP.

Initial construction activities (e.g. staging, utility relocation, construction BMPs) are required for the contractor to safely begin activities and in compliance with future environmental permit conditions (Sections 4.4, 4.5, 4.6). The expected in-water work “window” is expected to be June 15 to October 31. All information presented in this section should be considered feasibility-level and will be refined by the PDT and Local Sponsor during the D&I phase. The design and construction sequence may be impacted by environmental and other considerations.

Figure 6 Tentatively Selected Plan – Option 1

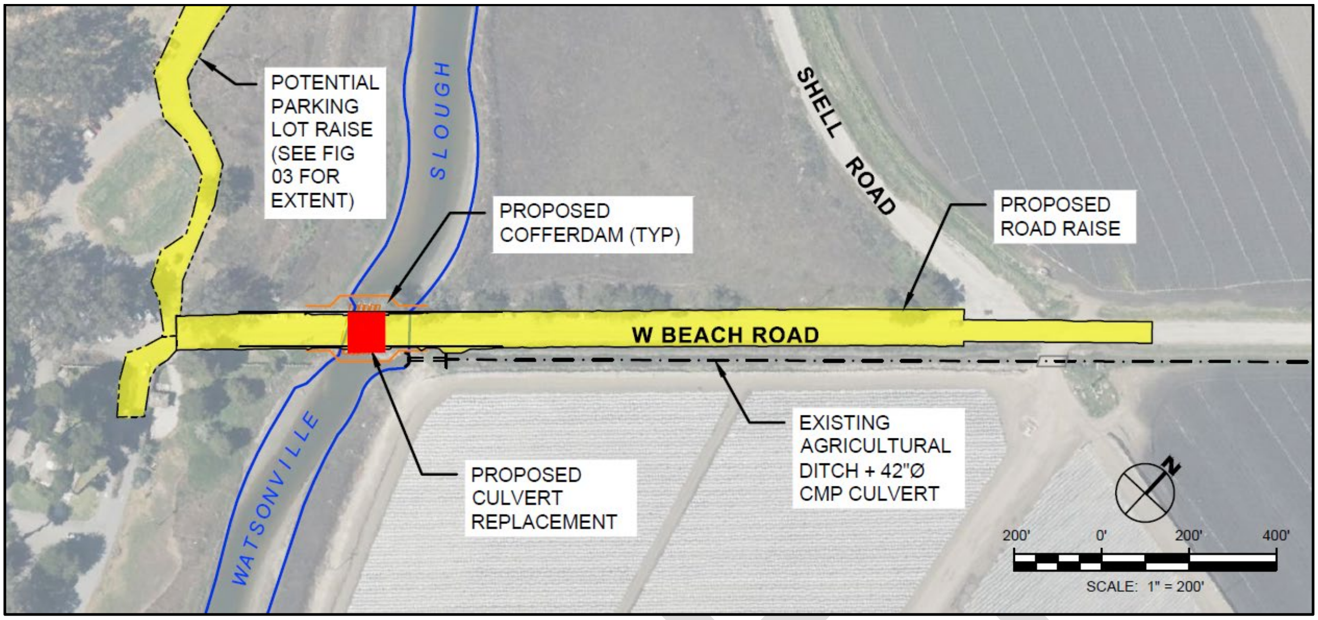
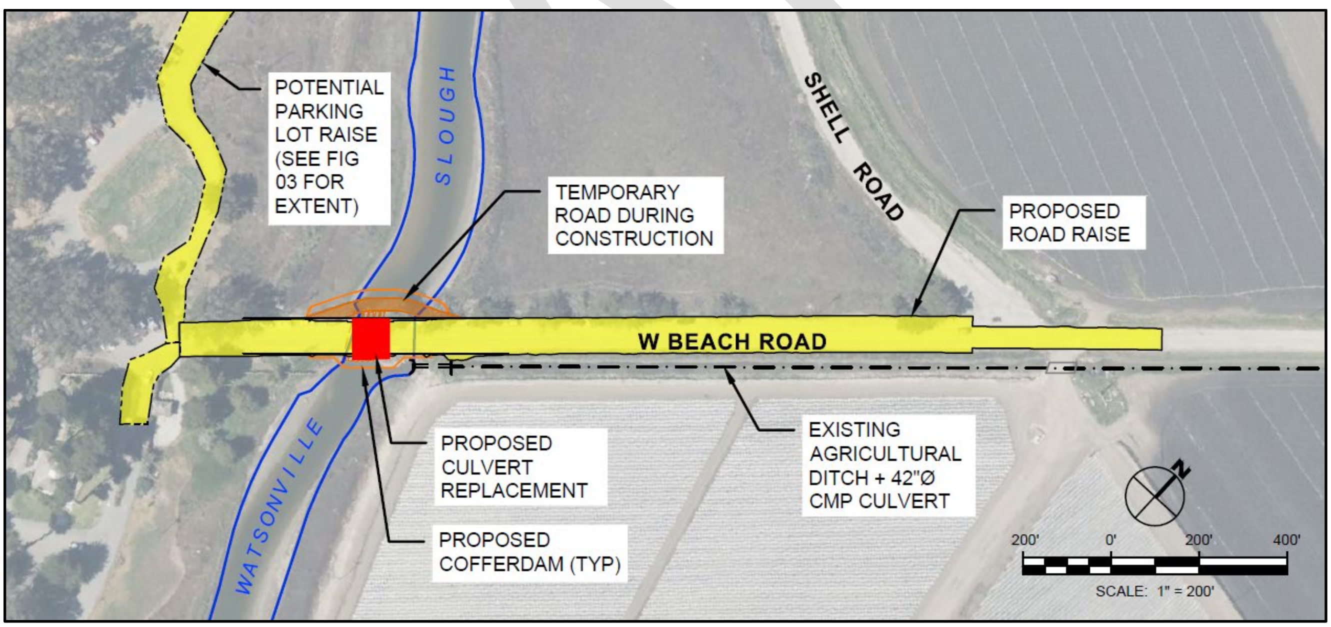


Figure 7 Tentatively Selected Plan – Option 2



4.1 Cofferdams & Dewatering

Cofferdam Installation & Types

Installation of a new culvert at the Beach Road crossing will require establishing and maintaining a dry working area in the Slough with local traffic required to maintain access to all properties west of the work site. This work includes building cofferdams and dewatering the area of construction. Water handling will also be required to replace the 42-inch pipe culvert at the agricultural/tidal ditch that runs parallel to West Beach Road near the toe of the south bank. More information is needed on the expected volume of agricultural water in this feature during the dry season.

The 42-inch CMP pipe culvert that passes under an agricultural crossing and discharges runoff into the Slough. As part of this project, the pipe will be replaced with an outlet with a flap valve, duck-bill valve, or similar to prevent slough water from entering the ditch. Like the main culvert replacement work, the work at this single culvert will need to be isolated by a temporary cofferdam or similar.

To minimize impacts to aquatic resources, the construction window for the project will likely be between mid-June and late-October (dry season), when flows to the Slough are low. During the dry season, when there is little to no precipitation, the Slough passes low flows of about 1-2 cfs[2]. The upstream Slough flow is also influenced by an upstream pumping station-(Shell Road Pump Station) about 1,200 feet north of the culvert site. Flows and releases from this pump station will/may need to be scheduled and noted to potential bidders in order to provide safe water handling around the project site in addition to the watershed flows. Slough water by-pass details are beyond the scope of this report, however the upstream cofferdam will need to be designed (with dewatering) to accommodate all possible flows during construction. Schematic plans of the slough de-watering are shown in Figures 8 and 9.

Expected cofferdam types for containment are shown below in Table 1. At this level of design, it is preferred to keep as many cofferdam materials and installation options available for construction and to be included in the compliance documents. The presence of existing utilities may dictate what is not acceptable due to cost and possible public safety at one or both of the cofferdam locations.

The 2 cofferdams (to be installed upstream and downstream of the existing West Beach Road culverts) will be installed with the slough at summer water levels. Due to the muted tides expected in summer, the 2 cofferdams may not be similar in preferred construction material. This would affect the desired heavy equipment to be used for economical and efficient installation. Fish barriers will first be installed outside of the limits of the future cofferdams with fish removal clearing the work area of fish species. It is preferred to have the future environmental permits allow several options of cofferdam types to include: Earthen Berm(s); Sand/Gravel Bag Barrier; Aqua-barrier; and sheet piles. Polyethylene sheeting, or similar impervious materials, may also be added to some of the cofferdam schemes to reduce seepage through the barriers. See Table 1 below for a brief description of each.

[2] PVWater gage data from WY2016 through 2021 show observed low flows of 1-2 cfs during dry season. The reader is referred to the HH&C Appendix Attachment A: Hydrologic Assessment for additional background.

Table 1 Cofferdam (Barrier) Types

BARRIER TYPE	**DESCRIPTION**	**INSTALLATION IN BRIEF**
Earthen Berm	A temporary berm or shallow ridge of compacted soil that is placed to form a barrier to prevent surface water access to the culvert work area. Potential for loss of berm material causing increases in turbidity must be balanced against design considerations.	Loader and excavator pushing soil (delivered by dump trucks and loaders) into slough.
Sand/Gravel Bag Berm	Reinforced fabric bags (super sacks) are filled with sand or gravel, laid end to end to form a barrier that prevents surface water from reaching a specific area (work area). Multiple levels of bags can be used and plastic sheeting incorporated into the barrier to help prevent water seepage through the barrier. Sand bags may be suitable at tidal ditch.	Fill 1 CY supersacks and install with excavator may access from slough shore then off of supersack base if needed for ground pressure.
Aqua-Barrier	Inflatable barriers made from laminated industrial grade vinyl coated polyester and available in a variety of sizes (lengths and heights) are used to prevent surface water from reaching a work area.	Probably least amount of surface and aquatic impact, however may not be as reliable as other cofferdam types.
Sheet piles	Long structural sections with a vertical interlocking system, in various sizes, used to create a continuous wall to exclude water from work areas.	Sheet may be installed with a vibratory hammer on excavator.

The desired cofferdam type will vary based on many factors, including whether Option 1 or Option 2 for culvert replacement is implemented. There are many variations (many beyond the scope of this report due to the schematic design nature of a feasibility study and due to being contractor-designed) that will drive the desired cofferdam type for this project. The following text provides preliminary construction considerations as related to cofferdam installation, access, and impact to the Slough.

Option 1 may allow more flexibility because the sheet-pile cofferdams can be installed using the one lane of the roadway for equipment access. This scheme allows local traffic to pass through the work zone on the remaining half of the roadway with existing shoulders used as part of the temporary roadways. Option 2 would require more impacts to the wetlands yet may give the contractor more flexibility with budget and schedule. Also of note is the presence of overhead power on PG&E poles along the northern edge of West Beach Road. The selection of cofferdam type on the upstream side of the slough may be dependent on safety and clearance of the overhead power lines with the equipment needed to install the cofferdam. The contractor will likely want the option to bring equipment down into the slough in order to install and maintain the cofferdam as well as the temporary bypass road for Option 2.

Option 2 has the cofferdams likely furthest away from the roadway to give the contractor space to build an earthen single-lane roadway that reroutes traffic off the existing paved 2-lane West Beach Road and allows the new culvert to be replaced at one time. This temporary re-routing of the roadway involves temporary filling of the slough which includes wetlands and sensitive vegetation and habitat. It is desired to allow borrow from the primary staging area to provide the contractor with a nearby soil source that could be returned and graded to near-original grade upon completion. Other temporary fill material (such as timber crane mats) may be desired to build the temporary roadway yet will be further studied with more geotechnical information is obtained. Once the cofferdams are installed the water handling systems may be installed.

Dewatering

There are 3 types of water systems needed for a project of this type and are similar for replacement of both of the existing culverts, the (6) 48-inch RCP culverts under West Beach Road and the (1) 42-inch CMP for the agriculture ditch. The 3 types are (and will be discussed below):

- Initial de-watering system;
- Bypass water handling;
- Nuisance pumping.

Initial De-watering:

De-watering will be similar for either Options 1 or 2 with the culvert work area needing to be initially pumped dry, likely with a 4 or 6-inch diameter diesel pump(s). A schematic representation of this operation is shown in Figures 8 and 9 with initial de-watering shown at assumed locations and nuisance pumps not shown. The permit condition discussions are too preliminary to interpret how this initial volume of water will be pumped/handled (and even what type of pump(s) is preferred) yet it is anticipated that the contractor will want to be allowed to pump the water into the marsh plain (upstream, downstream, or both). Outlet energy would be reduced/dispersed with initial flow into vegetated areas before allowing water to flow back into the slough. This report will continue under the assumption that the initial cofferdam volume may be pumped dry with needed energy dissipation and turbidity controls to limit environmental impacts. Once pumped dry the work area around the existing culverts will need to be dried out (by time and winds) and then periodically maintained with pumping of nuisance water.

Figure 8 Dewatering Schematic

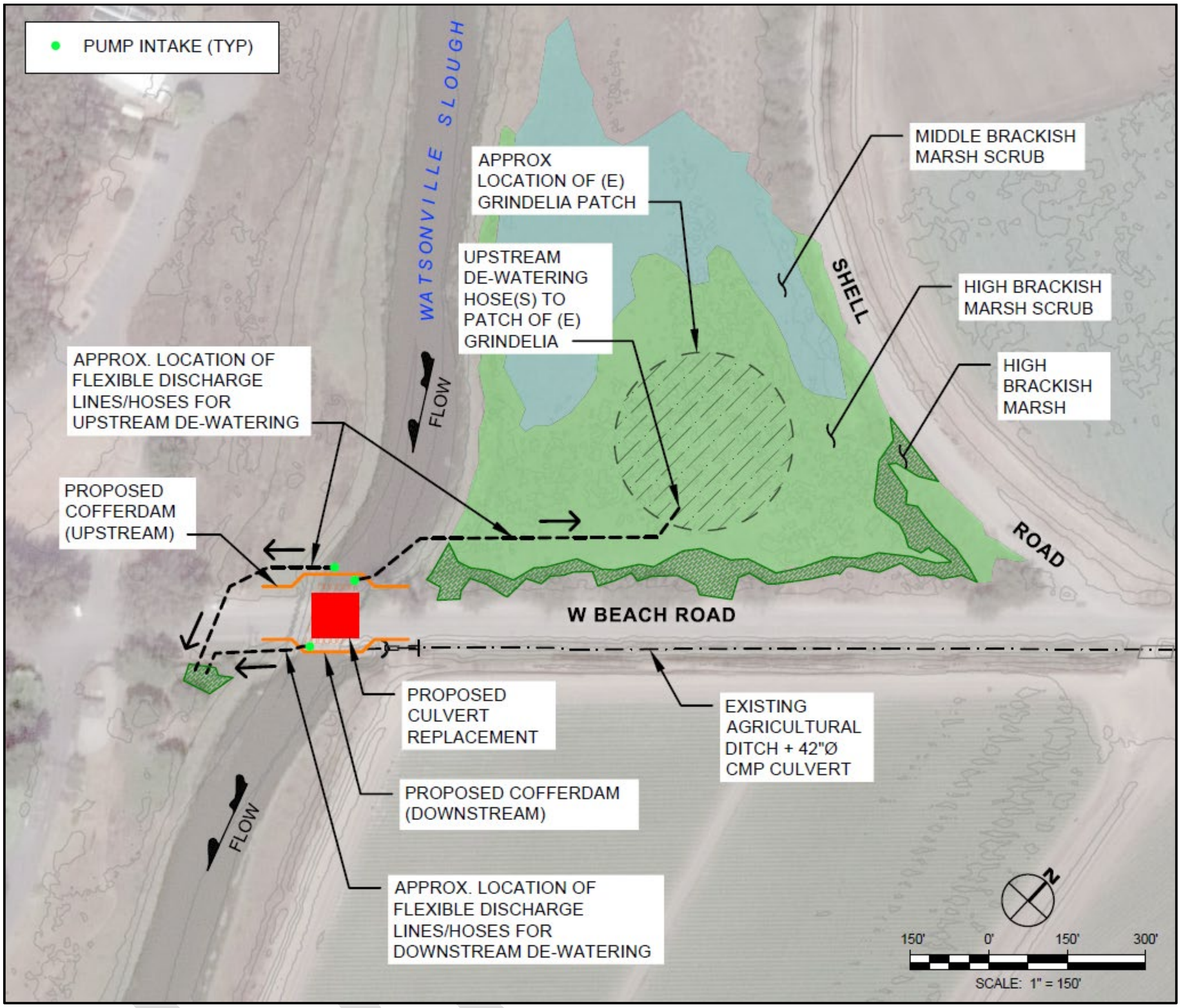
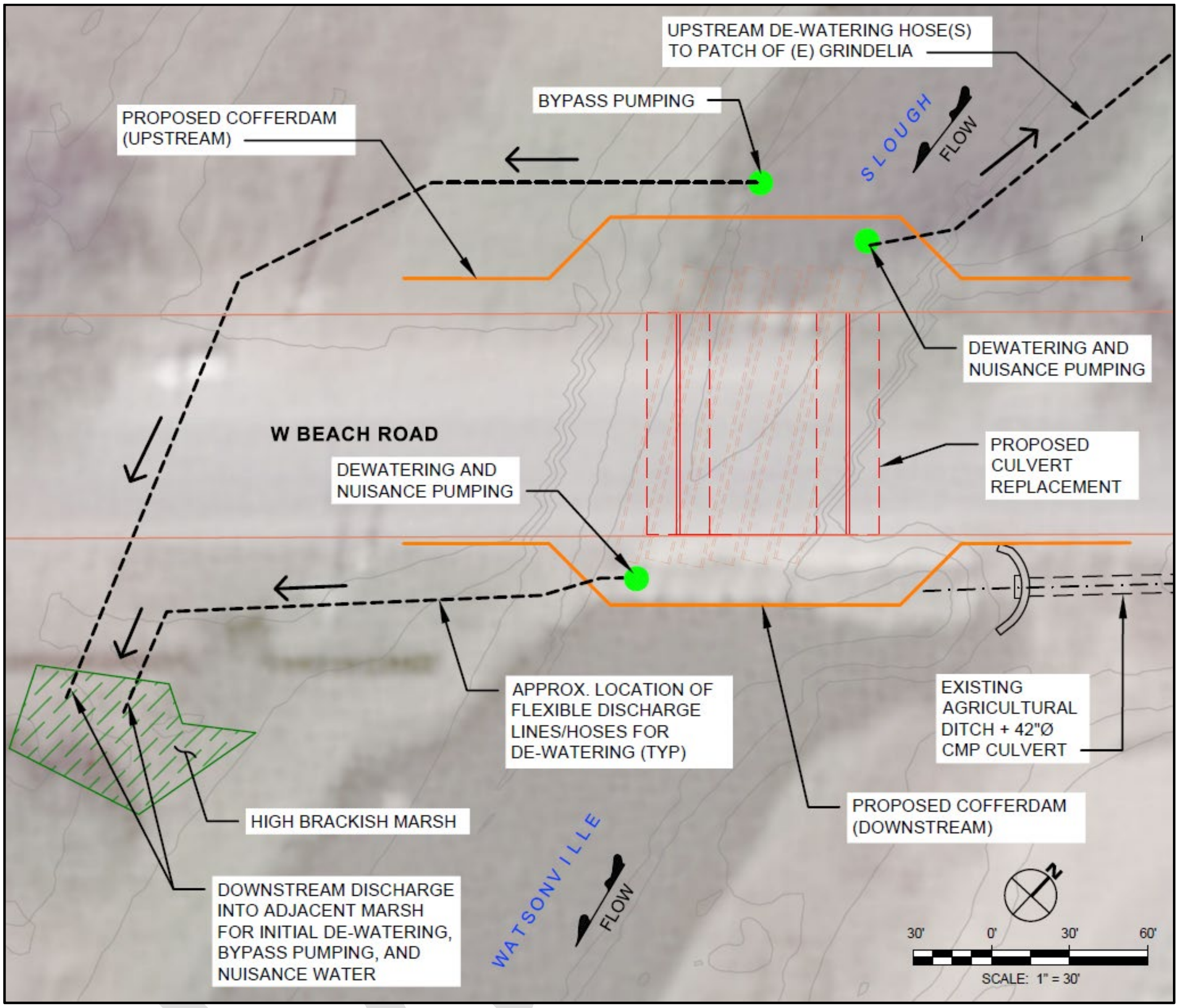


Figure 9 Dewatering Schematic (Enlarged)



Nuisance water handling:

Nuisance (water) pumping will be required due to leakage of the retained slough water past the cofferdams. Typically, 2-inch gas-powered pumps (or smaller electric pumps) are suitable for this operation and are monitored and run as an as-needed basis. Due to inherent nature of these pumps being portable the gas pumps are usually housed in a plastic tub or bin that provides spill containment with pumps allowed in the slough yet refueled outside of the waterway.

By-pass Pumping, as needed:

In addition to nuisance pumping a slough bypass pumping system will be needed to transfer (summer) slough flows from upstream of the cofferdam to downstream to maintain some of the natural functions during construction. The details of the bypass system will be determined as part of the permit and compliance effort yet is expected to use similar equipment as the nuisance pumping, however a more advanced system of float sensors and automated operations may be needed depending on the expected hourly flows. Similarly, this more advanced bypass pumping is expected to transfer water from the agricultural/tidal ditch at south bank around the southern cofferdam due to unknown and varying agricultural flows both in volume and discharge times.

4.2 Culvert Replacement

West Beach Road is the primary access route in and out of the Pajaro Dunes Community and Palm Beach State Park. An on/off traffic light and road signage will be maintained through the duration of construction to control traffic flow and support safety. It is expected that a single lane of local traffic (on West Beach Road) will be needed over a length of about ¼ mile: from just east of the Shell Road intersection to just east of the entrance to Sunset Beach. Additionally, the existing water and sewer mains will need to be temporarily rerouted to remain operational full-time with only minimal down time for both for transition through the construction zone.

The 2 culvert replacement options require passing of local traffic through/around the culvert replacement site. Safety barriers will be used to keep local traffic separated from work zones with additional crew for traffic control as needed for safety; a traffic control plan submittal will be required by the contractor. The 2 culvert replacement options are:

Option 1, Culvert replacement

West Beach Road will be “split” (or bisected) at culvert replacement site by installing (steel) sheet pile near the middle of roadway, parallel to traffic, to allow the existing culverts to be removed and replaced about ½ at a time. Alternate retaining of the remaining roadway may be studied besides using sheet piles. For the first phase of option 1, traffic would pass through the site on a single lane of the existing pavement while existing culverts are exposed, removed, and replaced.

With ½ of the roadway closed down, the paving and base will be removed with a trench cut to allow the sheet pile or similar installed along the center of the roadway. Next, about ½ of the existing culvert will be removed and site excavated to desired elevation to install the foundation. After the foundation is installed, the new (first ½ of the) culvert will be installed using a crane. Footings, culvert sections, and head or tail wall to be installed to a close distance of the temporary sheet piling that splits the former roadway. See Figures 10 and 11 for a representation of this configuration. Two cast-in-place concrete beams are expected to be cast at the outside edge of (top of culvert) culvert to provide a foundation for the future guardrail to keep the guardrail support independent of the head and tail walls of the culvert. After casting and curing of the beam, the culvert will be backfilled with approved fill before installing a temporary road base over that ½ of the culvert.

For both options, the temporarily relocated utilities will be moved to their final location. At this time, it is expected that both the 12-inch water line and 6-inch sewer main will be rerouted out of the roadway at new culvert due to the limited cover. The pipelines will be supported from backets on outside faces of the new concrete head and tail walls; details will be worked out with the local sponsor during design. Once complete, with guardrail installed, the phase 2 culvert will be backfilled with road base installed and traffic routed onto new work. Traffic will be shifted from the (original) paved roadway to the newly built half culvert; it is unknown if contractor will pave half of the roadway over the newly installed ½ culvert or if gravel will be used as temporary roadway with full paving coming at a later date. After traffic returns over the first half of the culvert, the Phase 1 roadway will be isolated to allow the 2nd half of the culvert to be installed.

Similar work for the culvert's 2nd half will occur with the original road prism excavated and the remaining portions of the (6) PC pipe culverts removed. The bank vegetation, rip rap and debris, and related material will be removed and stockpiled at a staging area. The existing in-slough scour material (concrete slab debris) will also be removed and discarded like for Phase 1.

Option 2, Culvert replacement

The 2nd option for removing and replacing the culverts under West Beach Road allows the (6) existing culverts to be removed at one time. For more detail, see a step-by-step description of this option in Section 4.5. This involves the building of a temporary roadway or bridge within the marshland and slough itself in order to get local traffic around the culvert site (Figure 12).

A temporary (single-lane) roadway would be built (north or south of West Beach Road yet likely on north side) from the existing roadway into the marsh then return traffic back onto West Beach Road just east of Sunset Park (state beach) entrance. This option will need to accommodate emergency vehicles and large trucks so roadway temporary design would need to be reviewed by local agencies. This report will continue on the premise that a temporary earthen-type roadway can be built (with all environmental compliance) and acceptable to highway and safety reviews.

Under that premise, the Option 2 roadway may be desirable to potential bidders if they can use a local, economical source (such as from the primary staging area) for soil to bring in and then remove allowing them to excavate the entire roadway. By having a bypass roadway outside of the culvert, removal and replacement is more conventional than Option 1 as Option 2 allows the culvert to be replaced at one time. A schematic representation of Options 1 and 2 in section view are shown in Figure 13. Note that Option 2 would include both the removal of a mature cypress tree (and probable other trees) and possible challenge due to the overhead power lines. If employed, the contractor may even prefer building the temporary roadway south of West Beach Road. There are other design issues associated with this option that will be further investigated during the D&I phase.

4.3 Roadway Raise and Paving

Approximately 1,300 LF of West Beach Road will be remove and replaced with a raised roadway to bring the new surface to elevation 9.2 feet for reasons noted previously and in the HH&C Appendix. Additionally, existing paved roads west of the culvert site will be raised to 9.2 feet for similar reasons at the state beach and at northern end of Rio Boca Road. Existing pavement will be removed and hauled off-site for recycling with the existing aggregate based to remain where viable to accept the new road work. The new, raised roadways will consist of new bituminous paving over aggregate base on compacted sub-base as described in the Geotechnical appendix.

Figure 10 Culvert Replacement Plan - Option 1

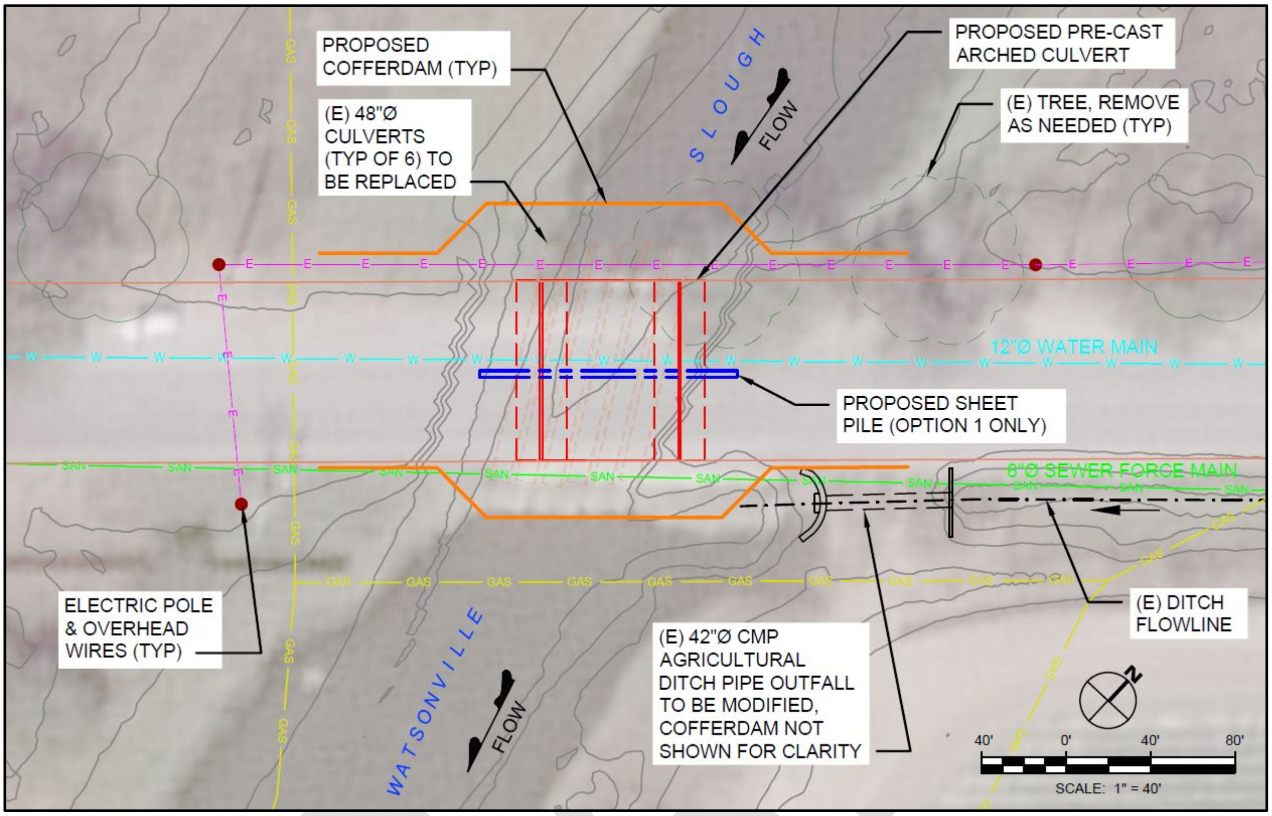


Figure 11 Culvert Replacement Elevation

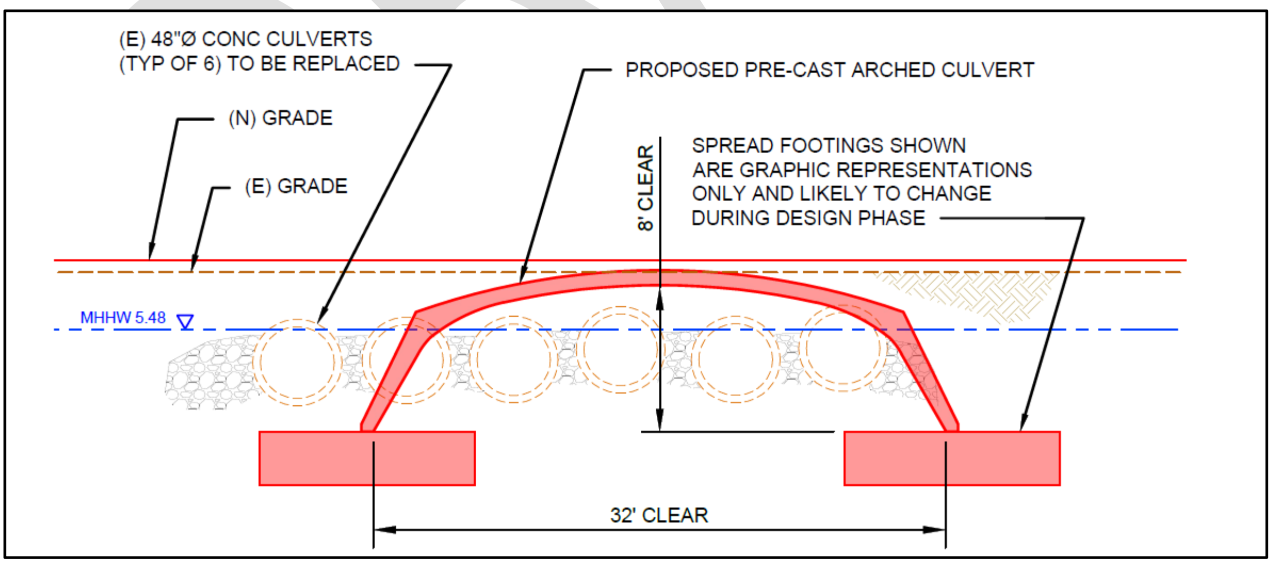


Figure 12 Culvert Replacement Plan - Option 2

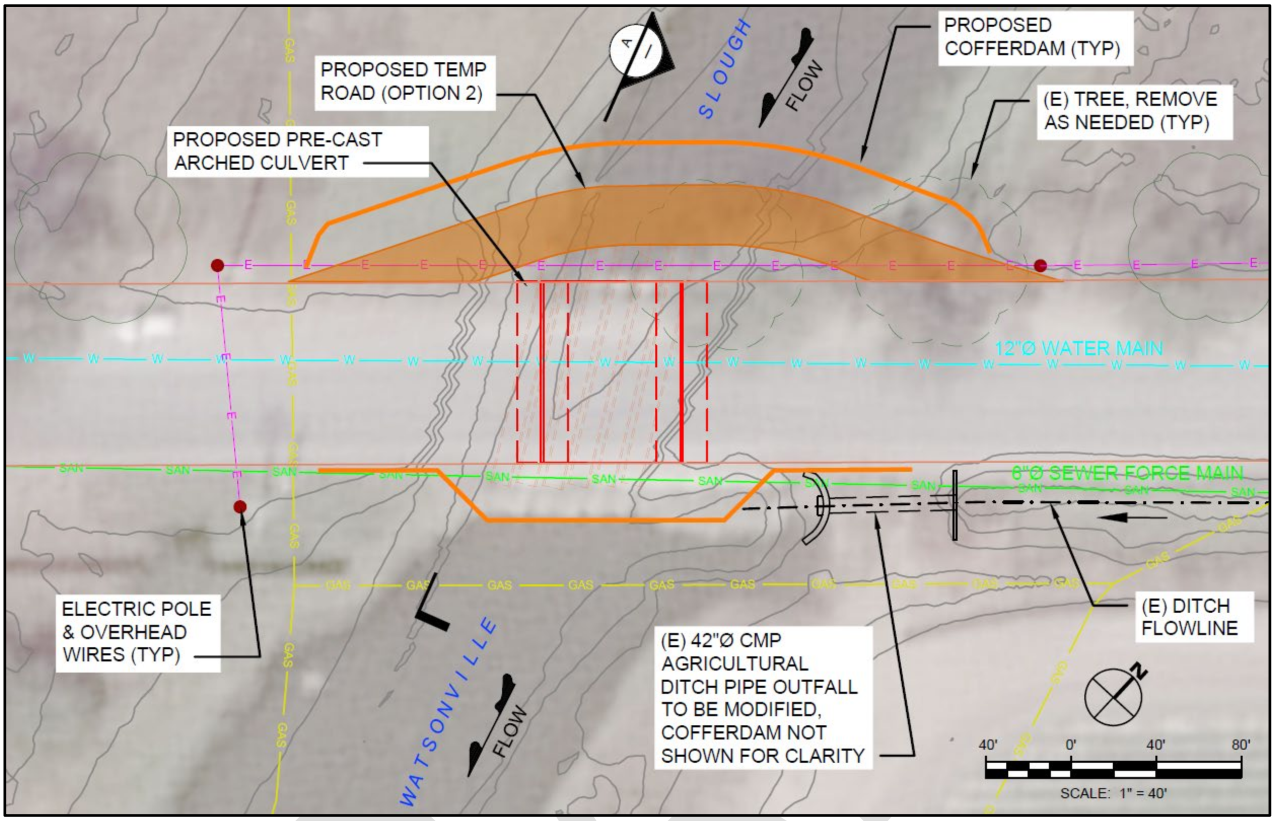
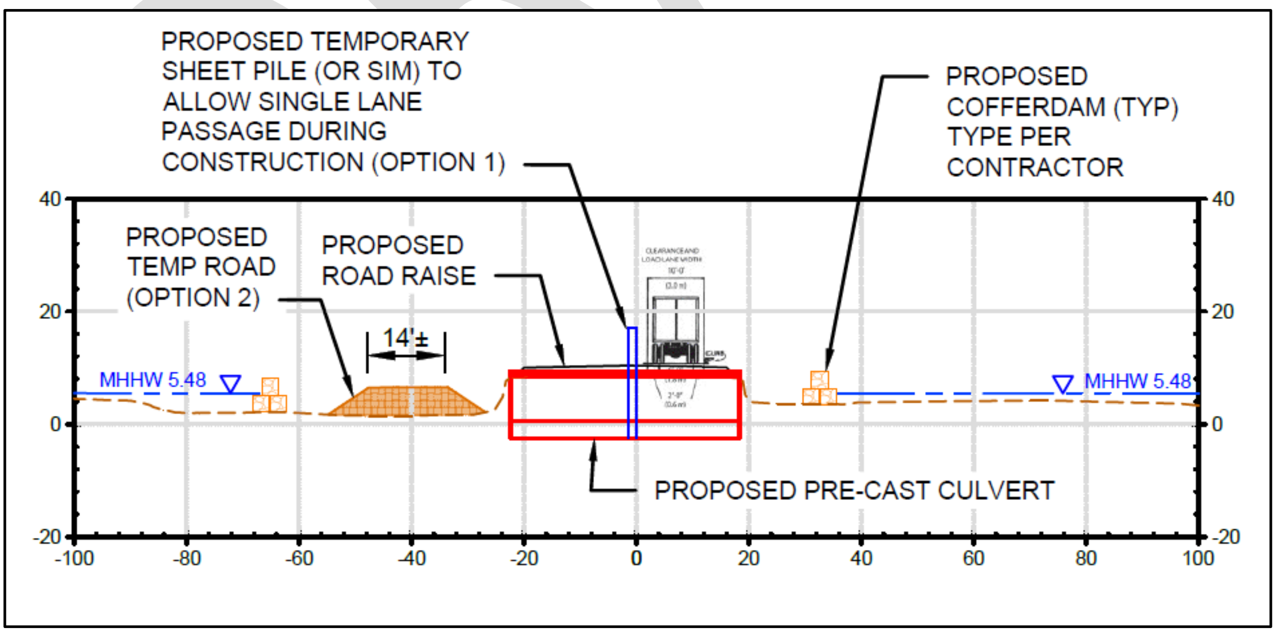


Figure 13 Road Section A (During Construction)



4.4 Access, Staging, Borrow and Contractor Use Areas

The primary construction zone will be focused around the area of roadway raising/improvement along West Beach Road and the culvert replacement at the crossing. Trucking access to the project site will be from Beach Road from the east (coming from City of Watsonville). The project intends to maintain emergency access through West Beach Road, as the roadway is the primary access route to/from the Pajaro Dunes Community and Sunset (Palm) Beach State Park. Access will be maintained such that emergency and service vehicles (e.g. fire, garbage trucks) will be able to service the area. The PDT has begun discussion with the County and local fire and safety departments on access needs and will continue as the design progresses.

The PDT has identified a potential staging area (approx. 56,800 sq. ft.) south of the Beach Road crossing (Figure 5) to store equipment and stockpile materials, debris, etc. This will be called the primary staging area in this report. The haul route passes through agricultural fields, approximately 0.35 miles from staging area to the culvert replacement site. Dust control will be required by the contractor to limit impacts to adjacent agricultural, waterways, and residential areas. Construction water is proposed to be taken from the County facility, Shell Road Pump Station, to be verified as design progresses and may also be purchased at nearby locations. The PDT has also initiated discussions with California State Parks, who operate Sunset/Palm Beach State Park, and Pajaro Dunes on a temporary area in the parking lot for contractor use (with equipment access to slough may be necessary), next to the Beach Road and Rio Boca Road intersection.

4.5 Utilities

Through the study, several utilities have been identified in the project footprint that will need to be modified during construction (Table 1-3). A water main and sewer line, owned by the City of Watsonville, run below/underneath the roadway crossing. Pacific Gas & Electric (PG&E) utilities are also in the immediate vicinity of the culvert replacement in addition to a low-voltage transducer that Santa Cruz County owns and monitors to assist in decisions to breach the Pajaro River mouth. At this location the lines are buried and serve the areas of Rio Road. Initial gas line mapping was provided by PG&E yet has not been verified. Overhead high-voltage electrical power lines run parallel to and at the north bank of West Beach Road before crossing the road at both sides of the culvert site. Utilities may impact the available options for temporary cofferdams and daily operations and will need to be further investigated during the D&I phase.

Table 2 Known Utilities in Vicinity of Culvert Replacement Site

Item	Known Utility	Location	Owner
1	12-inch D Water Main line, buried in roadway	At the box culvert, W. Beach Road	City of Watsonville
2	6-inch D Sewer (forced) line, buried in roadway	At the box culvert, W. Beach Road	City of Watsonville
3	Natural gas line(s), buried	In W. Beach Road and in slough south of (E) culverts	PG&E
4	Power lines, overhead and buried	Along W. Beach and Shell Road	PG&E
5	Communication: fiber optics cable TV? Ask fire department if they have any info.	Overhead (on PG&E poles) + buried	Unknown
6	Low voltage transponder for water level sensor, buried and above-grade in tidal marsh	Downstream of (6) culverts, right bank and pole mounted	Santa Cruz County

4.6 Construction Means and Methods

This section presents the expected sequencing of the contractor to build the project. Steps 1 - 18 (e.g. utility relocation, traffic control, environmental monitoring) are common to both Options 1 and 2. For simplicity, Steps 19 - 29 are similar for both replacement options and can be done in phases (Option 1) or at one time (Option 2). Steps 30 to completion are nearly identical for both Options 1 and 2.

1. Notify Underground Services Alert (USA) and perform buried utility locations with pot-holing as required.
2. Mobilize to site. Establish Staging area(s) with installation of exclusion and safety fencing. Install exclusion fencing for protected species (at direction of biological monitors) as required at staging area; haul routes; West Beach Road; and future culvert replacement site(s).
3. Delivery of fuel tanks to primary staging area and set up with spill containment.
4. Install Erosion control and BMPs. Clear and grub as needed and relocate any native vegetation that will be salvaged.
5. Establish traffic cones along West Beach Road (from Shell Road junction approximately to State Park entrance), but do not yet close down 2-way road traffic. Install temporary traffic lights on both ends of West Beach Road for future use.
6. Install upstream and downstream fish exclusion screens with fisheries biologists.
7. Perform fish/aquatic species removal in accordance with permit conditions.
8. Install traffic control and safety barriers where needed along West Beach Road.
9. If required, trim and/or remove trees at north shoulder to allow heavy equipment access.
10. Install cofferdam and de-watering system upstream and downstream of West Beach Road culverts. Note: Agricultural ditch culvert will not be isolated and de-watered at this time.
11. De-watering of cofferdam site: Pump out standing water in cofferdam area. Pump all water to state park parcel and discharge onto marsh using manifold / diffuser / stormwater BMPs like straw wattles.
12. Install bypass pumping system at main site: Ensure system is maintaining downstream flow of Watsonville Slough
13. Remove and store existing low-voltage (County-owned) transducer that records downstream water level
14. Remove existing concrete slabs in slough channel, dispose at landfill.
15. Perform nuisance pumping of water as needed and throughout all in-slough work.
16. Install full-time traffic control (with automated traffic signals) on about ¼ mile of West Beach Road including intersection of Shell Road.
17. Perform site access clearing near existing culverts with removal of vegetation at construction access footprint (around culverts and into slough, both sides of road. Note: Native vegetation may need to be transported to an on-site nursery and maintained if required at a permit(s) condition. Stockpile vegetation/revetment/debris in staging area for future reuse (rock revetment, only if viable quantity) at site.

18. Provide for temporary utilities – 12” water, 6” sewer, gas (potential leave gas line undisturbed, contact PG&E), with a temporary alignment through work zone. Work around overhead electrical and communication lines as needed.
19. Option 2: Install bypass road on north side of existing culverts. Material of temporary roadway may vary and to be determined at a later date.
20. Demolish existing road and culverts, haul to landfill. Include potential for special handling requirements for asbestos cement (AC) pipes (only if existing RCP culverts are found to contain asbestos).
21. Prepare subgrade for culvert installation (bedding material, foundation, etc). Culvert bottom will be at 0’ NAVD88 (or lower to ensure proper embedment), assume shallow foundation, however future culvert(s) foundation may also need to be a deep foundation. Deliver and install culvert footings with possible hybrid precast sections with some cast-in-place concrete to complete.
22. Deliver and install precast open-bottom culvert (32 ft W x 8.2 ft H x ~44 ft L, preliminary size used for cost estimating). May assume open- bottom culvert with foundation type to be determined at a later date. Embed culverts in slough channel bed as shown in design drawings.
23. Install precast concrete head/tail walls and wing walls
24. Install structural fill at culvert area only.
25. Install cast-in-place grade beams for future guardrails at culvert.
26. Relocate existing water and sewer pipelines with connections to outside face of culvert head and tail walls.
27. Install guardrail posts into grade beams near both ends of culvert.
28. Install base road fill at culvert area only.
29. Install Caltrans galvanized metal guard rails (about 50 LF each side).
30. Remove existing pavement for the remainder of West Beach Road, probably in phases to allow 1-lane road traffic.
31. Install permanent utilities along W Beach Rd (order may vary slightly)
32. Remove temporary access road on slough (Option 2) and restore slough bottom to final condition.
33. Remove primary cofferdams and fish screening.
34. Prepare subgrade and pave up to design elevation.
35. Install BMPs and fish screens on agricultural ditch
36. Install cofferdams on agricultural ditch
37. Pump out agricultural ditch culvert and install pump for bypass flows
38. Excavate soil cover and remove 42-inch CMP culvert, timber head wall, and masonry tail wall on agricultural ditch.
39. Install new culvert at agricultural ditch with flap gate and raise grade to at least 9.2’ NAVD88.
40. Re-install County’s transducer for slough level data
41. Perform work at State Beach roadway and Rio Boca Road entrance, similar to work at West Beach Road, to summarize: Install traffic control then BMPs; Remove existing pavement and dispose of off-site for recycling; add new road raise material

including base gravel and compact; install new paving; prepare and install new shoulders

42. Install new road base and prepare for new paving of West Beach Road
43. Remove invasive vegetation, install plantings
44. Paint road surfaces, clean up site and restore existing surfaces as needed including adding jute matting and seeding as needed.
45. Install interpretive park signage
46. Demobilize from staging area and remove BMPs and related from work areas
47. Monitoring and adaptive management as required by regulatory compliance.

4.7 Construction BMPs

Given the location of the project site and adjacent agricultural operations, the following Best Management Practices (BMPs) would likely be implemented to mitigate construction impacts:

- Access roads and disturbed ground along construction routes will be wetted ('for dust control' as a simpler alternative) regularly to limit dust to acceptable levels.
- Stockpiles (e.g. debris, soil, sand, other materials) that can produce dust will be wetted or covered.
- All fill material, rubble and spoil will be covered while in transport to/from the project site.
- All construction equipment would be cleaned before entering and upon leaving the study area to prevent introduction or spread of invasive species.
- Equipment previously used in a waterway or wetland will be disinfected to prevent spread of aquatic disease organisms.
- All existing paved roads (to remain) used during construction of the project will be protected from damage and/or restored to pre-project condition or better if damaged during construction.
- All ramps connecting to the main streets will be improved to accommodate heavy construction vehicular traffic.
- Use of construction mats (or grates) at exits to public roads to limit mud from heavy equipment
- Any damage resulting from road use by construction equipment will be repaired and restored to the original condition at the completion of the project.
- Add any additional conditions as stipulated by future regulatory/programmatic compliance

4.8 Post-Construction Inspections by USACE

Typical inspection activities (by USACE personnel), for the built elements of the Recommended Plan, may include: periodic condition inspections of the roadway, new culverts, and State Parks parking lot, especially after winter/high backwatering events. Inspection of the roadway and culverts would evaluate general condition and any potential impact on function, such as any cracks or depressions in roadway surface; depressions/scour/piping by guardrails; high water marks; sedimentation in culvert (if any); structural condition of the culverts; and signs of overtopping and any major changes since original construction.

4.9 References

AASHTO LRFD Bridge Design, 9th Edition, adopted by the American Association of State and Highway Transportation Officials (2020)

US Army Corps of Engineers. Engineer Regulation 1110-2-1150. Engineering and Design for Civil Works Project. August 31, 1999.

California Department of Transportation (Caltrans) Standard Specifications (2023)

US Army Corps of Engineers ®

San Francisco District

DRAFT

Appendix B-3

Geotechnical Appendix

Watsonville Slough CAP 1135 Ecosystem Restoration Project
Santa Cruz County, California

July 2025

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LIST OF ABBREVIATIONS AND ACRONYMS

CAP - Continuing Authorities Program

CGS - California Geological Survey

ESA - Environmental Science Associates

ft - Feet or foot

in. - Inch or inches

mm - Millimeter or millimeters

NAVD - North American Vertical Datum

NGVD - National Geodetic Vertical Datum

NMFS - National Marine Fisheries Service

USACE - US Army Corps of Engineers

USGS - US Geologic Survey

MHHW - Mean Higher High Water

1.0 INTRODUCTION

1.1 Study Area

The Watsonville Slough CAP study area is located at the confluence of the Watsonville Slough with the Pajaro River, in southern Santa Cruz County. The study area is bordered inland by low-lying, active agricultural fields and on the ocean side by the Pajaro Dunes Community. The project area is bounded by Shell Road at the upstream end, and the Pajaro River and Lagoon at the downstream end (Figure 1).

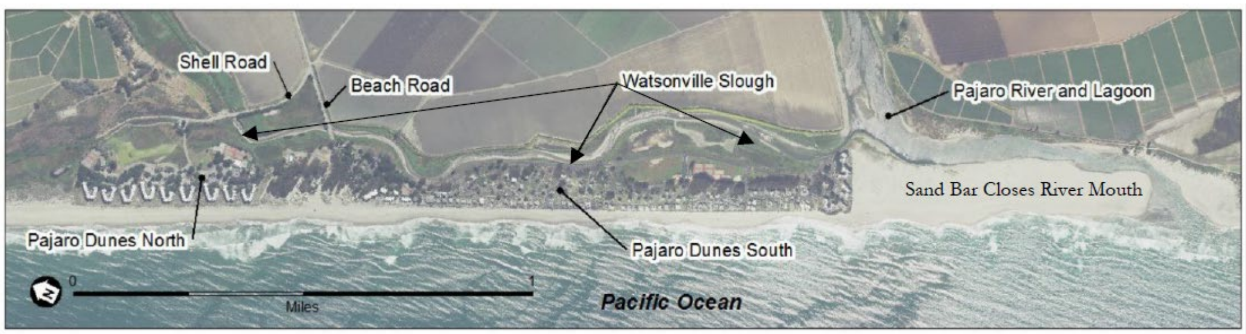

Figure 1. Map of the project area extents, showing the confluence of the Watsonville Slough and the Pajaro River at the Pajaro Lagoon (Source: Technical Memo from ESA, 2018).

1.2 Recommended Plan

The 1135 CAP Project goals are to restore the quality, complexity, and diversity of habitat along Watsonville Slough by restoring floodplain and channel habitat complexity, riparian vegetation diversity, and productive backwater habitat.

The Recommended Plan ("Crossing Improvements") consists of improvements at the Beach Road crossing at the Slough, including: 1) replacement of the culvert at West Beach Road and 2) raising an approximately 1300-foot-long segment of West Beach Road and a portion of the State Park parking lot to the west.

1.3 Scope of Geotechnical Appendix

This appendix describes the geology and local soil conditions based on a review of published information and limited subsurface explorations in the project vicinity and summarizes geotechnical considerations for the Recommended Plan.

2.0 GEOLOGIC CONDITIONS

2.1 Regional and Local Geology

The project area lies within the Pajaro Valley of Santa Cruz County and the Pajaro River creates the border between Santa Cruz and Monterey Counties. The Pajaro Valley is a wide valley bounded by the Coast Ranges and the Monterey Bay. The Coast Ranges are defined by their northwest-trending mountains and valley, created by many active faults in the area.

The geologic formations of the Santa Cruz-Monterey Area include sedimentary, igneous and metamorphic rock types ranging in age from pre-Cretaceous to recent (SWRB, 1953). Majority of the geology is characterized as marine sediments; however, some continental and tidal sediments are found on valley bottoms (SWRB, 1953). The Pajaro Valley basin consists mainly of Quaternary alluvium and other various geologically recent sediments.

The proposed project site consists mainly of recent surficial deposits underlain by Pliocene and younger deposits filling the valley. The surficial deposits include Holocene alluvium, consisting of unconsolidated gravels, sands, silts, and clays (Muir, 1972) and dune sands. The dune sand covers much of the surface near the mouth of the Pajaro river and along the shoreline, southwest of the subject site. The dune sand is moderately permeable, but probably contains little water because most of the sand lies above the zone of saturation (Brabb, 1989). Pleistocene Eolian sand is exposed along the northern edge of the project site, adjacent to the northside of the Watsonville Slough. The Eolian sand is weakly consolidated, well-sorted, fine-to-medium grained sand (Brabb, 1989). Underlying the alluvial deposits include the Purisima Formation. The Purisima consists of very thick bedded yellowish-gray tuffaceous and diatomaceous siltstone with thick bluish-gray semi-friable andesitic sandstone interbeds (Greene, 1977).

Watsonville Slough is filled with recent Holocene channel deposits consisting of soft fine-grained and organic (peaty) soils.

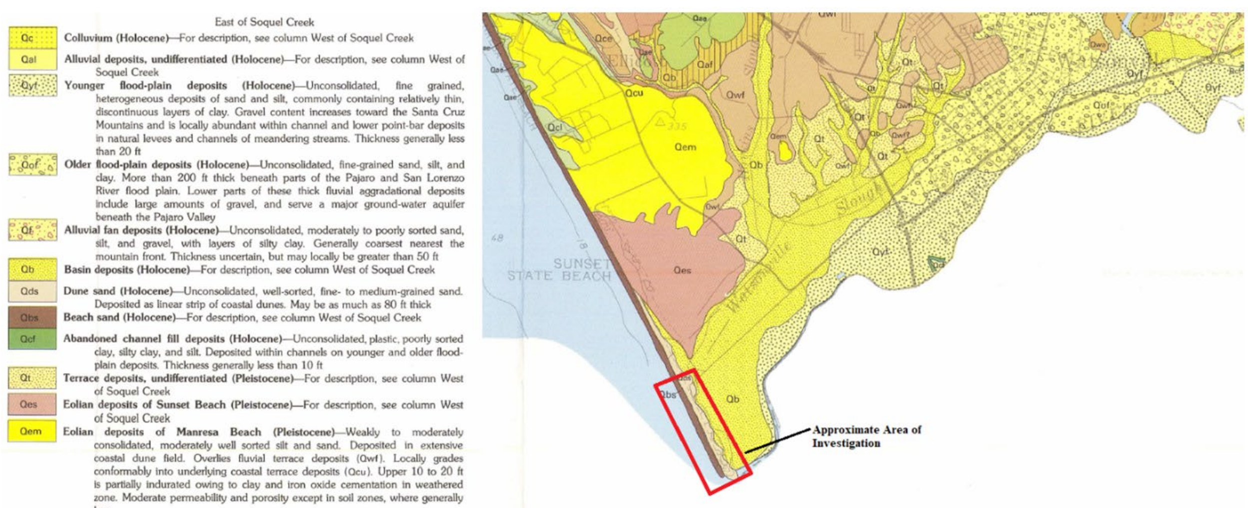

Figure 2. Geologic map of Santa Cruz County (Brabb, 1989)

2.2 Seismicity

The Pajaro Valley region is characterized as a seismically active area. The San Andreas fault zone trends northwest-southwest through the western edge of the Santa Cruz Mountains with multiple smaller regional faults that are splays of the greater San Andreas Fault system. All the faults discussed below are categorized as Earthquake Fault Zones under the Alquist-Priolo Act of 1972.

The San Andreas Fault is a northwest-southeast oriented, right-lateral strike-slip fault. The fault is located approximately 9 miles northeast of the project site. The San Andrea Fault Zone has had multiple large historical earthquakes in recent antiquity including the 1906 San Francisco earthquake and the 1989 Loma Prieta earthquake. The San Andreas Fault Zone is the largest fault zone in the region and capable of a significant magnitude earthquake.

The Zayante Fault Zone is approximately 6.3 miles northeast of the project site. It is the closest in proximity to the project site. The Zayante Fault Zone is a northwest trending, right-lateral strike-slip fault. The Zayante Fault has had recent Holocene seismic events, it is considered active.

The San Gregorio Fault Zone is approximately 14.5 miles southwest of the project site. It is located offshore in the Monterey Bay. The San Gregorio Fault Zone is northwest trending, right-lateral strike-slip fault. The San Gregorio Fault Zone is considered active.

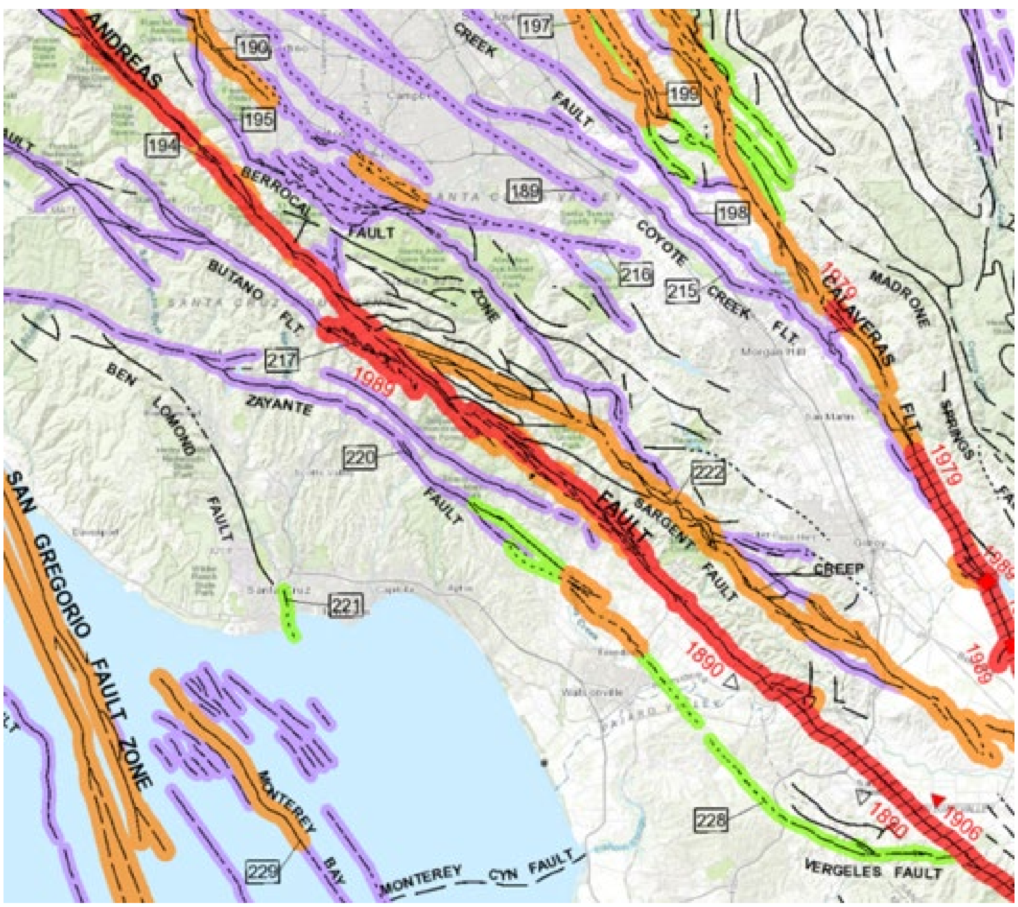

Figure 3. Fault Activity Map of California (Jennings, 2010)

The Peak Ground Acceleration (PGA) was calculated for return periods of 475 to 2,475 years using the on-line United States Geological Survey (USGS) Unified Hazard Tool. Based on review of available borings, local geology, and nearby shear wave velocity measurements, the site can be classified as Site Class E for preliminary seismic design. Seismic design should comply with requirements of ER 1110-2-1806.

Table 1. PGA for different probability of exceedance

Annual Probability of Exceedance	Return Period (years)	Peak Ground Acceleration
2% in 50 years	2,475	0.76g
5% in 50 years	975	0.62g
10% in 50 years	475	0.51g

2.2.1 Fault Rupture

As discussed above, several faults are located within approximately 6 miles of the site. No known faults cross the site. The site is not located within an Alquist-Priolo Earthquake Fault Zone, known formerly as a Special Studies Zone. Therefore, fault rupture is not a significant geologic hazard at the site.

2.2.2 Liquefaction

Liquefaction refers to the phenomenon of loose, saturated, coarse-grained (sandy) soils losing strength during earthquakes. The liquefied soils may flow laterally or may flow up to ground surface and the occurrence of liquefaction may cause damages to structures and utilities. There are many documented cases of liquefaction occurring along the Pajaro River during the 1906 and 1989 Earthquakes. The most common effects were sand boils, lateral spreading of soil toward creek or river channels, and slope in stability. The soils recent channel deposits should be considered potentially liquefiable. Liquefaction should be further evaluated during the design and implementation phase.

3.0 SITE CONDITIONS

3.1 Surface Conditions

Watsonville Slough is defined as predominately open channel, flanked by riparian vegetation in the overbank areas. The slough outlets into the Pajaro River south of the site. Watsonville Slough flows south at the project site but can flow in reverse if a sand bar develops and blocks the Pajaro River flow at the beach front.

3.2 Subsurface Conditions

The available subsurface information from the Pajaro Dunes residential and commercial developments indicates site soils consist of “clean dune sand” which refers to wind-blown and friable and loose sand deposit but with increasing blow counts at depth below ground surface. The boring logs for the Shell Road Crossing of Watsonville Slough which is located approximately 1,300 feet upstream of the project site show the presence of soft and very soft clay and very loose sand at the surface to depth of 26 feet including soft peat soil at depth of 20 feet. Sand was present at depth of 30 feet with field blow count of 14, and dense to very dense sand was present at depth 40 feet to the end of the boring at about 54 feet.

A site-specific geotechnical investigations and characterization study for this project will be required for the design phase in order to properly design and build the culvert and the approach roads, and a complete geotechnical analysis and recommendations to be accomplished.

The soils found in the lower Pajaro River Valley are sand, gravel and various fine grain material. The alluvium in the Pajaro Valley area is a highly variable mixture of unconsolidated gravel, sand, silt and clay (Muir, 1972). The eolian sands are a windblown medium to very fine grain sand. Majority of the soils at or adjacent to the beach are a coarse to very fine grain quartzose rich sand. The soil along the flat of the valley consist mostly of fine grain materials of silt and clay. Surface soils exhibit various characteristics that depend on location, slope, parent rock, climate, and drainage.

4.0 GEOTECHNICAL ENGINEERING CONSIDERATIONS

The Tentatively Selected Plan ("Crossing Improvements") consists of replacing the existing culverts across Watsonville Slough and raising West Beach Road. Geotechnical considerations for the TSP design elements are summarized below.

4.1 West Beach Road Raise

The Recommended Plan includes raising approximately 1300 feet of W. Beach Road by approximately 1 to 2 feet. The current elevation of W. Beach Road varies from approximately Elevation 8.0 to 8.5 feet (NAVD88), with the lower elevations at the water crossing. The proposed raise will daylight to existing grade at Elevation 9.2 feet. The construction activities specific to a road raise will include excavation and removal of existing road, excavation of in situ soils to accommodate a new road cross section and side slopes, compaction of an engineered fill section and compaction of soils of the road embankment including asphalt concrete (AC) over aggregate base (AB).

The proposed road raise is feasible from a geotechnical engineering perspective. Construction should include proper preparation and compaction of the subgrade soils.

4.2 Culvert Replacement

The Recommended Plan includes replacing the current culvert system (six 48-inch precast concrete culverts) at the West Beach Road crossing with a new design to improve flow capacity and assist in habitat restoration. The existing culvert system consists of 6 concrete pipe culverts of approximately 48-inch inner diameter, which have sedimented in. The flowline of each pipe ranges from approximately Elevation 0.5 to 1.9 feet.

The proposed culvert is an open-bottom pre-cast 3-point culvert with an open bottom. The new culvert has a 32-foot horizontal span and an 8-foot clearance from top of footing to ceiling of arch peak. The highest elevation of flow for the proposed culvert would be approximately 8 feet; MHHW is 5.48 feet. The open bottom is proposed to increase efficiency of habitat restoration which is the primary focus of this project.

The current plan is to support the culvert on shallow foundations, which is likely feasible depending on the soil conditions and design loads. A subsurface investigation should be performed during the design and implementation phase. Due to the potential for liquefaction, the culverts will need to be designed for seismic lateral earth pressures and uplift pressures and may require a deepened footing or pile foundation.

The use of a box culvert in lieu of the open-bottom culvert should be explored during design. The open-bottom reduces the footprint of a structural footing and concentrates the loading. A traditional box culvert spreads the load across the entire footprint. A deepened box culvert filled with a layer of soil could achieve the same habitat restoration benefits of an open-bottom culvert. Additionally, the open-bottom and shallow foundation system may be susceptible to scour and undermining of the foundations; the box culvert would not be as susceptible to scour.

4.3 Excavations and Temporary Slopes

Construction of the proposed culverts will require an excavation of approximately 12 feet below the roadway elevation. As previously discussed, soils along the edges of the slough will likely consist of dune sands; soils within the channel will likely consist of soft, saturated fine-grained soils. Excavations should be sloped in accordance with requirements of EM 385-1-1. For planning purposes, assume that the maximum permissible side slope of 2:1 (horizontal:vertical). The Recommended Plan includes a temporary road adjacent to the culvert excavation. Surcharge loads should be set back far enough from excavations to ensure excavation safety.

4.4 Dewatering

Water diversion and dewatering will likely be required to allow construction activities to be performed on dry and stable subgrade. Potential diversion and dewatering measures are discussed in the in the Civil Design Appendix. Water diversion and dewatering methods are typically considered construction means and methods; the contractor will ultimately be responsible for the design and operation of temporary dewatering system.

5.0 REFERENCES

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