What if…

→ **A Scenario-Based Planning Approach and Adaptive Pathways Framework to Improve Our Understanding of Sea Level Rise and Incremental Adaptation**

The fate of coastal and estuarine landscapes in the face of sea level rise is often simplified to a portrait of vast inundation across low-lying lands.

100-yr still water level (blue)

100-yr + 6.4 ft Sea Level Rise (red)

Humboldt Bay: Sea Level Rise, Hydrodynamic Modeling, and Inundation Vulnerability Mapping, 2015

Mean Higher High Water

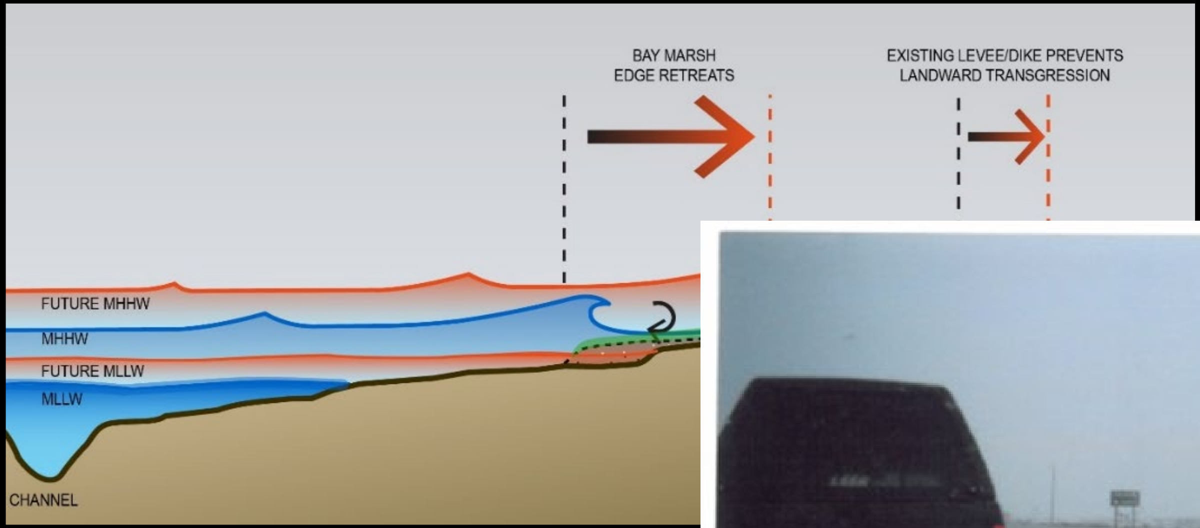
Mean Higher High Water
+2.5 feet Sea Level Rise
Projected Water Level

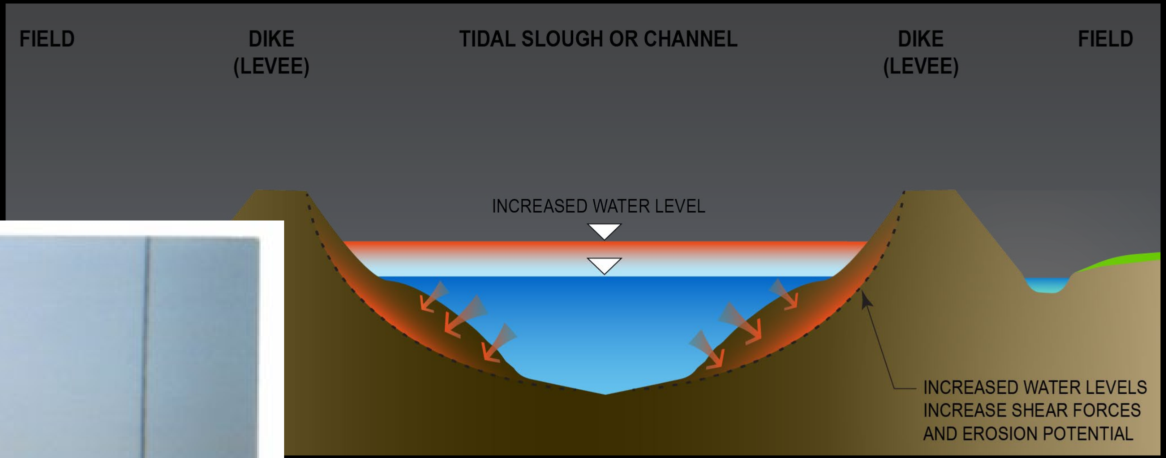
Mean Higher High Water
+2.5 feet Sea Level Rise
Modeled Tide

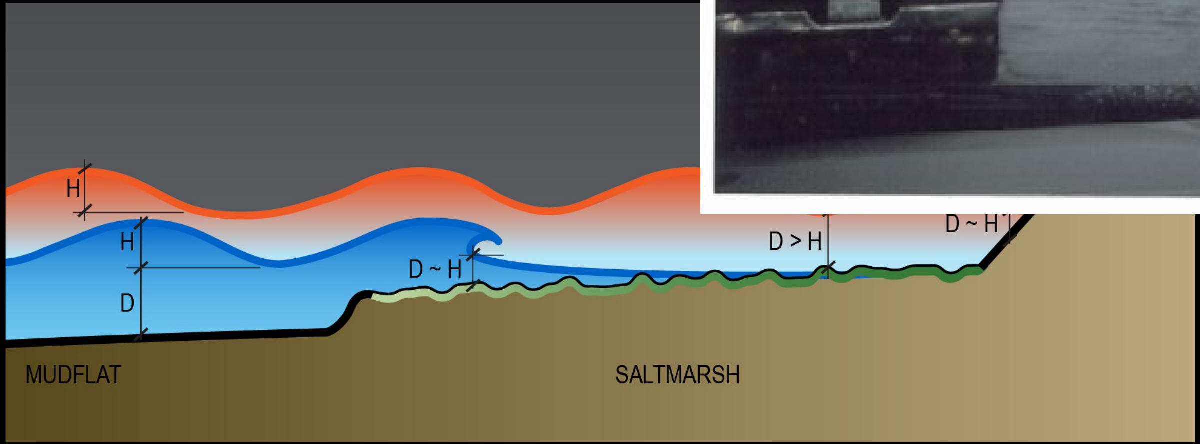
Mean Higher High Water

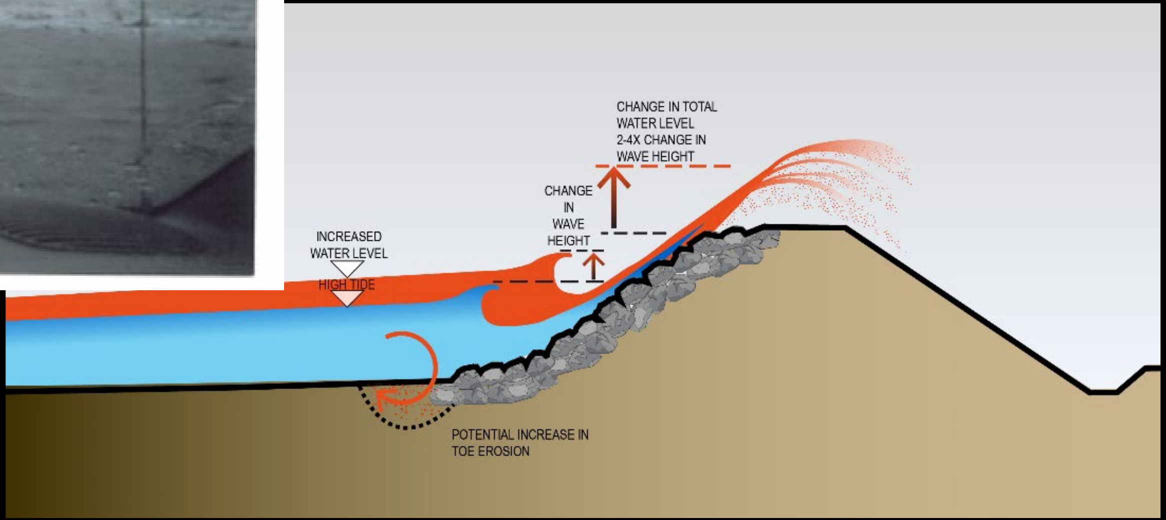
Mean Higher High Water
+2.5 feet Sea Level Rise

Mean Higher High Water
+2.5 feet Sea Level Rise
+ 50-yr Wind


BAY MARSH
EDGE RETREATS
EXISTING LEVEE/DIKE PREVENTS
LANDWARD TRANSGRESSION
FUTURE MHHW
MHHW
FUTURE MLLW
MLLW
CHANNEL


FIELD
DIKE
(LEVEE)
TIDAL SLOUGH OR CHANNEL
DIKE
(LEVEE)
FIELD
INCREASED WATER LEVEL
INCREASED WATER LEVELS
INCREASE SHEAR FORCES
AND EROSION POTENTIAL

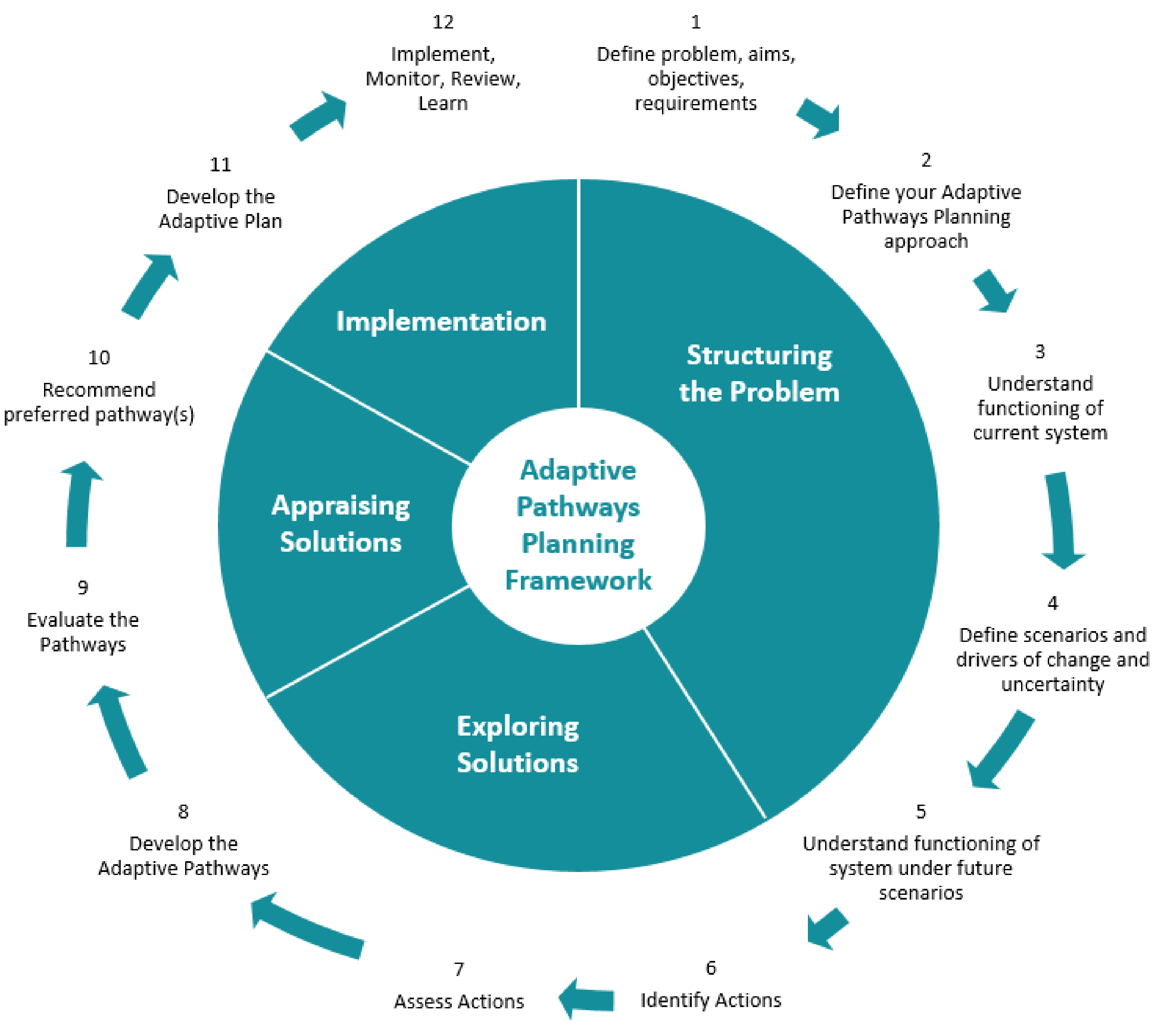

H
H
D
D ~ H
D > H
D ~ H
MUDFLAT
SALTMARSH


CHANGE IN TOTAL
WATER LEVEL
2-4X CHANGE IN
WAVE HEIGHT
CHANGE
IN
WAVE
HEIGHT
INCREASED
WATER LEVEL
HIGH TIDE
POTENTIAL INCREASE IN
TOE EROSION

Scenario-Based Planning

- → Explore a range of plausible future conditions coupled with more detailed evaluations of the interaction between coastal hazards and the landscape to provide a “what if” decision support tool

Adaptive Pathways Framework



Framework is adapted from the nine-step *Guide to Using and Developing Pathways* developed by Environment Agency UK for the TE2100 Plan (Reeder & Ranger, 2011 and Reeder, 2017)

GHD

Objectives:

→ Improve understanding of tidal dynamics, flood events & SLR

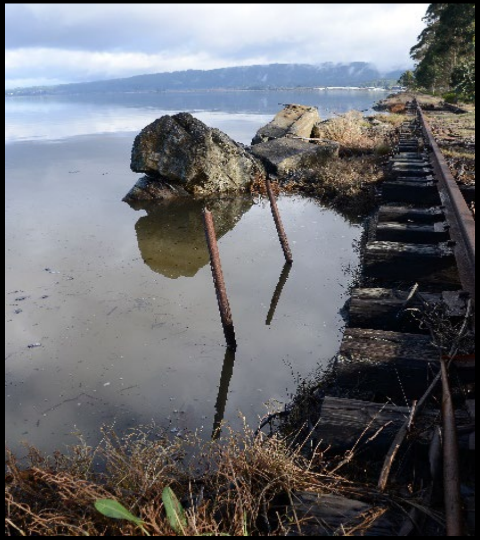
Explore thresholds and tipping points

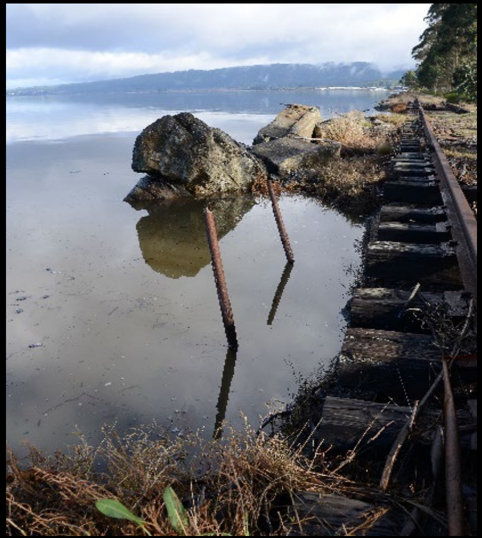
Understand risk

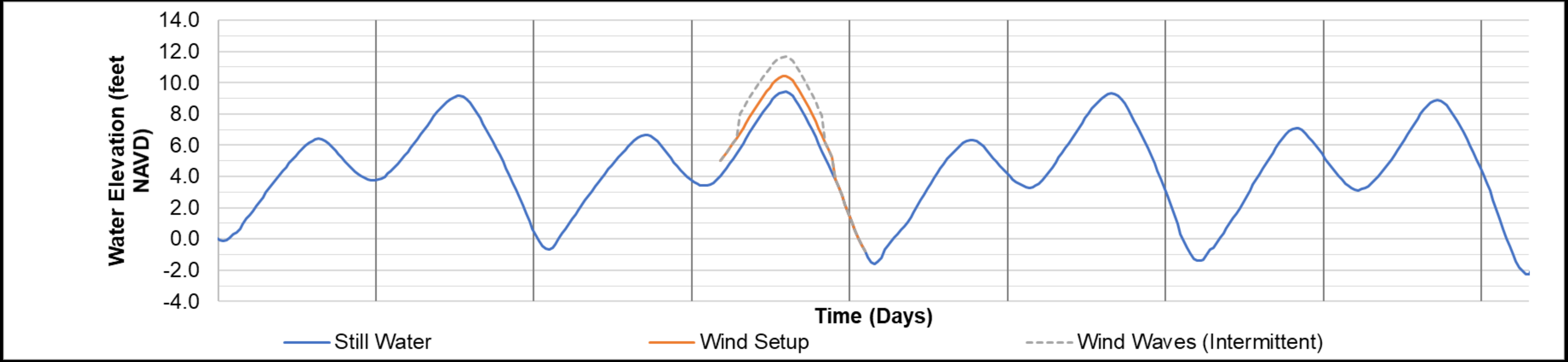
Identify management actions

Inform design objectives for adaptation projects

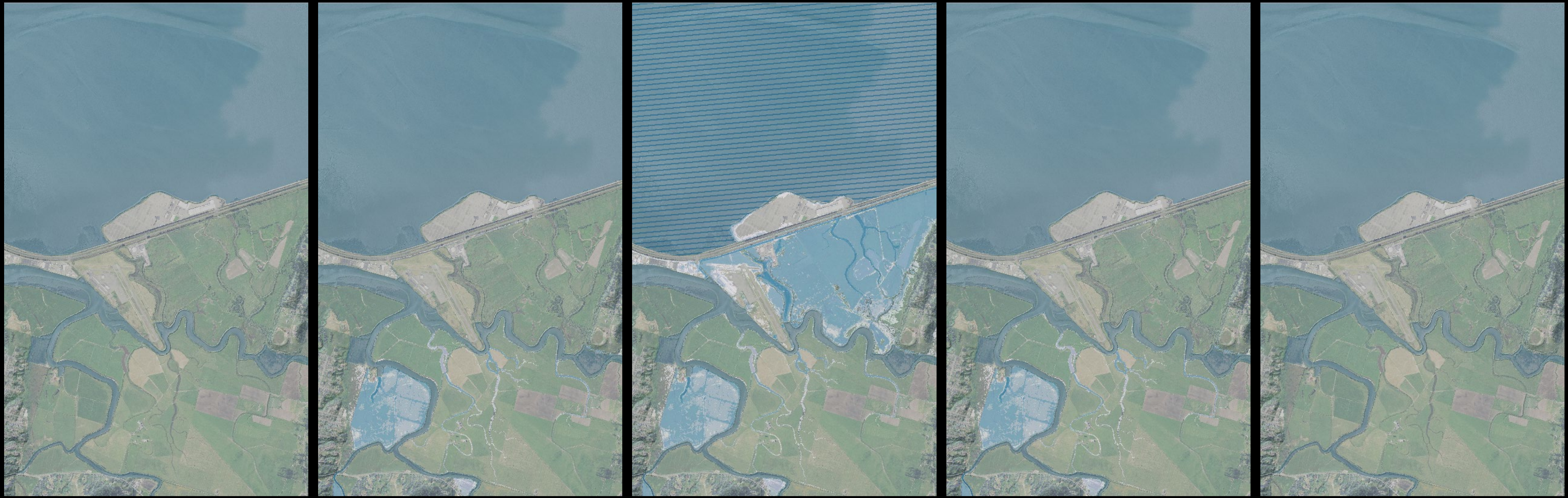
Tidal Dynamics, Flood Events & Sea Level Rise

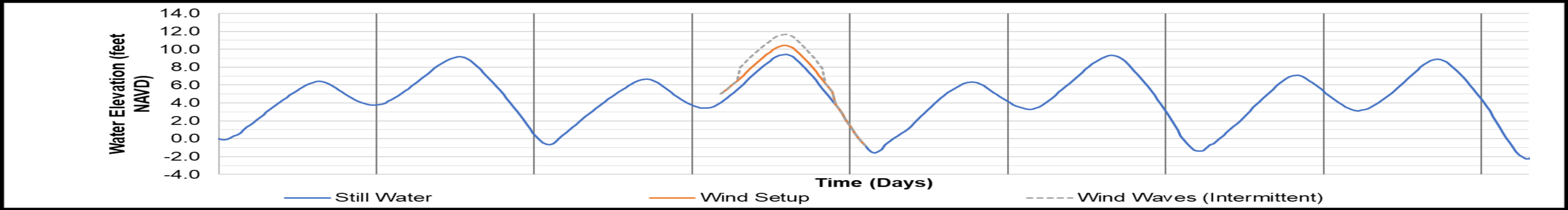




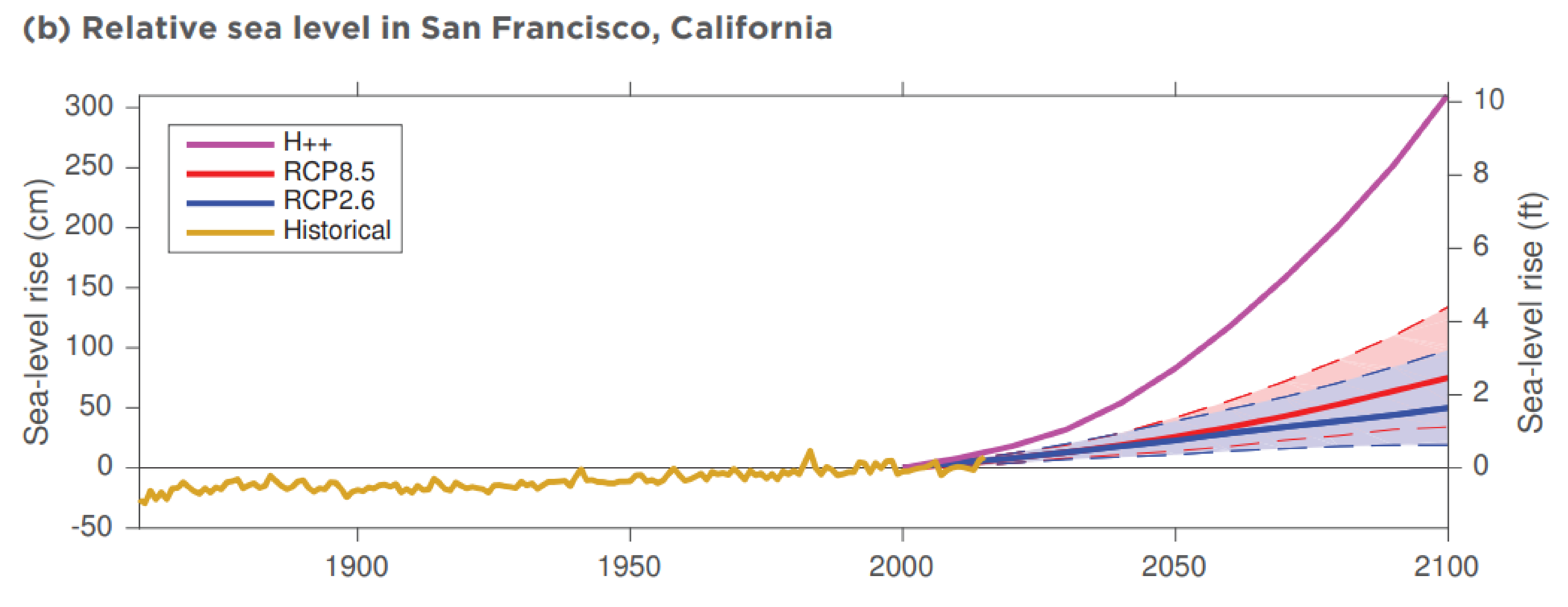


Tidal Dynamics, Flood Events & Sea Level Rise

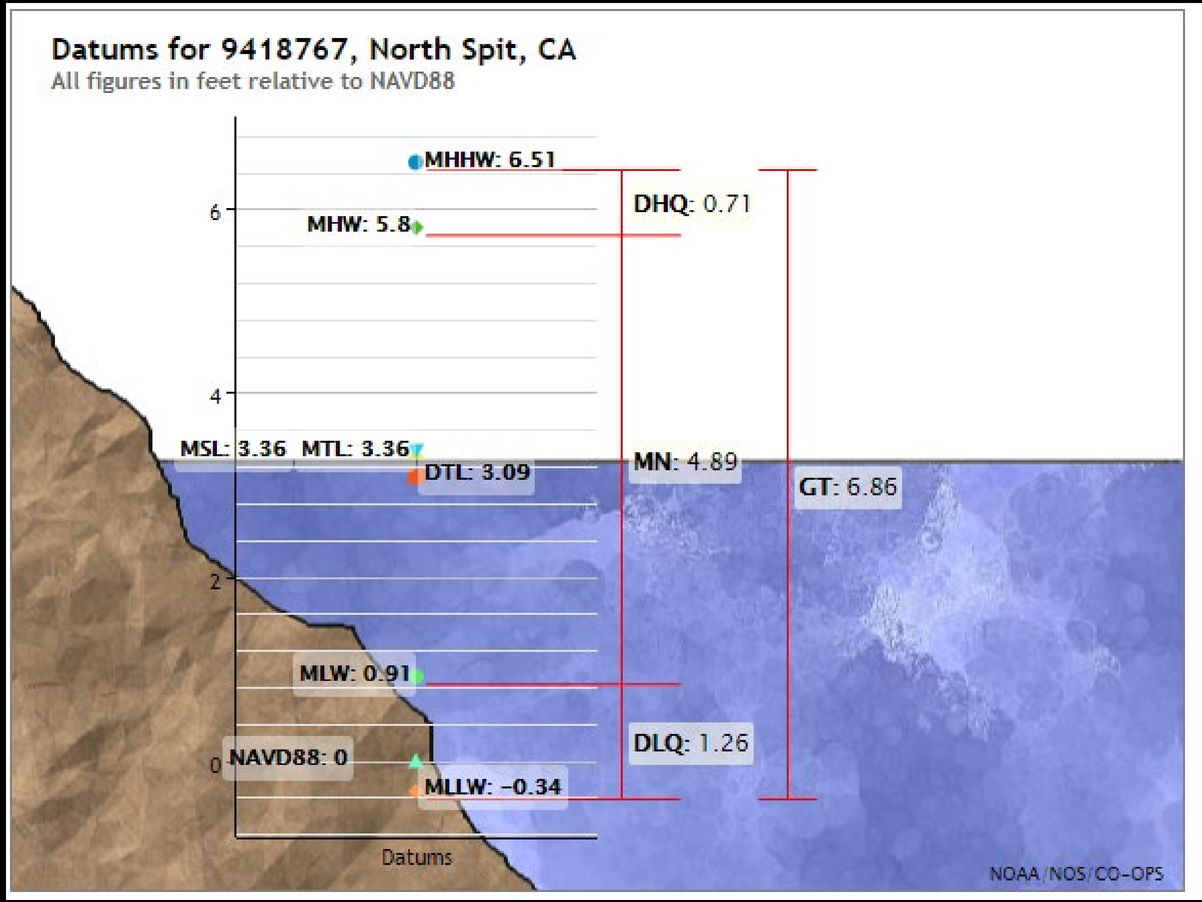




Tidal Dynamics, Flood Events & Sea Level Rise



Tidal Dynamics, Flood Events & Sea Level Rise



Tidal Still Water Level (NAVD)	9.0 ft		
Equivalent Still Water Event with SLR	2-yr	+	0 ft SLR
	MHHW	+	2.5 ft SLR
	MHW	+	3.2 ft SLR

Apply projected sea level rise rate to estimate year

Highest Observed Tide: 9.5 ft

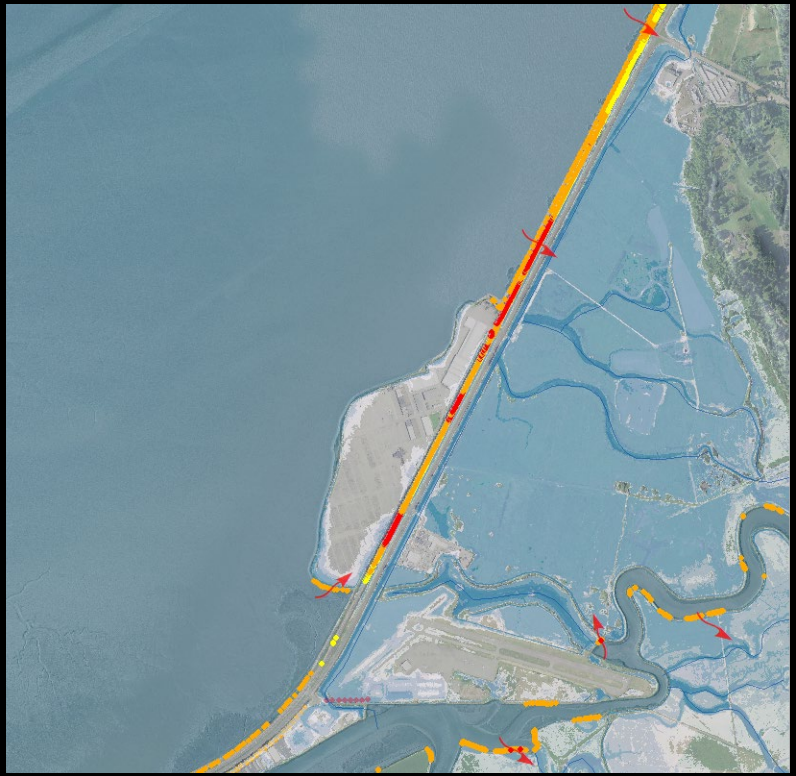
Factors: Tide, Storm Surge, Wind

Recurrence: 5 to 10-yr

Explore Thresholds and Tipping Points

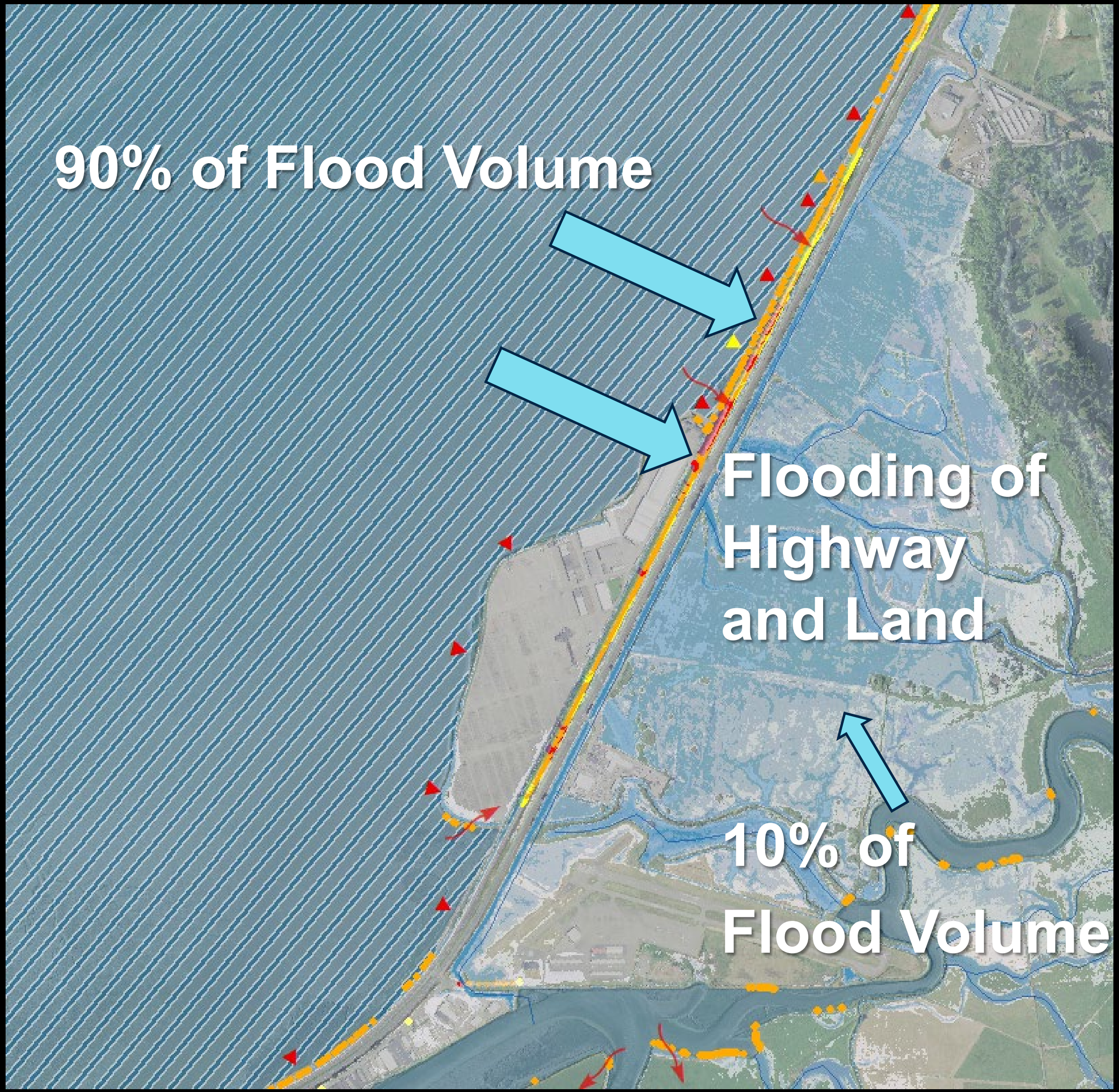
Tide 10 ft
Calm
Water Level 10.0 ft

Tide 9.5 ft
+ 50-yr Wind
Water Level 10.3 ft
Waves 2-5 ft



Tide 10.6 ft
Calm
Water Level 10.6 ft

Explore Thresholds and Tipping Points



Identify locations and contributions

Approximate Flood Depth from Overtopping

- < 0.5 ft
- 0.5 - 1 ft
- 1 - 3 ft
- 3 - 6 ft
- >6 ft

Explore Thresholds and Tipping Points

Shoreline Overtopping Depth | Duration | Response

- > 1 ft | > 2 hrs | High Potential of Failure
- Inches - Feet | Minutes to Hours | Rill Erosion
- Still Water Overtopping Pathway

Travel Lane Flood Depth | Duration | Response

- > 12 inches | Hours | Damage
- 3-12 inches | Hours | Functional Disruption
- < 3 inches | Hours | Hazardous Conditions

Explore Thresholds and Tipping Points

Critical Resource		Physical Process	Location/Exposure	Flood Depth/Duration/ Extent	Impact to Resource
Shoreline Protection	Earthen Levees/ Dikes	Overtopping (depth and time)	Cell A	>1ft and >2 hrs	Potential Failure
			Cell B	>1ft and >2 hrs	Potential Failure
			Cell C	>1ft and >2 hrs	Potential Failure
			Cell E	>1ft and >2 hrs	Potential Failure
			Cell F	shallow (<1ft) and/or short (< 2hrs)	Top and Land-facing Slope Rill Erosion
			Cell G	>1ft and >2 hrs	Potential Failure
			Cell H	shallow (<1ft) and/or short (< 2hrs)	Top and Land-facing Slope Rill Erosion
Protected Lands	Residential/ Commercial/ Industrial	Surface Flooding (ft)	Rainbow Storage Indianola Cutoff	-	none
			2nd and Y Street	0.7	Shallow Flooding
			6th and Tydd Street	-	none
			Hoover Street	1.1	Damage/Stranding
			Park Street	2.6	Damage/Stranding
			Edgewood	-	none

Explore Thresholds and Tipping Points

Tidal Still Water Level		Approximate Equivalent Still Water Event with Sea Level Rise		
8.8 feet NAVD	Existing (2012 baseline) King Tide (~1-yr) 99% chance per year	1 foot MMMW 5 to 6 events per year	2 feet MHHW Daily - Weekly	3 feet MHW Daily

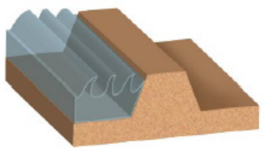
Introduction (See Exhibit HS 1-1):

This case study describes a scenario characterized by typical hydraulic conditions that occur from November through January, when the highest tide of the year, a King Tide, coincides with a wind event from the west-northwest. Winds elevate water levels (wind setup) along eastern Arcata Bay, in addition to producing waves. Waves either dissipate as they travel across the salt marsh or uprush on the rail prism (wave runup) which increases erosion potential. Shallow, short duration overtopping occurs in limited locations, where previous erosion has decreased rail prism elevation and where wave runup splashes over. The King Tide overtops the low elevation area of Park Street, which is typical of tides above 8.0 feet (NAVD) that occur multiple times a year. Little to no overtopping occurs throughout the rest of the study area.

Example King Tide with Wind Wave Runup on Rail Prism

Highlighted shoreline processes and responses in this scenario include wind wave erosion, overtopping with rill erosion on the land-facing slope, and typical roadway flooding. Conceptual examples shown below.

Wind Waves	Overtopping and Erosion	Typical Roadway Flooding
Arcata Bay Shoreline Minor Erosion and Overtopping	2 locations Arcata Bay Shoreline <1% of Interior Slough Levees	Park Street



Concept Shoreline Wind Wave Erosion (National Science Foundation, 2020)

Hydraulics and Sea Level Rise:

This scenario combines the highest spring tides that occur during the year, typically from November through January, during average meteorological conditions and any combination of astronomical conditions with continuous winds from the west. High spring tides of similar elevation occur multiple days in a row on separate occasions during this time of year and are not considered extreme. Certain meteorological conditions may increase water levels, as represented by the strong winds. Increases may be modest to extreme. The modest increase associated with this scenario is intended to represent common meteorological conditions and the highest tide of the year, also known as the King Tide. Based on observations made on January 11, 2020 during a King Tide, strong winds generated waves across Arcata Bay and elevated water levels along the eastern shore. Predicted high tides leading up to the King Tide, exceed 8 feet for three days prior to the peak and one day

Tidal Still Water Level		Approximate Equivalent Still Water Event with Sea Level Rise		
10.3 feet NAVD	Existing (2012 baseline) ~50-year 2% chance per year	1 foot 2-year 50% chance per year	2 feet MMMW 5 to 6 events per year	3.5 feet MHHW Daily - Weekly

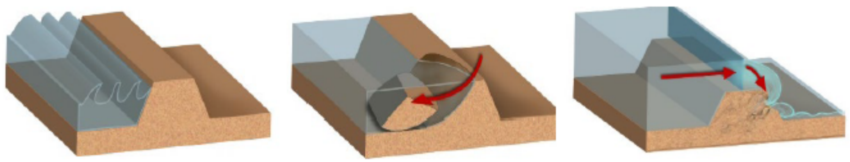
Introduction (See Exhibit HS 3-1):

This case study describes a scenario characterized by similar hydraulic conditions observed on December 31, 2005, the highest observed tide affecting the Study Area[1]. An extreme high tide coincided with a high wind event from the west-southwest. The strong winds elevated water levels (wind setup) along eastern Arcata Bay, in addition to producing waves. Water levels overtopped large sections of the rail prism, which exceeded the capacity of the adjacent drainage channel, flooding the southbound travel lanes of Highway 101. Flood waters entered the median drainage ditches and were conveyed into the drainage network east of the highway. Northbound travel lanes were not flooded. The storm impacts resulted in flooding throughout the Study Area; hazardous conditions for motorists traveling southbound on Highway 101 and eventual closure of the highway for multiple hours; damage to the rail prism requiring repairs to restore pre-event flood protection; and extensive post storm cleanup of roadways, drainage channels and flooded areas.

Photo of December 31, 2005 storm from Highway 101 Southbound.

Highlighted shoreline processes in this scenario include wave erosion, slope failure/erosion of bay- and slough-facing slopes, and overtopping with land-facing slope erosion. Conceptual examples shown below.

Wind Waves	Slope Failure/Erosion	Overtopping and Erosion
Arcata Bay Shoreline Erosion and Overtopping	Arcata Bay Shoreline Rail Prism	53% of Arcata Bay Shoreline 15% of Interior Slough Levees

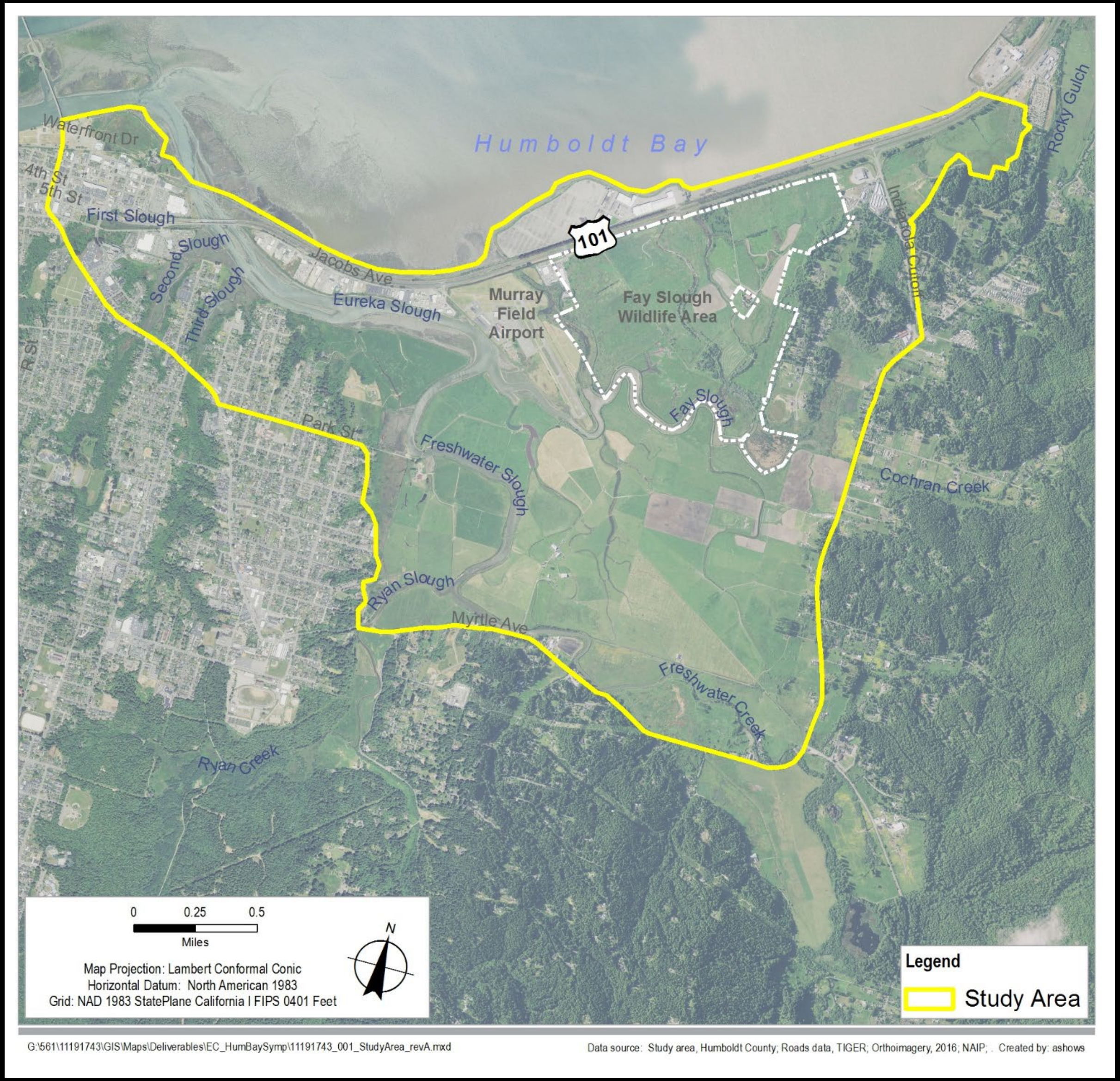


Example Shoreline Structure Responses (National Science Foundation, 2020)

Hydraulics and Sea Level Rise:

This scenario combines extreme spring tides that typically occur in the months from November through January, with a low-pressure system (storm surge) that increases predicted tidal water levels entering Humboldt Bay and strong, continuous winds from the west that elevate water levels along the eastern shore of Arcata Bay and generate waves. Based on predicted tides leading up to a still water level event of 9.3 feet (NAVD), high tides exceed 9.0 feet (NAVD) the day prior to the peak and the day following[2]. On the day of the 9.3 foot (NAVD) peak tide, wind setup increases water levels by 1 foot throughout the Study Area, to 10.3 feet (NAVD). The wind produces a significant wave height of 2.4 feet, which intermittently increase water levels to between 12 and 15 with wave runup on the rail prism and levees. Based on modeled wind speeds of 45 mph from the west/southwest in Eureka Slough, wind waves in the sloughs are not a significant erosional process and are therefore not added

Explore Thresholds and Tipping Points



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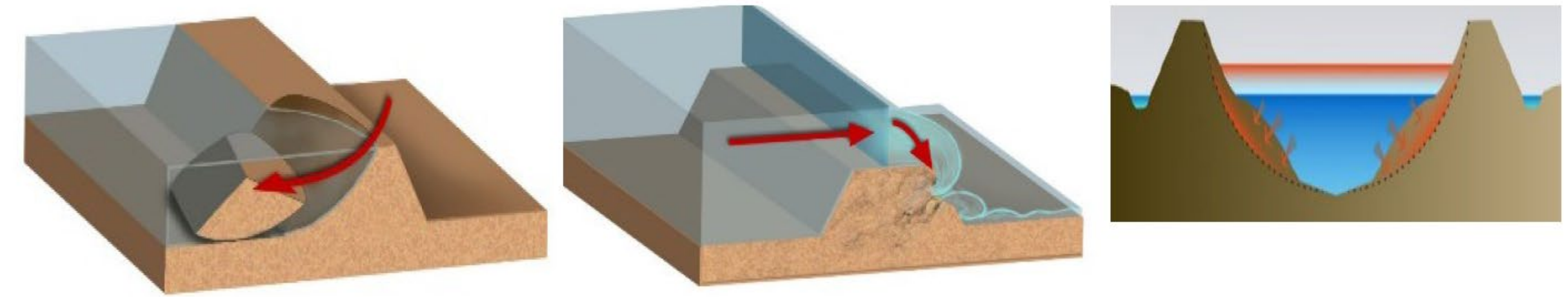

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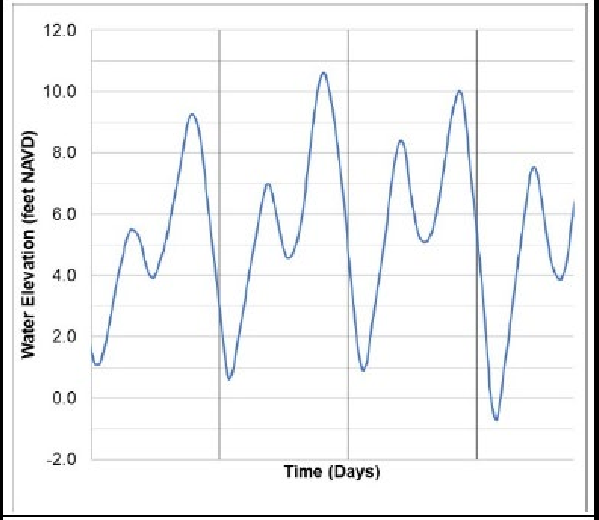
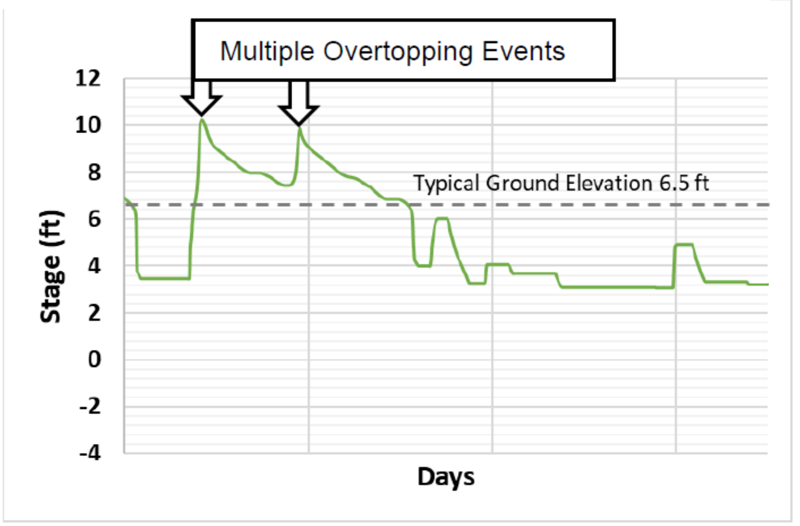
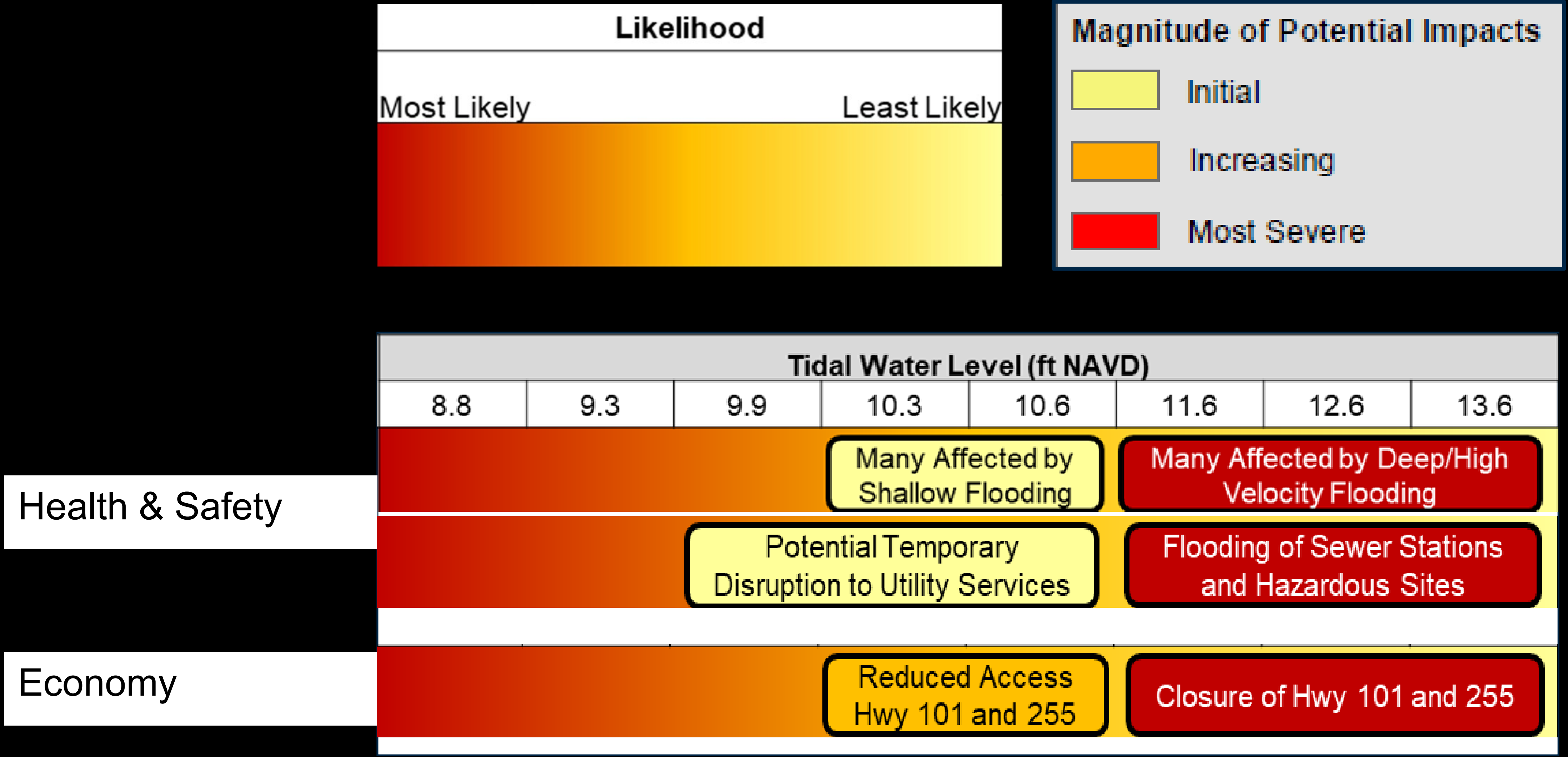




Understand Risk



Understand Risk

Example: Humboldt Bay

January 31, 2005

Tide 9.5 ft
+ 50-yr Wind
Water Level 10.3 ft
Waves 2-5 ft

Frequency
5 to 10-year (10-20% Annual Chance)

Consequences

Dangerous Conditions

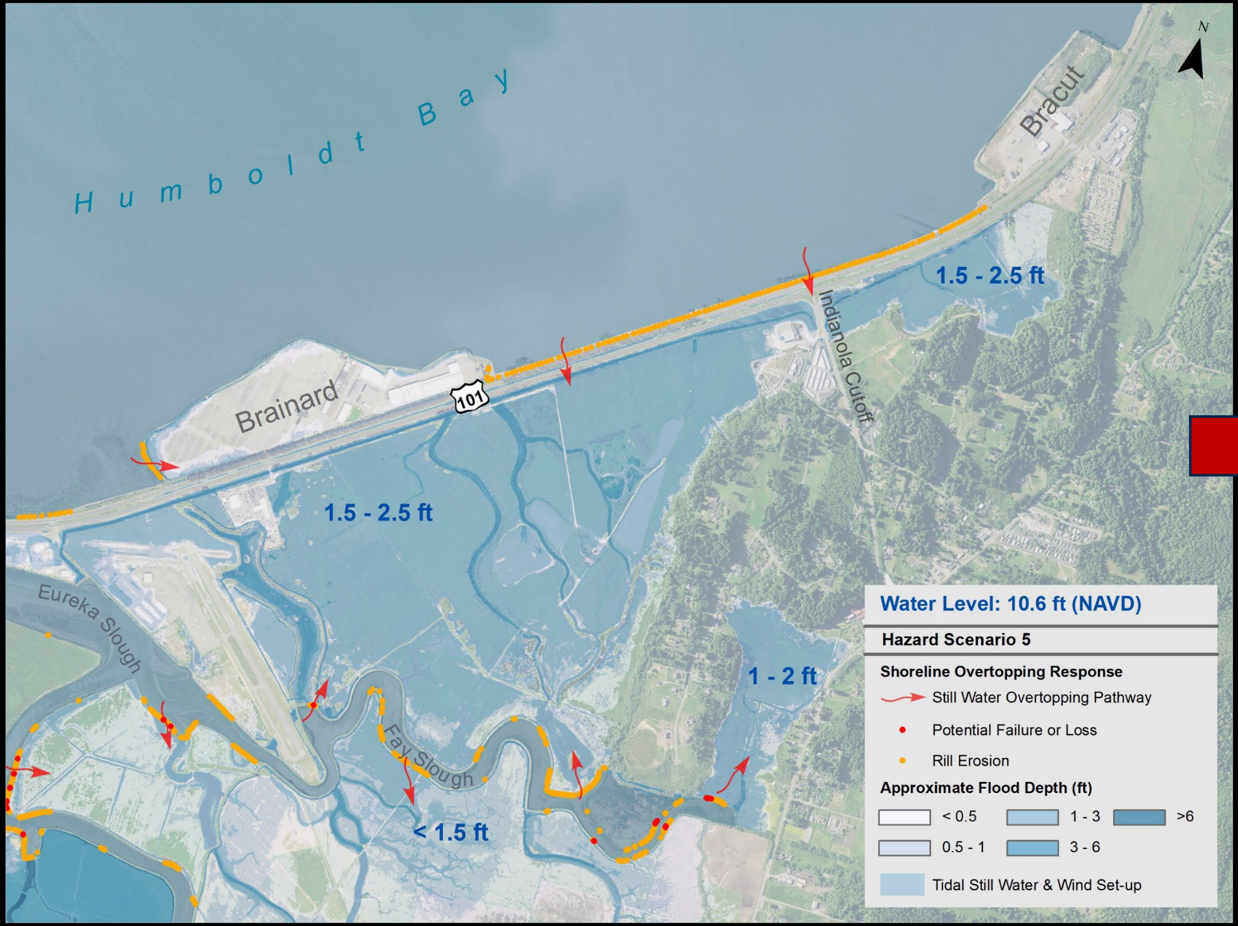
Eventual closure of Hwy 101 (6 hrs)

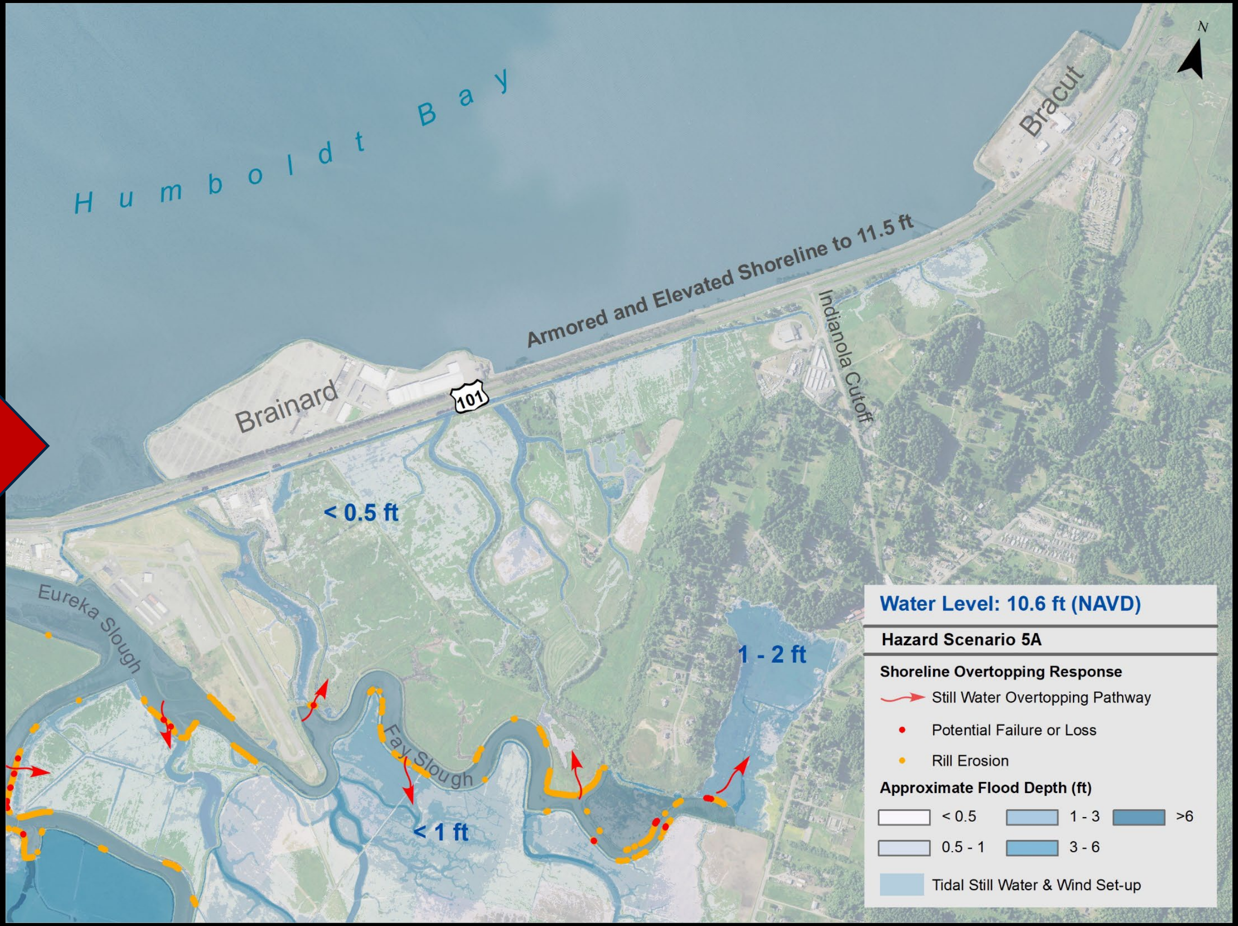
No significant flood damage reported (debris cleanup)

Understand Risk

Tidal Still Water Level (NAVD)	10.6 ft		
Equivalent Still Water Event with SLR	100-yr	+	0 ft SLR
	10-yr	+	0.5 ft SLR
	MHHW	+	3.5 ft SLR

Identify Management Actions and Inform Design Objectives for Adaptation Projects





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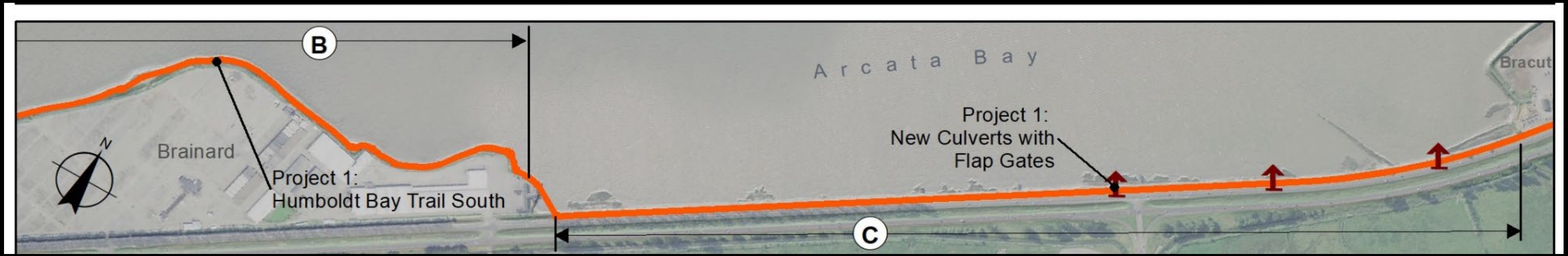
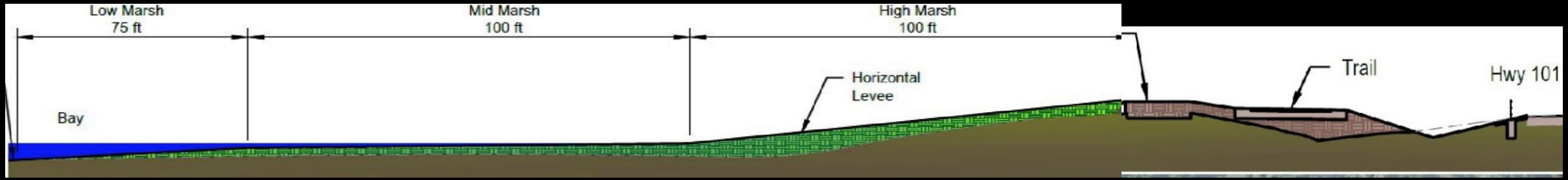
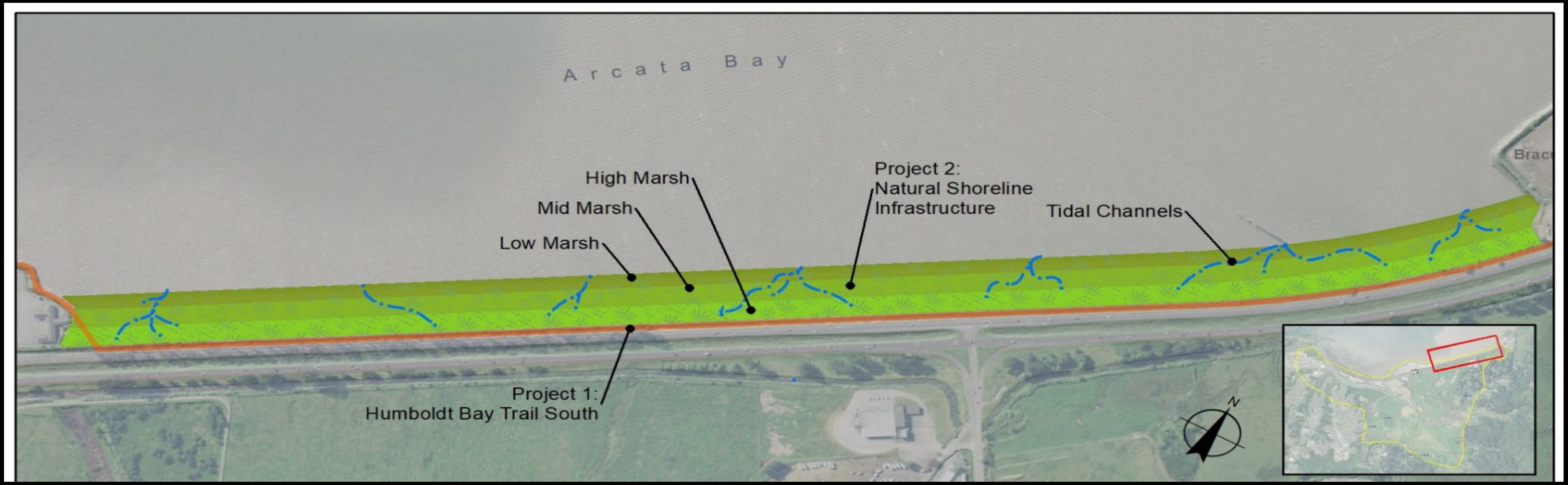
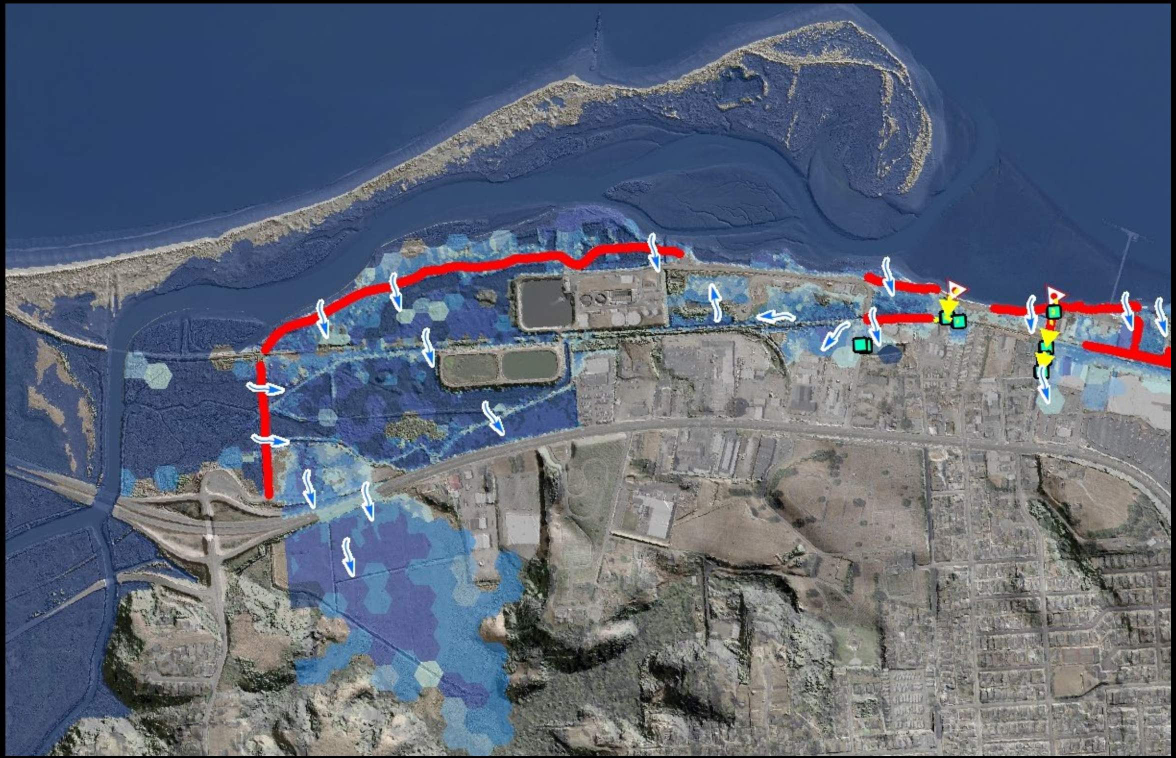


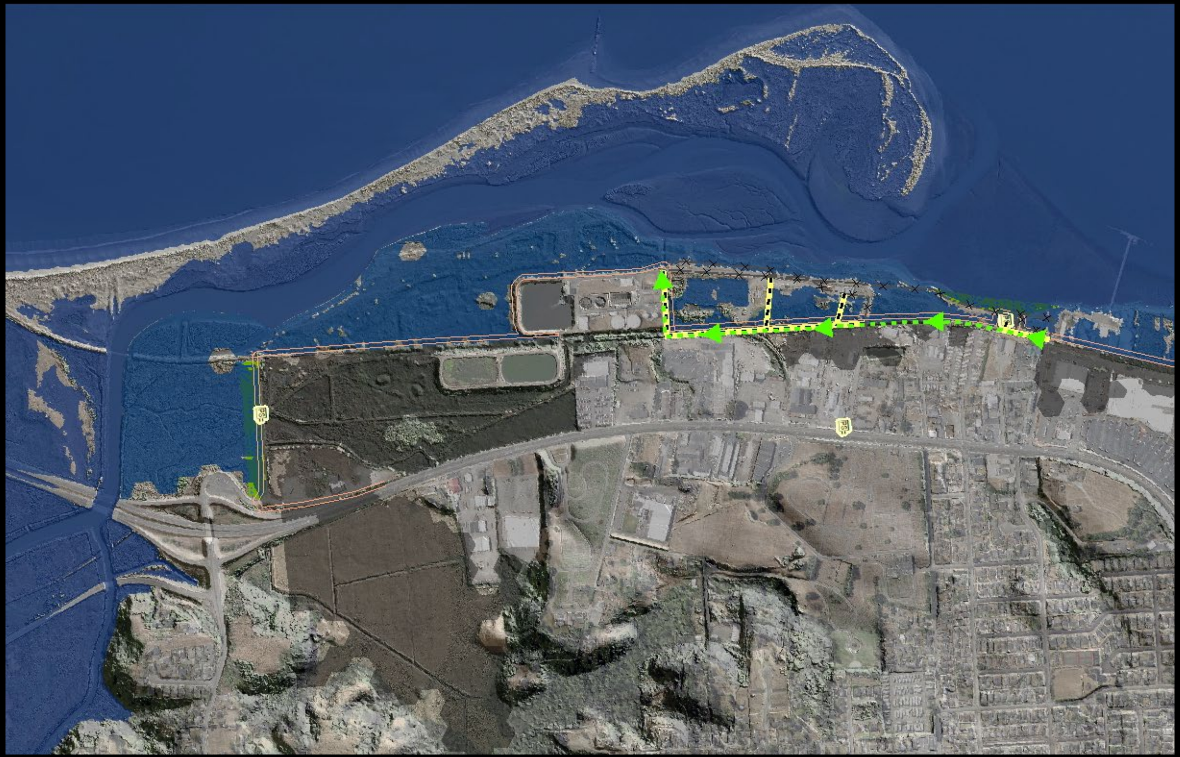




Inform Design Objectives for Adaptation Projects

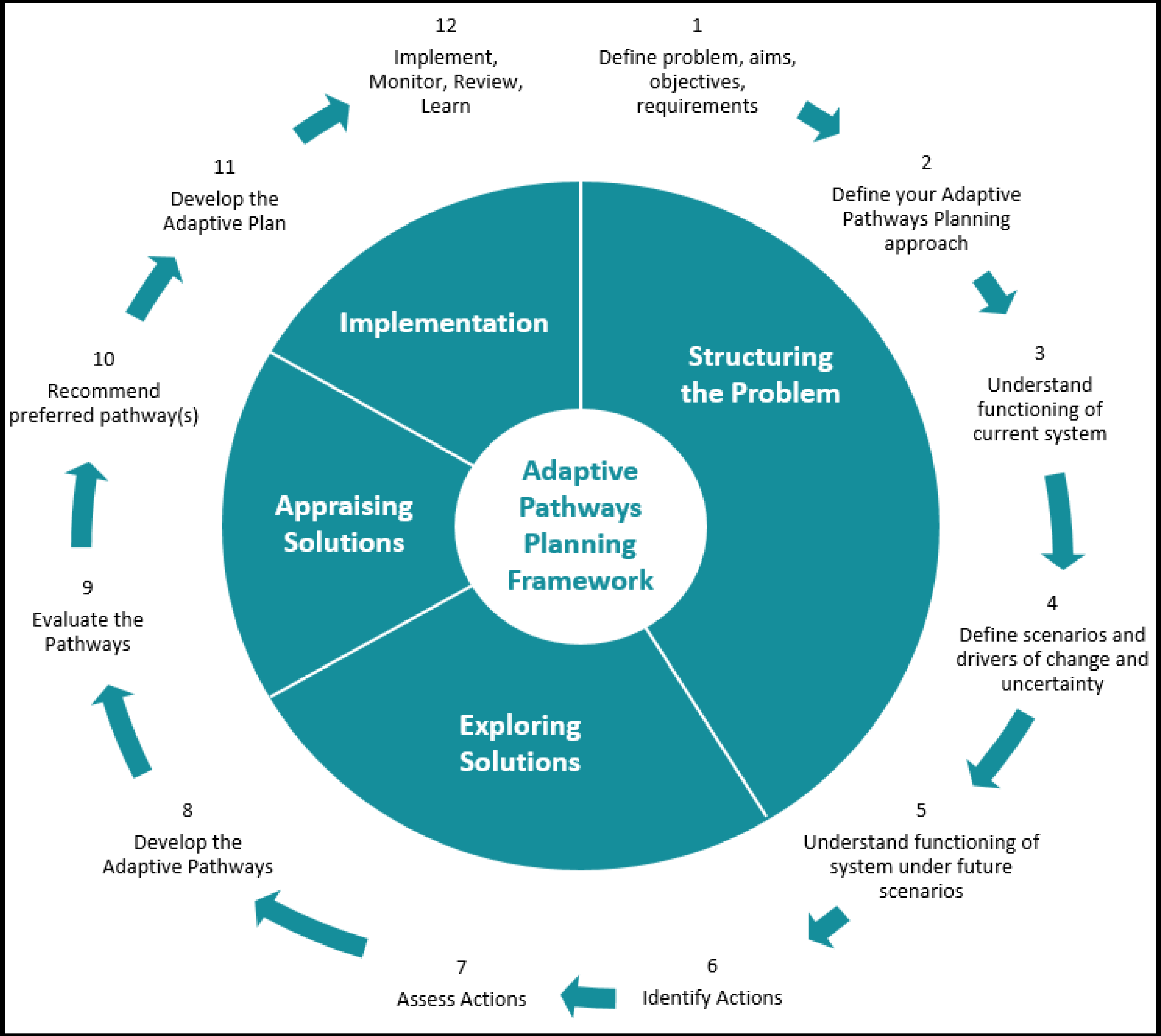


Existing Pathways of Inundation and Depth of Flooding



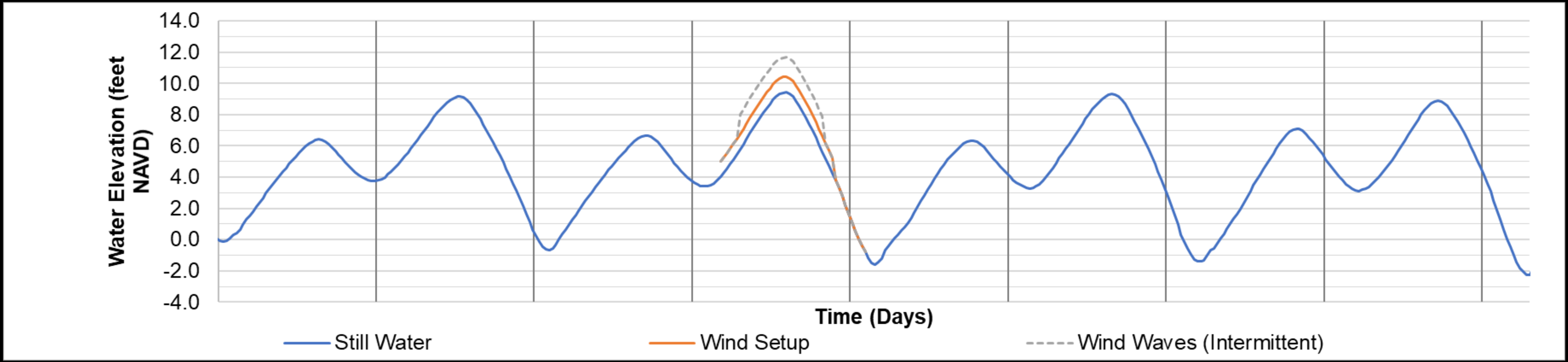
First Phase of Planned Retreat and Removed Flooding

Adaptive Pathways Framework



Framework is adapted from the nine-step *Guide to Using and Developing Pathways* developed by Environment Agency UK for the TE2100 Plan (Reeder & Ranger, 2011 and Reeder, 2017)

Understanding of tidal dynamics, flood events & Sea Level Rise



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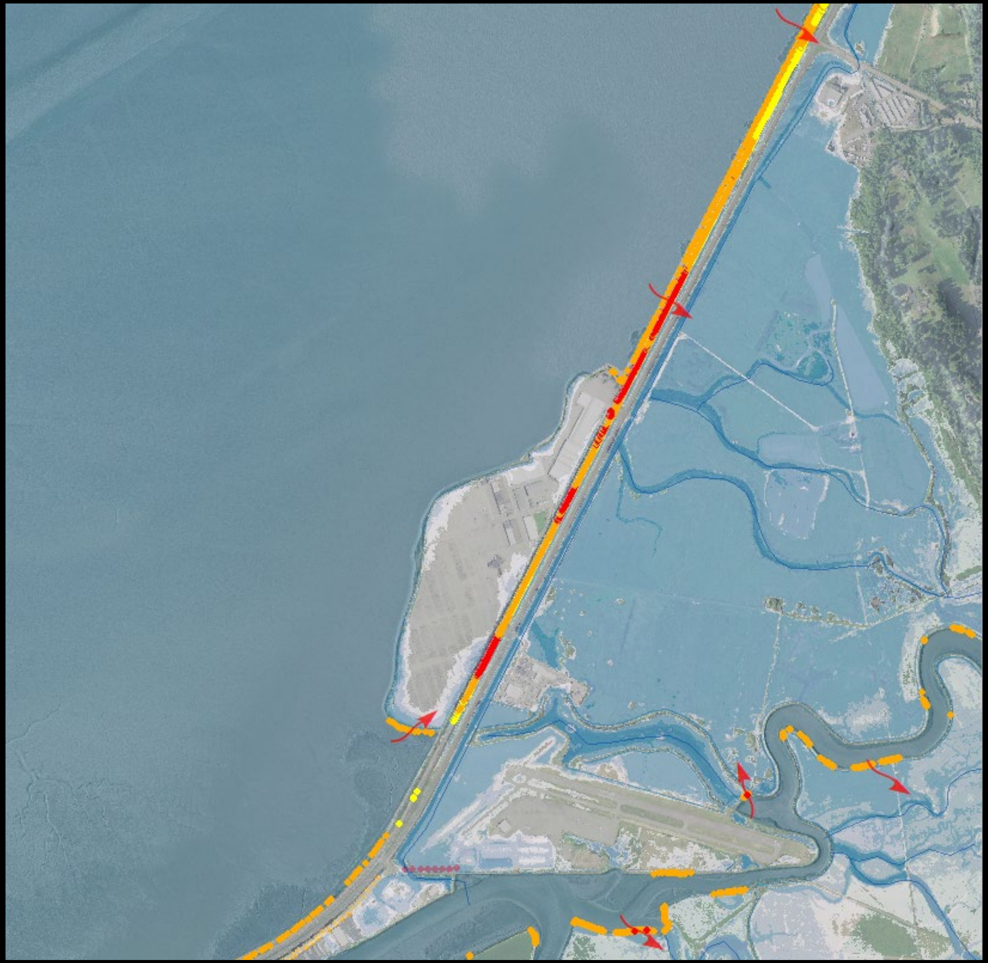
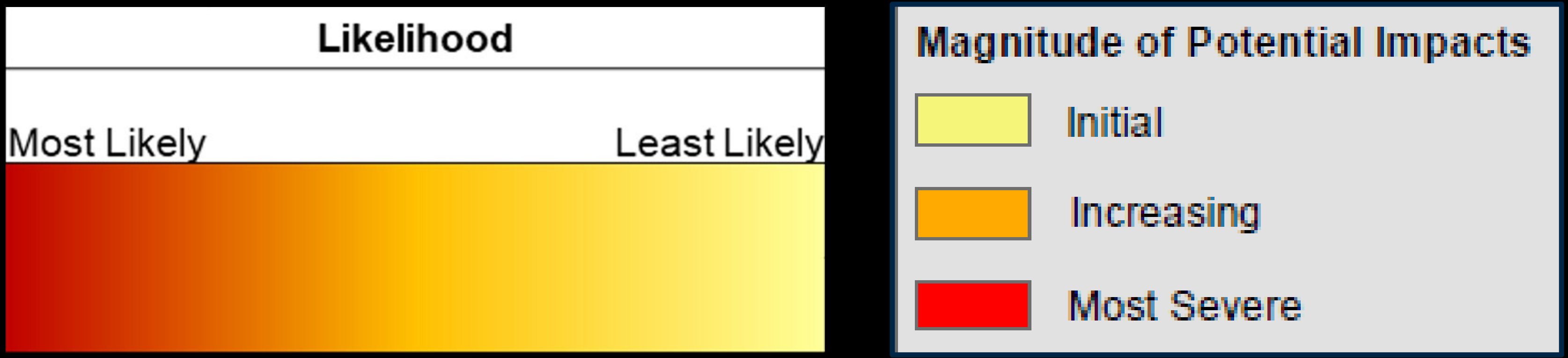
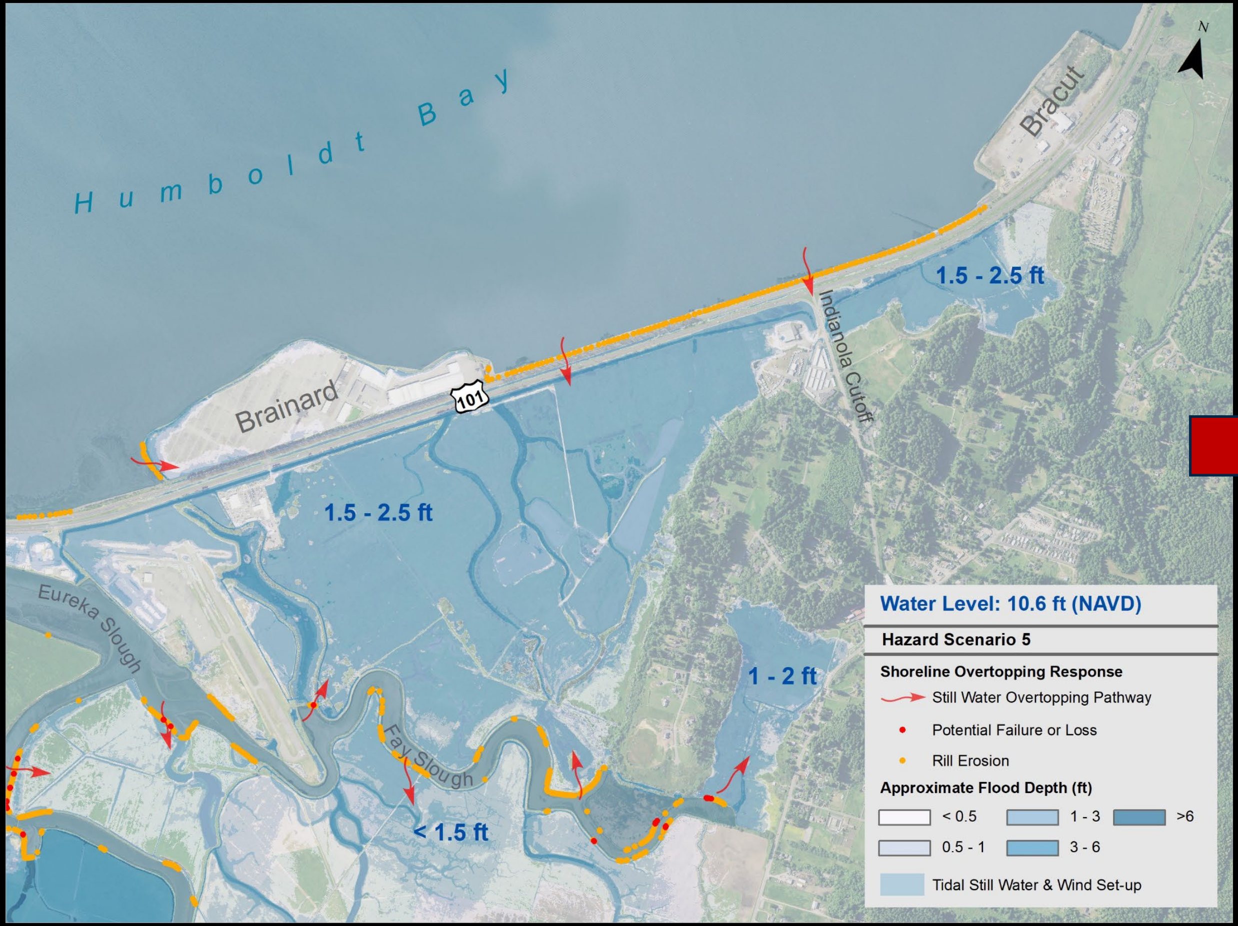
Thresholds and tipping points

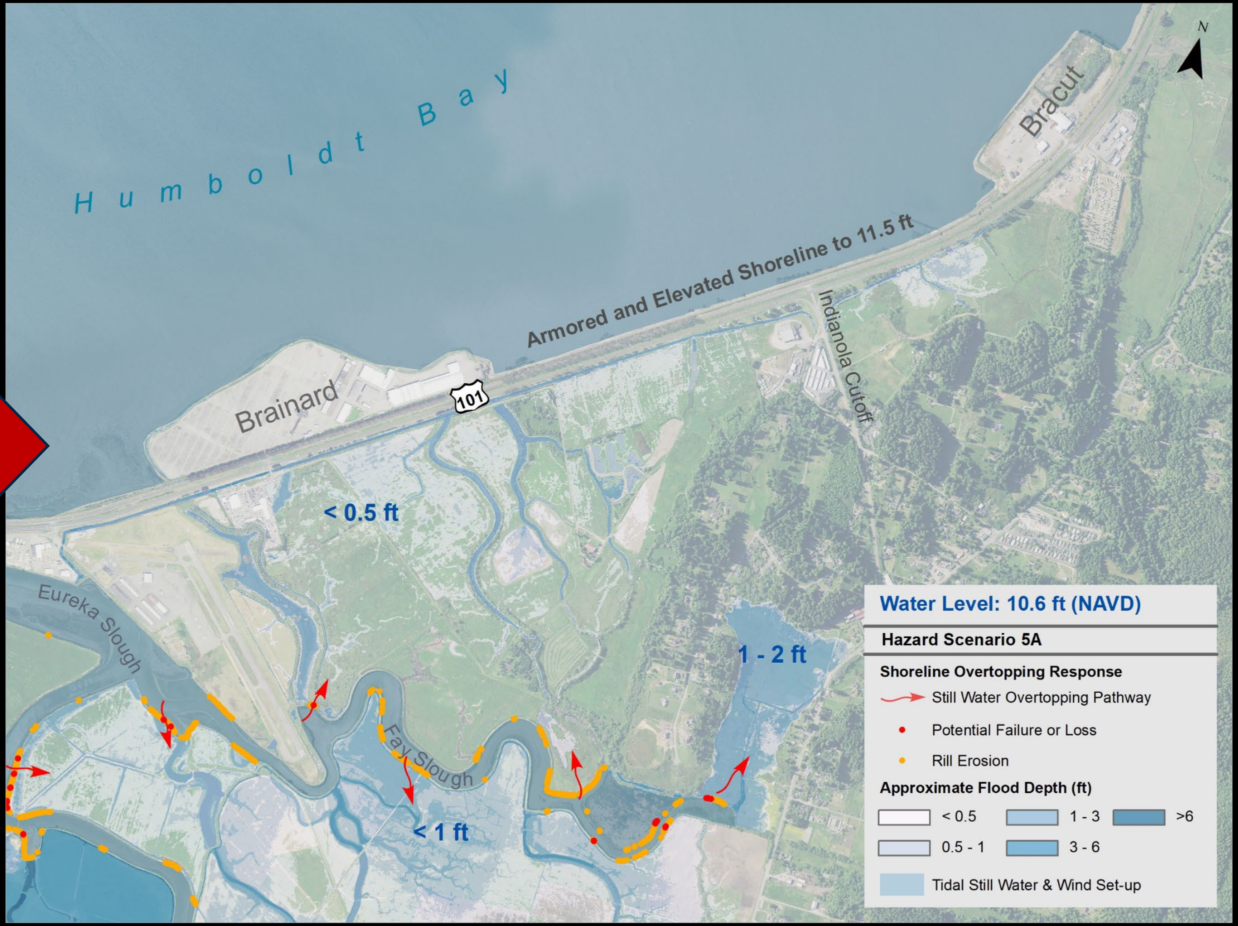


Understand Risk

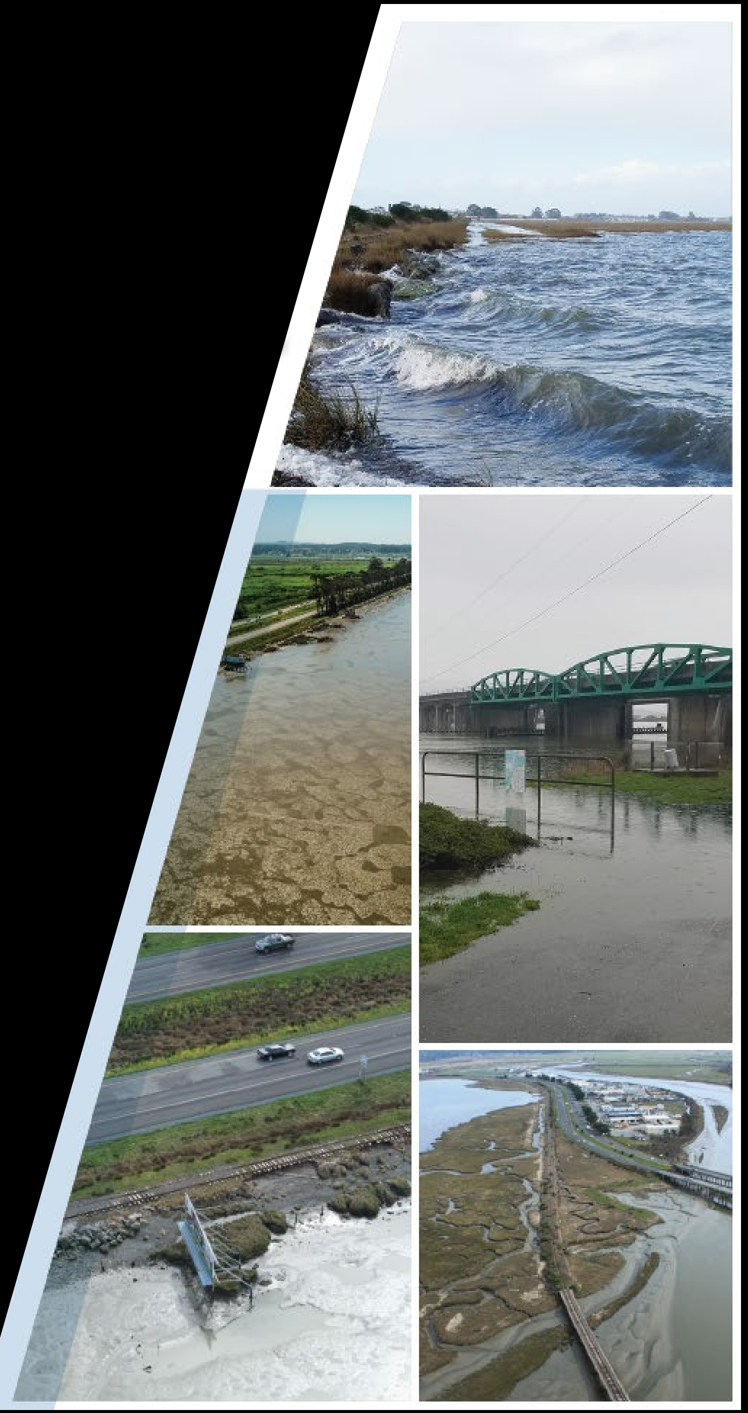


Identify Management Actions & Inform Design Objectives for Adaptation Projects





Thank You



Thank You

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