SEA LEVEL, STORMWATER, AND LAND USE:

INUNDATION IN CITY PLANNING FOR COOS BAY, OREGON

C Stillman

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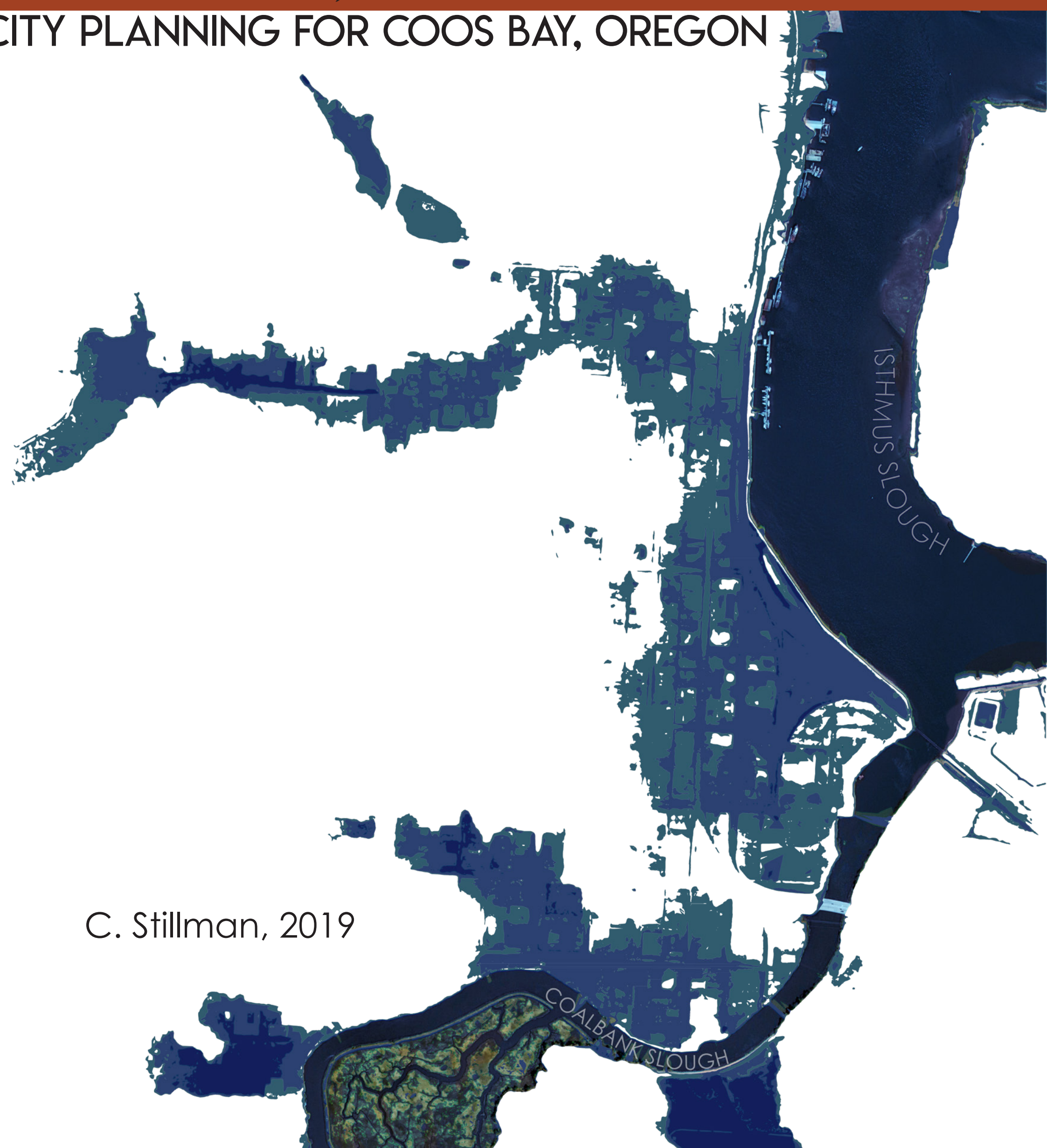

C. Stillman, 2019

APPROVAL

Project Chair: R. Ribe

Committee Member: C. Enright

Committee Member: M. Eischeid

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The work of my life, and specifically the works required for this master's degree, have required so much more than I was capable of giving. I have failed over and over. These past three years I have been pushed to the edge of my own limitations until I simply fell over the edge, again and again. Each time, it's been a struggle to get up and try again... and again and again. It is actually strange to arrive at this portion of my life-story, when I pick myself up, dust myself off, and recognize a difficult truth. In passing old limitations I discovered a more formidable me, somehow closer to the badassery to which I aspire.

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Chris, I am so lucky to have you in my corner. We all are. We get *so much* from the example you set. In being your formidible self, guiding with humility, and engaging struggles with honesty you've made us all more than we were before.

ABSTRACT

Using a study site in rural coastal Oregon (within the City of Coos Bay) this project generated a transferable process for rural coastal towns in need of efficient and pragmatic flood-mitigation plans. By observing the spatial relationships of inundation processes to their local context and analyzing how they change through time, this research identified critical failure points, a potential timeline for failures, pragmatic opportunities for flood mitigation, and locally relevant intervention options at the study site. The transferable framework requires researchers to identify and map inundation drivers such as sea-level rise, rainfall, and storm surge across the site for selected scenarios (current, 2030, 2050, and 2100). Next, associated flood control infrastructure, including levees and tidegates, are mapped. Relevant context, including buildings, land uses, roads, railways and any known temporal change is then added. Analyzing the resulting maps draws on local inundation, protections, and context to derive intervention opportunities for the study site.

The impacts of sea level rise have drawn global attention and yet there is no agreed upon approach for how to plan for it. Cities have already begun confronting flooding from natural disasters, from elevated average high tides, and from land subsistence. Global models of climate change provide generalized information that must then be applied and corrected at the regional scale. Regional models then need to be mapped within their local spatial context to inform urban planning processes. The framework developed in this research offers a method for how to incorporate sea level rise, stormwater, and regional protections at a local planning scale.

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TERMS AND VERNACULAR: PRIMER

This brief and informative primer will outline the key terms and abbriviations of coastal processes. Also included are specific terms used for this research.

To make this research more accessible for all interested readers, this primer will define typical coastal processes specific to the subject of coastal water management. Drivers of inundation and inundation controls are specialized to the landscapes that they occupy and are, therefore, often not part of popular knowledge. At the study site for this research, downtown Coos Bay City in Oregon, coastal processes include tides, surge events, rain event, levees, tidegates, and stormwater infrastructure. These interconnected processes work together to create the iconic waterfronts of our coastal areas. These historic processes, as outlined in this primer, are being dramatically impacted by rising seas, the subject explored in this larger research project.

TERMS AND VERNACULAR:
P R I M E R

GLOSSARY

2-year event – a rainfall and/or surge event that has a 50% chance of occurring in any given year

100-year event – a rainfall and/or surge event that has a 1% change of occurring in any given year

Acre-Feet – a volumetric unit of measure, one acre-foot equals the volume of one acre filled one foot deep

Base Flood Elevations - defined by FEMA and used as basis for national flood insurance

Digital Elevation Model (DEM) – a three-dimensional graphic representation of a surface, typically terrain

Estuary - water body where fresh water from rivers and streams flows into the ocean

Exceedance probability - likelihood water will exceed given elevation

Head of Tide – the uppermost extent of tidally influenced waters

Land use - human activities, often with management or zoning connotations

Levee – A natural or artificial elevated embankment that provides protection to land behind it from flooding by rivers or tidally influenced channels. (Cornu & Sounder, 2015)

Mean sea level – the average water level based on tide station observations

MHW – (mean high water) the average of all high tides (e.g. high tide)

MHHW – (mean higher high water) the average water height of the higher of the two high tides

MLLW – (mean lower low water) the average water height of the lower of the two low tides.

MSL – (mean sea level) the average water level based on tide station observations

Mean High Water - (MHW) is the average height of all high tides (e.g. high tide)

Mean Higher High Water - (MHHW) the average water height of the higher of the two high tides.

Mean Lower Low Water - (MLLW) the average water height of the lower of the two low tides

Rainfall Event – an abnormal amount of precipitation over and above normal precipitation rates. Typically expressed as rainfall depth per amount of time.

Resilience - ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions" (resilience as defined in executive order #13653, Section 8c)

Sea level Rise – (SLR) an increase in the volume of water in the world's oceans, resulting in tan increase in global mean sea level. Usually attributed to global climate change by the thermal expansion and increasing melting of land-based ice. (NOAA)

SLR – (sea level rise) an increase in the volume of water in the world's oceans, resulting in tan increase in global mean sea level. Usually attributed to global climate change by the thermal expansion and increasing melting of land-based ice. (NOAA)

Storm event – a weather event that is statistically uncommon, may be rain event or surge event

Storm surge -- higher water levels caused by non-astronomical events (wind or low pressure systems)

Surge event – the abnormal rise of water generated by a storm over and above normal astronomical tide. Typically expressed as a height above normal water levels. (NOAA)

Tidegate – A culvert or opening placed in a levee fitted with hinged doors that open if the inner water level is higher than the outer water level. Drainage takes place during low water. (USACE)

Topography – measurements of the heights of earth's terrain (NOAA)

Vertical Datum – base elevation used as a reference from which all heights (or depths) are measured

TERMS AND VERNACULAR:
P R I M E R

COASTAL PROCESSES

Each coastal city has a unique pattern of terrain and tide fluctuation. A tide chart, like Figure P.1, shows the water height through time. In this example, one week's tidal levels is represented by day. In Figure P.2, one can see how the tidal fluctuations would ebb and flow over low-lying areas adjacent to tidally influenced waterways. A site's unique topography is instrumental in defining inundation areas.

Because water levels are constantly in motion, heights are often given as statistics taken from local, historic water levels. *Mean sea level* is the average of all water levels. On the Oregon coast, it is typical to experience two high tides per day. Averaging the highest tide of each day is a value called *mean higher high water (MHHW)*. MHHW is a term used

Figure P.1
Typical tide charts plot water height (graduated along the y-axis in feet) by time (x-axis).

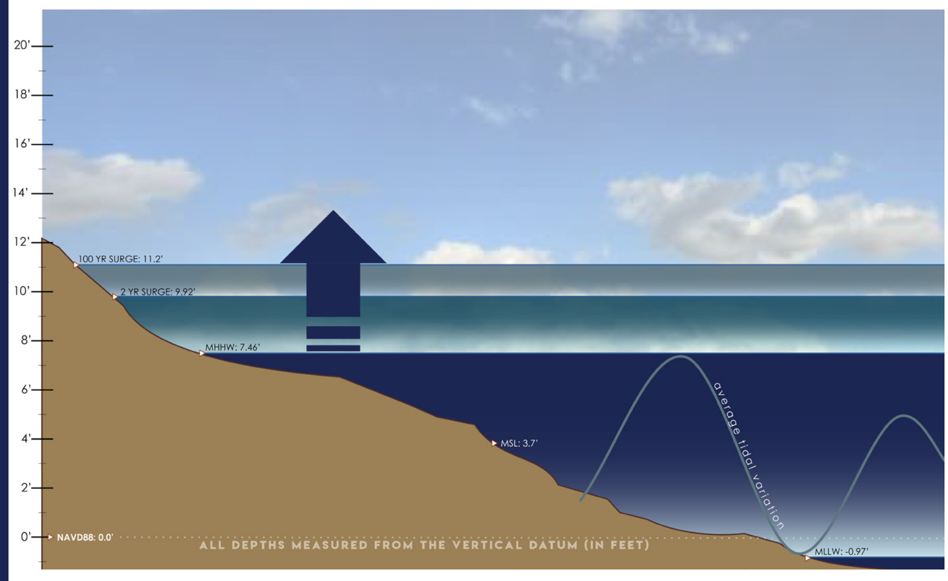


Figure P.2
Typical water levels at Coos Bay including daily, 2-yr, and 100-yr surge events.

throughout this research. Inundation maps are visualized at the MHHW level. MHHW designates the highest tide per day, on average, as well as identifying events likely to occur daily.

In addition to daily tide levels, such as MHHW, occasional coastal surge events cause abnormally high tidal levels. This research considers two types of surge, illustrated in Figure P.2 with respective depths in feet. The 2-year surge event, occurring on-average every two years, and the rare 100-yr surge event.

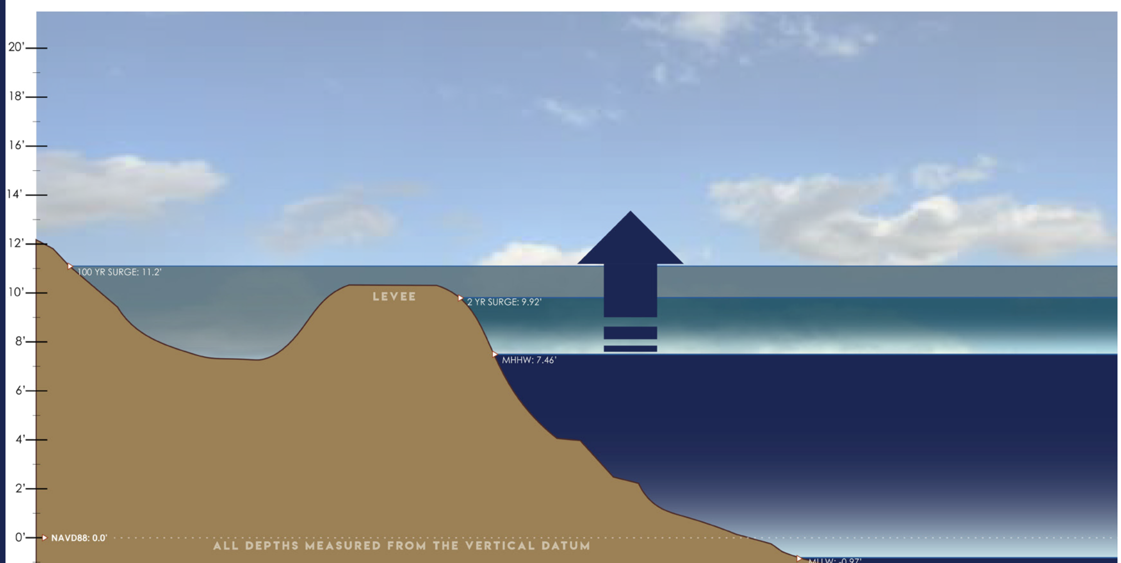


Figure P.3
Typical water levels at Coos Bay including daily, 2-yr, and 100-yr surge events. With levee protections coastal locations can occupy waterfront closer to the tidal waterways.

Coastal protections are tailored to a site's typical water levels, illustrated in Figure P.3. Coastal developments have historically used flood-control structures to prevent flooding. The addition of a levee (a waterfront embankment) can expand the land available for human uses. In Coos Bay, a waterfront levee prevents most surges from flooding the city.

Barriers like levees prevent water from getting into the city but they can also prevent rain flows from getting out. Not all coastal inundation comes from rising seas. Figure P.4 contrasts the distinction between types of storm event. Rain creates flows that drain *down* the landscape, as contrasted to surges that rise *up* from waterways. Both types can cause inundation in coastal cities and each has its own unique infrastructure to mitigate flooding. Through this report, to designate surge versus rain events, I will deliberately identify by name, for example, 2-yr surges or 100-yr rain-events.

By adding stormwater pipes, as in Figure P.5, water drains from urban areas, through levees, and into the bay. This infrastructure will allow tidal-waters into the cityscape without a protection preventing backflows through stormwater pipes.

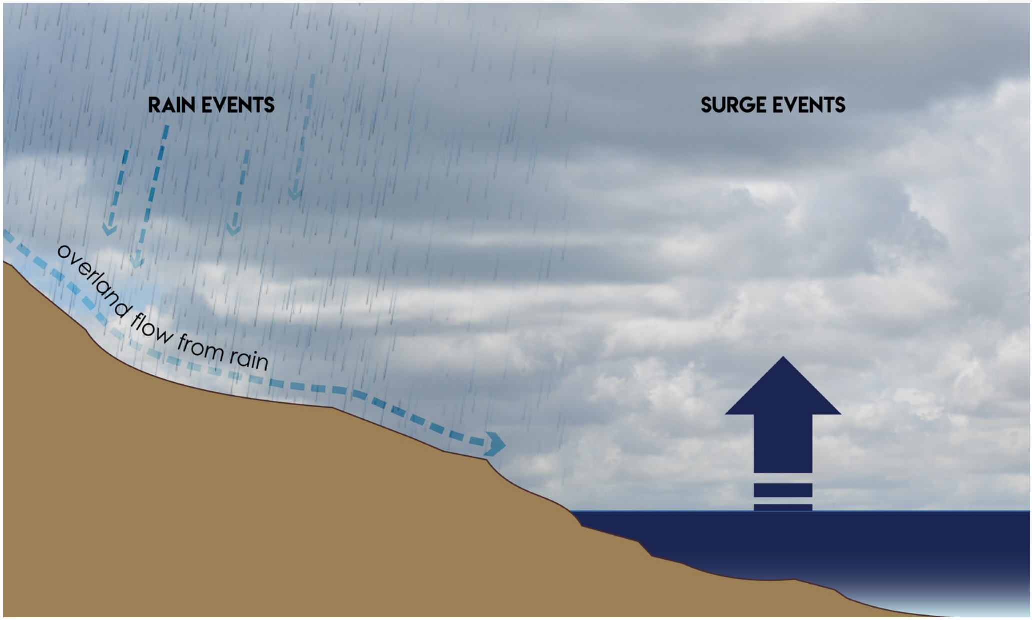


Figure P.4
Rain events specify precipitation that becomes overland flow down the landscape. Surge events specify inundation from rising tidal waters.

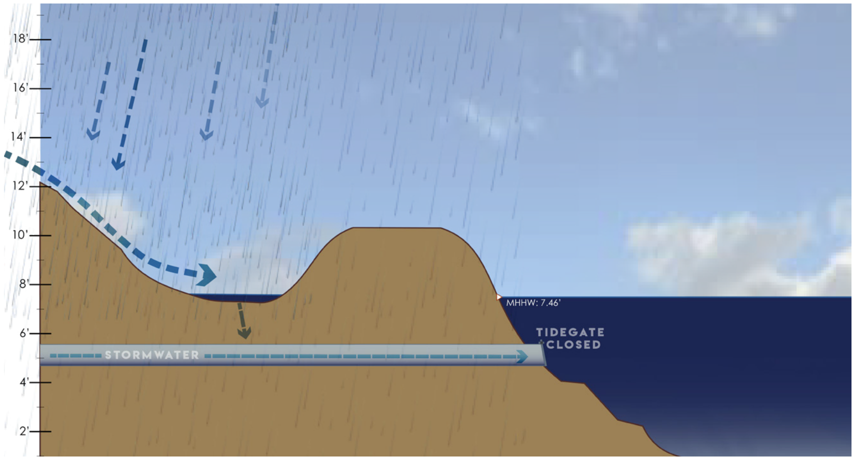


Figure P.5
By adding stormwater pipes, water drains from urban areas, through levees, and into the bay.

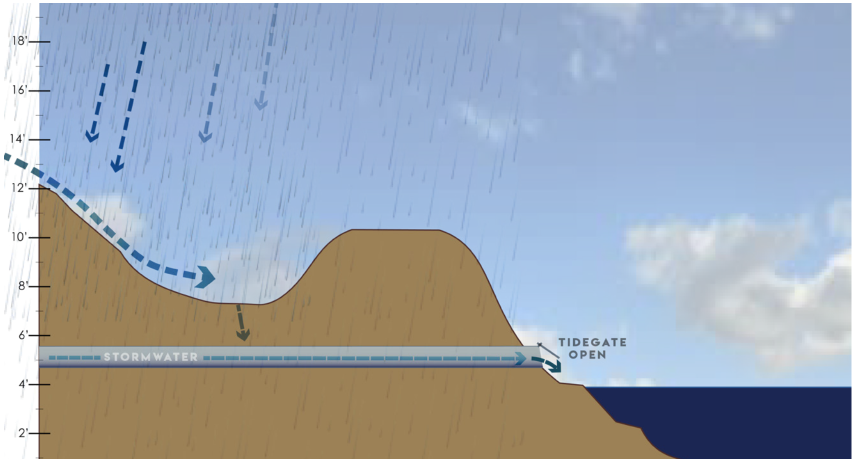


Figure P.6
A hinged 'lid' covers the end of the pipe – a tidegate. Storm-water drained from urban areas pushes it open at low tide.

A hinged 'lid' covers the end of the pipe – a tidegate. Stormwater drained from urban areas pushes it open at low tide as in Figure P.6. The weight of the tidal-water holds the tidegate closed which prevents back-flows from flooding the city (Figure P.5).

It's clear how interconnected the drivers of inundation are to the inundation controls. Sea level, surge, and precipitation will be mapped independent of control structures. Levees and tidegates will also be mapped individually so each process/structure can be fully understood. Then, processes are combined with protections and analyzed for (dys)function through time.

"The shorelands of Coos Bay see the most impact of all of the estuaries [in Oregon] from sea-level rise in the near-term. Highways, local roads, railways, and critical infrastructure across the system will experience increased flood events with the City of Coos Bay being particularly vulnerable."

Source: Sepanik, Lanier, Dana, & Haddad, 2017, p. 126

1

INTRODUCTION

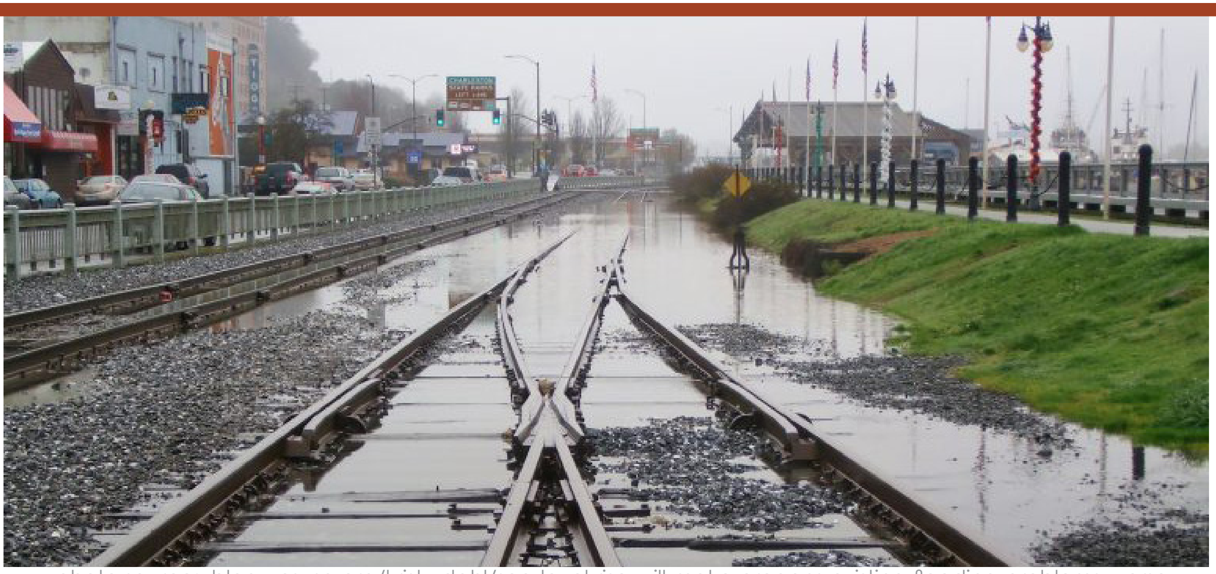


photo source: blog.ucsusa.org/kristy-dahl/sea-level-rise-will-make-oregons-existing-flooding-problems-worse

1.1 How is coastal flooding affecting Oregonians and Coos Bay residents?

Sea level rise is here. Coastal cities like New York, Houston, New Orleans, Miami and so many others have already experienced billions of dollars in losses from sea level rise (AI, 2018, p. 4-7). With nearly 40% of Americans living in coastal urban areas, flooding affects an overwhelming number of us. In some places such as the Oregon coast, we expect a 4.7 foot rise in sea-level over the next 80 years (Sepanik, Lanier, Dana, & Haddad, 2017, p. 173). Of estuaries in Oregon, Coos Bay (Figures 1.1, 1,2, and 1.3) has the most infrastructure at risk of flooding in the next 11 years (Sepanik et al., 2017, p. 126).

In the greater Coos Estuary, sea level rise (SLR) would lead to biennial floods for two fire stations before 2030. Blossom Gulch Elementary will experience biennial flooding by 2050. If the city does nothing, by 2100 2-year floods occur at all those sites, a third fire-station, and the police department downtown. Perhaps most significantly for human and ecosystem health, two sewer treatment facilities would flood by 2030 as well. By 2100, there are four sewage facilities in the two-year floodplain (Sepanik, Lanier, Dana, & Haddad, 2017, pp. 128-129).

More than simply rising seas, the destructive capacity of oceanic storm surges (surge events) increases as seas rise. Additionally, precipitation (rainfall events) compounds urban flooding in coastal areas and adds to already elevated water levels. Given projected sea level rise, 7,400 Oregonians' homes will be flooded at high tide by 2100 (ignoring projected population increases). In Coos County, that risk means thousands of people living in the flood zone, their homes, roadways/ evacuation routes, and critical infrastructure, like fire stations and even sewage treatment facilities, are at risk (Oregon Climate Assessment Report, 2017, p. 35).

Figure 1.1 Coos Estuary located on the central Oregon coast.

Figure 1.2 City of Coos Bay located at the confluence of Coos Bay and Isthmus Slough.

Figure 1.3 Downtown Coos Bay City adjacent to Coalbank and Isthmus Slough.

Given its location, it may be surprising that downtown Coos Bay is affected by tides. It is important to recognize the extensive reach of oceanic processes to effectively plan for tidal effects in adjacent landscapes. Contemporary planning is beginning to recognize the extent of tidal ecologies and expand their definition of "coastal" management efforts. Figure 1.4 identifies the uppermost point affected by tides (also called head of tide) for this study area. Downtown Coos Bay City, as shown in Figure 1.4 is a tidal landscape that will, prepared or not, face the many challenges and uncertainties of rising sea levels.

Land uses such as urban development and agriculture have historically built infrastructure to "protect" lands from natural tidal inundation. This infrastructure, e.g. tidegates and levees for Coos Bay, effectively converts wetlands into terrestrial landscapes by routing water off the land and preventing flow onto the land. "As much [as] 70-95% of the historical extent of [the Coos Estuary's] tidally-influenced wetlands has been converted to terrestrial-based land uses…" (Cornu & Souder, 2015, Chapter: 7, p. 8-20). Situated in low-lying areas, many of these converted landscapes are at greater flood risk from both seas and rainfall. Within the larger Coos Estuary, more than 17,300 acres are currently protected by levees and tidegates (Cornu & Souder, 2015, Chapter 7).

1.2 Who will use this information?

In recent years, flood vulnerability maps have been critiqued for under-representing inundation risk. Historic maps delineated lands as either IN or OUT of floodplains, neglecting the varied, dynamic character of water flows. In alignment with modern work in resilient coastal planning, this research visualizes flooding and flood infrastructure at the regional scale, identifies inundation change through time, and offers descriptive but indeterminate scenarios. These recommendations follow the precedents set by acclaimed work in the field of planning, design, and landscape architecture. In the creation of a transferable framework for other small coastal towns, particularly those in similar political and ecological settings, I leaned heavily on the contemporary strategies from revered work.

Nordenson, Nordenson, & Chapman, authors of the book *Structures of Coastal Resilience*, has focused on novel approaches to coastal resilience planning. Specifically, Guy Nordenson and Catherine Seavitt's work "One the Water: Palisade Bay" received the American Institute of Architects College of Fellows Latrobe Research Prize. As outlined in their book (Nordenson, Nordenson, & Chapman, 2018), I explored causes of flooding including surge events, mapped a variety of possible flood events onto the study area at an urban scale, and recommended layered solutions for increased flood resilience/avoidance (Nordenson, Nordenson, & Chapman, 2018, p. 124). Hazard maps in this

Figure 1.4
Head of Tide just upstream of the study area. Mapping head of tide defines where tidally-influenced waters separate from strictly riverine processes. In this landscape water flows are northward consequently, waters north (downstream) of the head of tide will rise and fall with the tides.

report show inundation at a scale suited for design and land use planning (Nordenson, Nordenson, & Chapman, 2018, p. 137).

Since being converted from wetlands to drained landscapes, coastal developments have become our homes and communities. They are spaces of attachment, dwelling, and value. Contemporary planning processes engage communities in designing their coastal city-scapes. They outline how we shape development and define what values hold sway. Coos Bay City and County are currently visioning these essential factors as part of the Coos County Estuary Management Plan (written in 1985 and under review now) and while my research would benefit from knowledge of these factors, they are currently in-process.

Interestingly, the Federal Marine Fisheries Service, which regulates habitats for migratory fish, suggested development in the floodplain should be disallowed to better protect endangered fish. Because downtown Coos Bay falls well within the floodplain it, therefore, also falls within historic salmon habitat. Coos Bay City challenged the Federal Marine Fisheries Service in a lawsuit in 2017 which was subsequently dismissed. The goal of the lawsuit is to preserve the ability to self-manage land-use at the regional, county, or city level (Moriarty, 2017; Pacific Legal Foundation, 2019).

Consequently, the captivating question for Coos Bay asks: "What will local planners and residents do when historically terrestrial landscapes become tidal water-scapes?"

> ***"There is no bigger challenge today than the management of coastal ecologies."***
>
> (Kimmelman, 2017, pg x)

There is recognition in the city of Coos Bay that SLR is likely to cause land use changes, that infrastructure will impact flooding and flood risk and that existing levee protected lands will retain their protections (Cornu, C. E., & J. Souder, 2015, Chapter: 7). As the city and county define the city's relationship to shared lands and waters, the products of my research serve to inform those planners/managers of flood risks and intervention options. By isolating and identifying flood hazards, mapping where they occur, and defining the hazards' timeline, I contribute to an informed local planning community, a collaborative global planning community, and deliberately confront the realities of coastal dwelling. Planners/collaborators can then engage regional planning efforts in full awareness of the probable flood risks as well as pragmatic intervention options for their city-scapes.

1.3 How did I go about this project?

I used targeted questions to explore the main research objective: "What opportunities for flood mitigation emerge by mapping drivers of inundation and inundation controls?" This series of questions strategically explores the factors that control how water moves in and across a landscape. Using

WHAT OPPORTUNITIES FOR FLOOD MITIGATION EMERGE BY MAPPING DRIVERS OF INUNDATION AND INUNDATION CONTROLS?

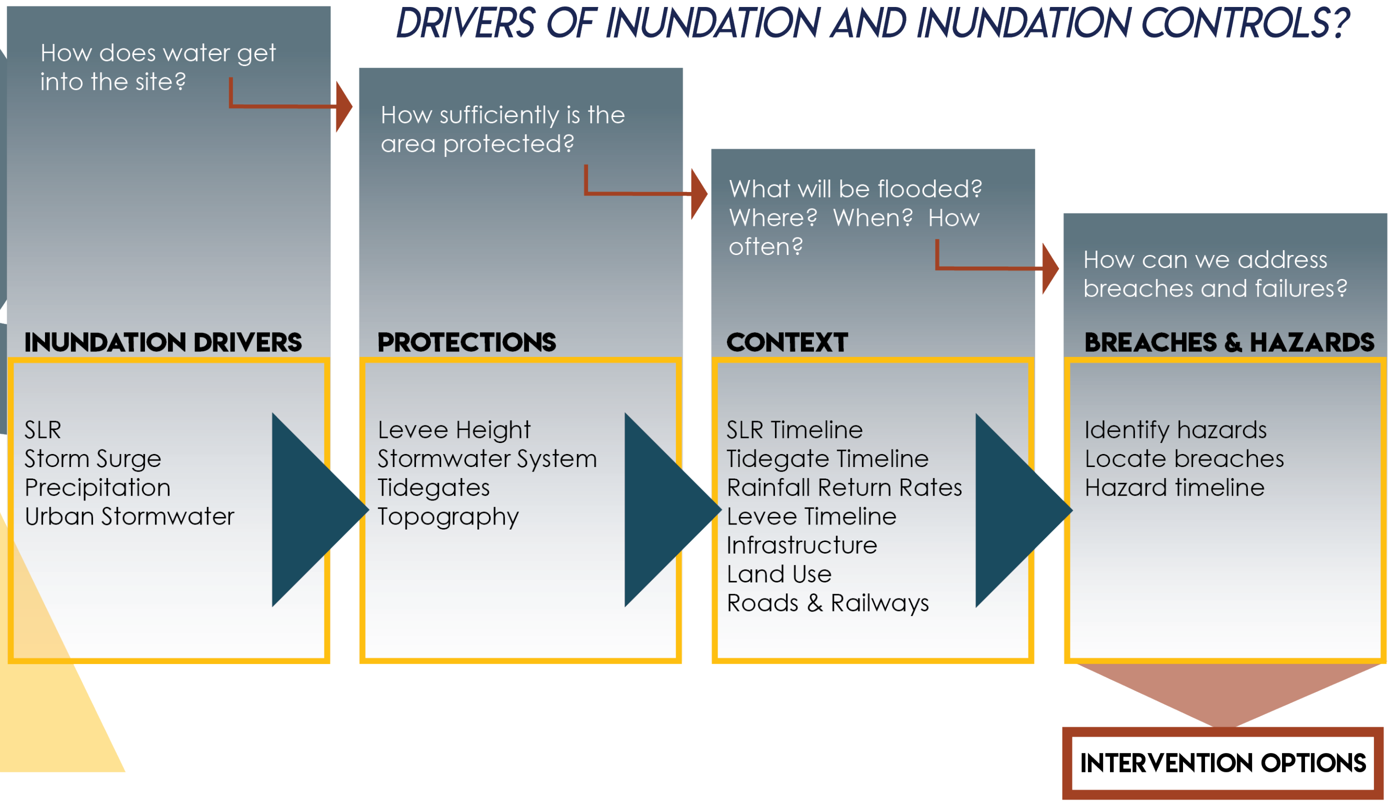


Figure 1.5
Process diagram and outputs for this project

maps to answer these questions creates spatial information in such a way that each process can be evaluated for interactions with other processes and plotted through time. Using these targeted questions s as framework applied to a specific area of interest, Coos Bay City, honed the process and tests its functionality.

Figure 1.5 illustrates how targeted questions connect a problem, such as floods in downtown Coos Bay, to solution options for addressing hazards. Following the precedents of Nordenson, Nordenson, and Chapman (2018), the answers to each question define flood extents, hazard change over time, and resulting intervention opportunities. Interventions that can then be planned for in both space and time. This research places focus on first-cut hazard maps, contextually relevant site assessment, and intervention opportunities for water management planning. Simultaneously, in exploring the framework, this research will provide planning options and opportunities for downtown Coos Bay City.

Asking the right questions

Figure 1.5 outlines the process for my research. Each question (at the top of the blue boxes) is answered using maps or spatial data (within the yellow boxes underneath). The targeted questions guide the research process as well as the resulting maps. In combining and analyzing the relationship between inundation drivers and controls, hazard targets and intervention options were brought to light.

Inundation Drivers

What causes flooding in this landscape? How does water get into the study site and how will it get there in the future? These questions clarify the drivers of inundation related to floodwater supply. The inundation drivers that should be mapped (e.g. define the spatial extent) for downtown Coos Bay City include sea-level rise, storm surge, and precipitation. The inundation maps created for Coos Bay City are outlined in Chapter 2.

Protections

In coastal locations, there are almost always protections already established in the landscape. For downtown Coos Bay, there are levees, stormwater pipes, and tidegates that keep structures from flooding. It is important to remember that elevation, e.g. being above the flood zones, is a simple and effective protection strategy. For this reason, topography is included in a list of protections.

Isn't the City of Coos Bay already protected from flooding? If tidegates and levees keep historic levels of tide-water at bay, is the city sufficiently protected? This question clarifies how protections spatially relate to inundation drivers to prevent flooding infrastructure downtown. Protection maps and processes are further explored in Chapter 3.

Spatial Context

What urban development is likely to be flooded? When? How often? When the inundation drivers, protections, context, and breaches are mapped along with projected changes through time, what flood hazards emerge? Context maps can then be analyzed for targeted intervention wherever and whenever flood hazards emerge. Mapped temporal and spatial context generated an estimated timeline of tidegate (dys)function, rainfall volumes, levee (dys)function, at-risk structures, and at-risk land uses. More on these in Chapter 4.

Breaches & Hazards

What opportunities are there to manage flood hazards? When will they occur? In downtown Coos Bay, what and when are the hazards? Analysis of the hazard maps clarifies options for at-risk structures, identifying both where and when protections ought to be fortified.

Intervention Options

With knowledge of hazards and breaches through time, it is possible to plan targeted strategies. Intervention options that respond to specific spatial hazards can form the beginnings of resilient water-management systems. These are taken from contemporary sea-level rise planning and applied to the local site conditions (outlined in Chapter 5).

Defining the scope

Climate change is likely to bring a variety of changes to estuaries and estuarine communities. Predicted changes include SLR, ocean acidification, water warming, upwelling, freshwater runoff, sedimentation, and more (Dalton, Dello, Hawkins, Mote, & Rupp, 2017, p. 39). Inundation is only one of many factors driving water management needs. Given the constraints of master's work, the focus for this project is on a transferable framework for inundation and the products of the framework within a defined area of downtown Coos Bay. For the study area in Coos Bay, the priority is to develop first-cut inundation assessments, hazard maps, contextually relevant site assessment, and intervention opportunities for water management planning.

Where did the data come from?

Generating spatial maps involved gathering data, data [re]visioning, and/or data generation. The data required for this project fell into three categories: existing research that was already mapped, research where data were available but not spatially presented, and data generated through this research process. Spatial data sources are summarized in Appendix E.

1.4 Are there "solutions" to coastal flooding?

Responsible Design

What do "good" interventions even look like? What is resilience but functionality with a future? In a 2009 Report from the US Environmental Protection Agency (EPA), estuary-specific challenges from climate change are paired with strategies that sustain, protect, and/or strengthen the resilience of both landscapes and water-scapes. If one goal of planning is to support human and non-human communities to hand vibrant, healthy lands to the next generation, then these strategies offer a structure for how to intervene.

> ***"[R]esilience means the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions"***
>
> executive order #13653, Section 8c

In identifying strategies that support our future, planners can make a deliberate move toward a resilient relationship with estuary ecologies, one that allows human and estuary ecologies to evolve *with* a changing climate.

Relevant excerpts (EPA, 2009) for this study include:

- Remove impervious surfaces, replace undersized culverts to accommodate precipitation changes in support of water quality (p. 19)
- Design new coastal drainage systems to accommodate precipitation changes and SLR in support of water quality (p. 19)
- Lengthen land-use planning horizons that incorporate climate predictions to accommodate precipitation change and SLR to support preservation and development (p.17)
- Fortify levees to accommodate SLR and precipitation change in support of water quality and preservation and development (p. 15)
- Redefine river flood zones to match projected flood frequency and extent to accommodate SLR and precipitation change in support of preservation/ development and wetland health (p. 14)
- Realign structures affecting river and estuary flow to accommodate SLR and precipitation in support of preservation, wetland health, vulnerable species and sediment transport (p. 11)
- Land exchange programs (owners exchange property in floodplains for county owned land outside flood zones) to accommodate SLR and precipitation changes in support of vulnerable species and wetland health (p. 10)
- Protect, maintain, restore wetlands to accommodate SLR and precipitation change in support of water quality and vulnerable species (p. 7)

Evaluating SLR information today allows a community to take action sooner, potentially lowering cost, increasing preparedness, and improving resilience to the inherent unknowns of climate change and SLR. The very premise of using SLR information as a component of vibrant development and resilient ecologies supports these goals both today and in the future. Mapping predicted inundation zones, their frequency, and spatial extent (Chapter 2) will inform climate-ready planning efforts. Planners support climate-ready estuaries if/when interventions remove impervious surfaces, when climate-projected volumes are addressed in stormwater designs, and when infrastructure accommodates predicted flooding.

In the act of protecting wetlands, maintaining their integrity, and incentivizing restoration work water managers build resilience and climate adaptability.

1.5 Coastal Water-Management Planning

The EPA (2009) admits some strategies are difficult and many are costly to implement. They also suggest the sooner interventions are completed, the "easier and perhaps cheaper they will be compared to the costs of inaction" (EPA, 2009, p. 22), a timely reminder that doing nothing in the near-term will defer cost to future generations.

> ***...Near-term implementation of resilience strategies can be more efficient and cost-effective than taking no action.***
>
> (EPA, 2009)

By observing city-scale land-use, flood extents, and failure points (in space and time), it may be possible to lower project costs and maximize benefits through targeted interventions and planning, a process supporting resilient ecologies as well as a more resilient economic foundation.

Both books, *Structures of Coastal Resilience* and *Adapting Cities to Sea Level Rise*, suggest layering diverse strategies as an important aspect of adaptive capacity and resilience. How do we know what strategies could work? What strategies could work for Coos Bay? Let's explore how other cities have incorporated resilient, coastal interventions.

1.6 Intervention Options

What resilience strategies are being built today? What can these precedents tell us about intervention options for Coos Bay? What is a "good" intervention for the conditions at Coos Bay?

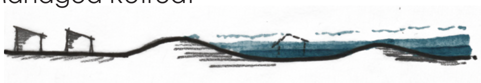
Selected strategies from a variety of case studies are summarized here (Figure 1.6). Information on where an intervention is used and how it functions provides a baseline for where each strategy could be best utilized in the study area presented here.

This is by no means an exhaustive list. It is, in fact, a list that is perpetually expanding as we learn from existing interventions, develop new flood strategies, and redefine resilient infrastructure. The precedents and interventions presented here are a first-cut analysis of options and tools relevant for this study area.

1.7 Mapping Excerpts

This research process begins by asking how water gets into downtown Coos Bay. The following four map excerpts (Figure 1.7, 1.8, 1.9, and 1.10) preview the outcomes of this framework process. The first excerpt shows drivers of inundation for a selected scenario. The process diagram, Figure 1.5, summarizes that this first question will be answered by defining and mapping the inundation processes at work in this landscape. For Coos Bay City, processes that drive

Managed Retreat

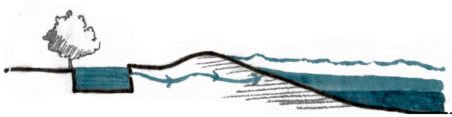


In the Netherlands, there is an extensive network of flood-prevention infrastructure. In "Room for the River" the Dutch government fortifies levees (also called dikes) and provides storage space for floodwater. Low-lying lands are allowed to flood, thereby lowering water levels and decreasing flood risk elsewhere. As SLR floods housing more often, strategic retreat relocates housing behind newly fortified levees (AI, 2018).

Floodable Public Space

As in Cumberland Park, Nashville, Tennessee, public plazas can be designed to capture stormwater and provide community recreation opportunities. These multi-purpose spaces function as public greenspace under typical conditions and stormwater reservoirs during storms. At Cumberland Park, brownfields are remediated as part of the design (AI, 2018).

Store & Pump



Polders, strips of low-lying lands enclosed by levees, have been made famous by Dutch landscapes. In polder landscapes water flows are channeled off lands, routed through polders, and pumped during storm events. Polders can hold water briefly, then route flows to water-pumping stations. Long-term implication of polders indicate they may contribute to land subsidence (sinking), so this is not a long-term option (AI, 2018).

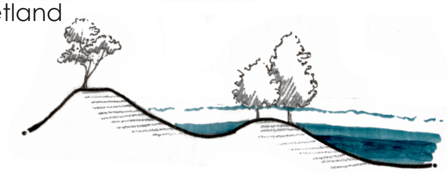
Fortify Levees

Levees function as a barrier between low-lying areas and tide-waters. In "Room for the River" the Dutch government fortifies levees and provides storage space for floodwater as a tool for regional flood prevention (AI, 2018).

Multi-purpose Levees

In Ho Chi Minh City, Vietnam, levees are incorporated into planned roads that encircle the dense, high-value parts of the city. The city is also using underground water storage and green infrastructure along roads (AI, 2018, pp. 48-49).

Wetland



In New Orleans, Louisiana, the "Resilient New Orleans" plan incorporates layered strategies (in alignment with (Nordenson, Nordenson, & Chapman, 2018). New Orleans will, as part of this plan, collaborate with the Louisiana Coastal Protection and Restoration Authority to restore coastal wetlands that offer natural flood protection (AI, 2018, p. 42), habitat, and a local sense of place.

Street Trees

Many cities, coastal and inland, recognize the benefits of a healthy urban canopy. Street trees intercept rain and decrease the volume of water routed into stormwater pipes lowering the cost of urban infrastructure, its maintenance, and providing economic/ecologic benefits.

Figure 1.6
Intervention options, associated site of implementation, and probable function.

inundation include SLR, surge events, and the precipitation that becomes urban stormwater. The inundation process maps will ignore any protections, effectively mapping inundation based solely on topography and inundation levels. Then, the following protections map (Figure 1.8) will explore protections independently. Then, the context excerpt (Figure 1.9) will combine inundation, protections, and development to actively explore the relationship between components through time.

Each map presented in this report captures one moment in the life of these processes. Each process, dynamic in space and time, interacts with the others. Processes change through time, some in highly predictable ways, others unpredictably. By capturing the relationship between processes through time, a map can explore what interventions will function under future conditions.

In coming chapters, as stated in Figure 1.5, many "results" from this research are presented as maps showing spatial representations of the processes that govern water movement in this landscape. The following are excerpts of this larger report. Let us explore how data become maps and how an analysis of mapped data offers insight for planning more resilient coastal communities.

Excerpt: Inundation Drivers

The 2050 data for SLR and storm surge show extensive inundation (in blue) across the study area (Figure 1.7). Inundation maps *do not* include protections such as tidegates and levees. Inundation maps *strictly* show the relationship between water level and land elevation. Levee and tidegate protections are explored and mapped in Chapter 3. Chapter 4 is partly dedicated to exploring how protections may effectively control (or fail to control) these inundation extents. Mapped protections and their relationship to inundation drivers is explored in Chapter 3.

Mean Higher High Water (MHHW) is the typical highest-tide of the day. *SLR + 2-yr Surge* represents floodwater from the slough likely to occur every two years. *SLR + 100-yr Surge* represents floodwater from the slough likely to occur every 100 years. Stormwater infrastructure is mapped in blue lines. These routes channel precipitation that falls in urban areas off paved surfaces and into the slough. Rain Events also occur at predictable rates that is further explored with inundation drivers (greater detail in Chapter 2).

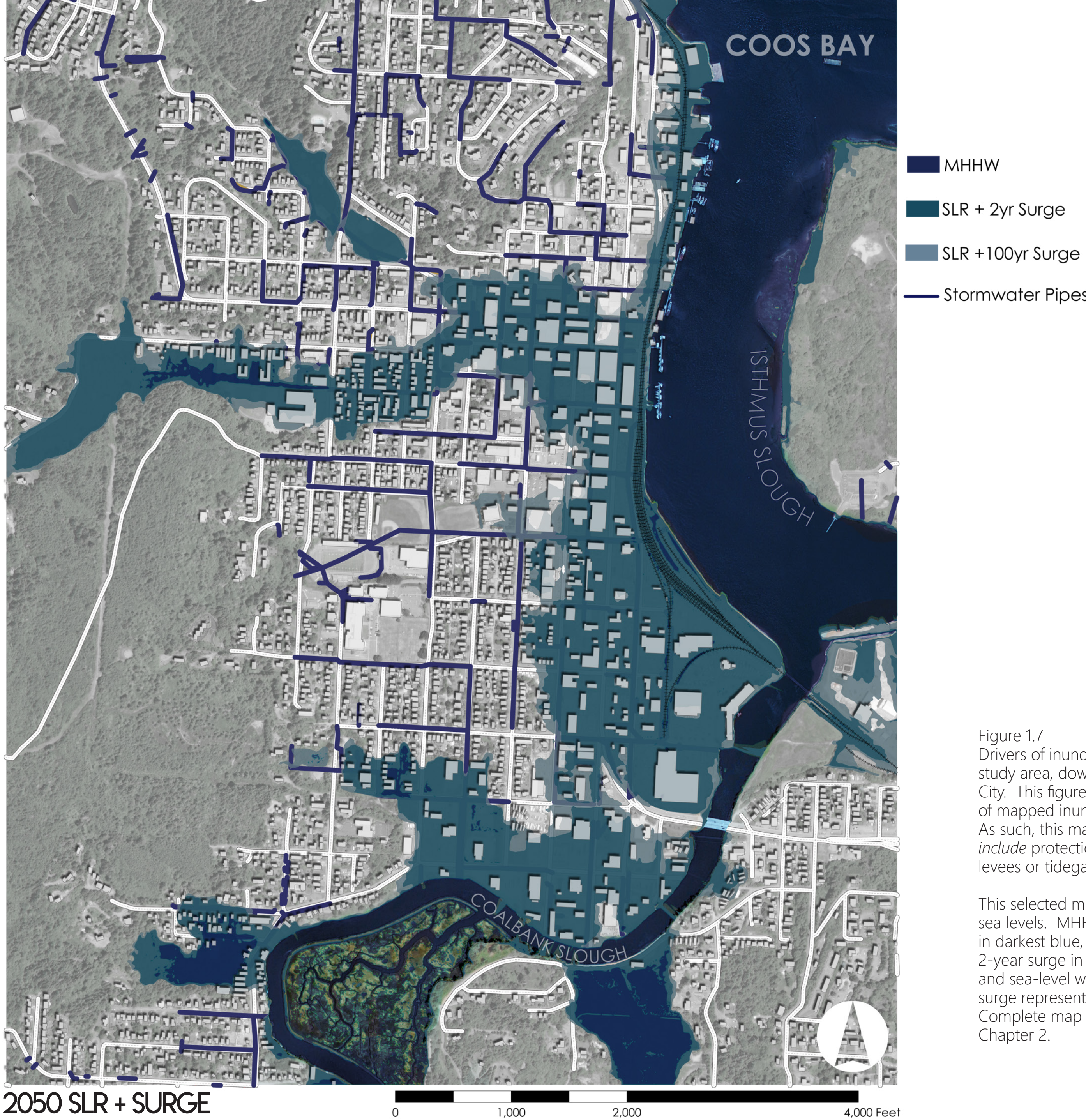


Figure 1.7
Drivers of inundation at the study area, downtown Coos Bay City. This figure is an example of mapped inundation drivers. As such, this map *does not include* protections provided by levees or tidegates.

This selected map is for 2050 sea levels. MHHW is shown in darkest blue, sea-level with 2-year surge in medium blue, and sea-level with 100-year surge represented in light blue. Complete map set found in Chapter 2.

Excerpt: Protections

Existing protections (Figure 1.8) include stormwater infrastructure, tidegates, levees, and topography (elevation is itself a protection). These structures prevent water from flooding downtown but each has unique interactions with water in the landscape.

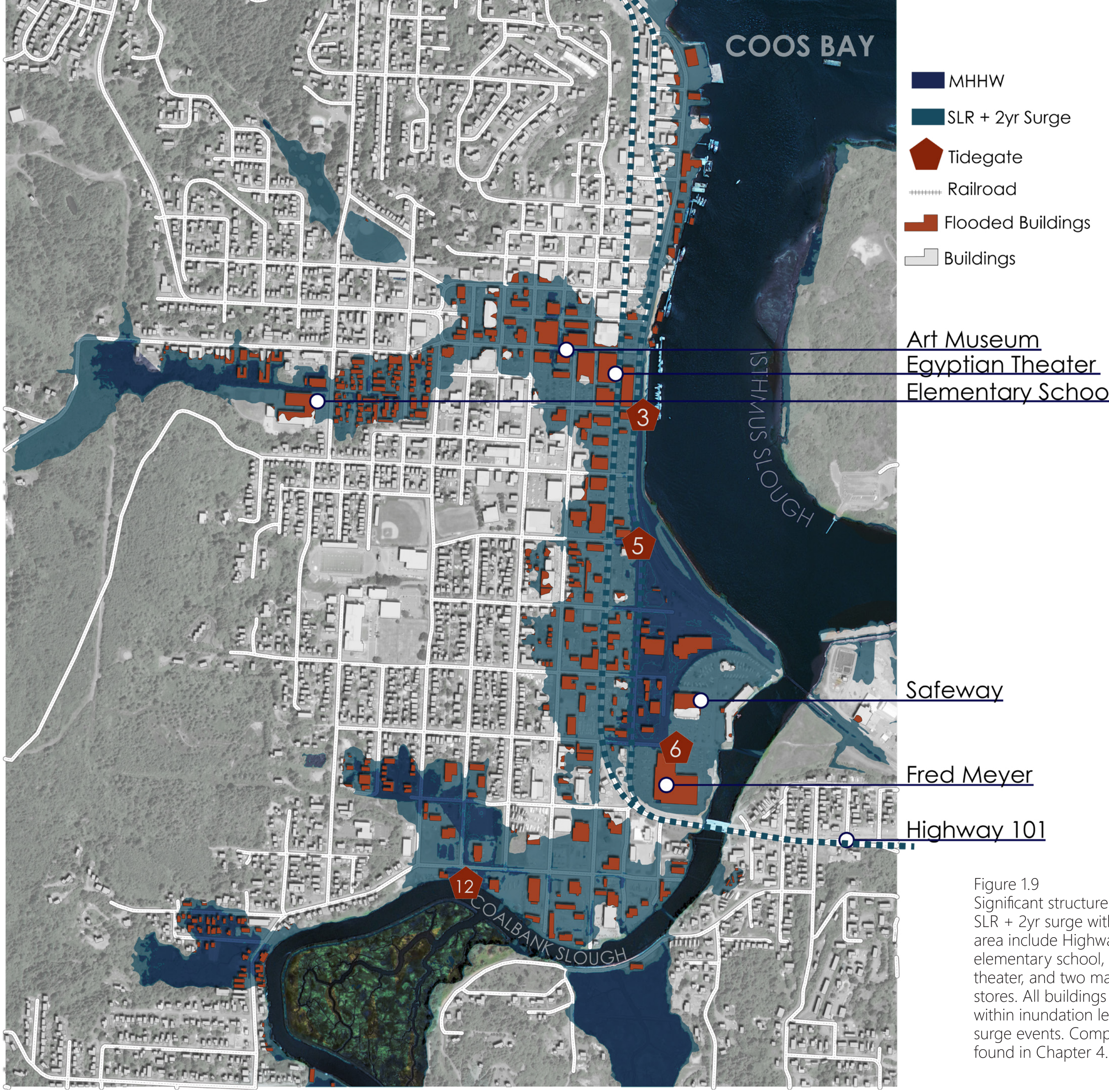
For stormwater pipes, rain is routed from paved surfaces quickly into these (blue lines) and from there to the slough or bay. Those pipes drain through a tidegate (in red). The pipe and tidegate are typically part of the levee (a protective raised embankment). Stormwater pipes route water to the tidegate. The levee/tidegate prevents bay-waters from flooding the city. The tidegates allow accumulated stormwater out. In the future, these systems must work together to handle predicted overland flows and rising surge events.

Systems currently protecting the city from floods have potential to fail as seas rise. When water levels in the slough rise above the level of the tidegate, urban flooding will result as tidegates fail to drain urban stormwater.

Figure 1.8
Protections within the study area. This infrastructure includes selected tidegates, lands functioning as levees, and existing topography. Complete map set found in Chapter 3.

Excerpt: Spatial Context

Significant structures that are likely to experience biennial floods in 2050 are mapped in Figure 1.9. More than 300 buildings (in yellow) would flood in this *2050 SLR + 2yr Surge* event. With urban stormwater also potentially accumulating behind tidegate 5 and 12. Note that Highway 101 is among the structures at-risk, potentially impacting access and evacuation routes. Most structures of significance are associated with the waterfront levees east of 101. Fewer structures are within the floodplain south of 101 along Coalbank Slough.



2050 SLR + 2YR SURGE

Figure 1.9
Significant structures at-risk of SLR + 2yr surge within the study area include Highway 101, an elementary school, a historic theater, and two major grocery stores. All buildings in yellow are within inundation levels for 2-yr surge events. Complete map set found in Chapter 4.

Excerpt: Hazards/Interventions

The detailed analysis found in Chapter 4 details the spatial extent of levee breaches in a 2-year surge event in 2030 Beyond 2030, the levee begins to fail to a much larger extent. *2050 SLR + 2-yr Surge* breaches are shown in red in Figure 1.10. By 2050, larger-scale levee fortifications, as shown here, are required along the eastern waterfront and stormwater begins to flood behind the tidegates unable to open due to higher seas.

These intervention options layer diverse strategies to mitigate urban coastal flooding. Layering diverse strategies follows the EPA's suggestions for climate-ready estuaries. It is also suggested in *Structures of Coastal Resilience* (Nordenson, Nordenson, & Chapman, 2018) as a strategy toward resilient coastal planning. Diverse strategies also support a tailored approach that addresses the unique challenges of each targeted intervention site, allowing emergent hazards to be paired with resilient interventions specific to the site's needs. Detailed phasing and intervention options are found in Chapter 5.

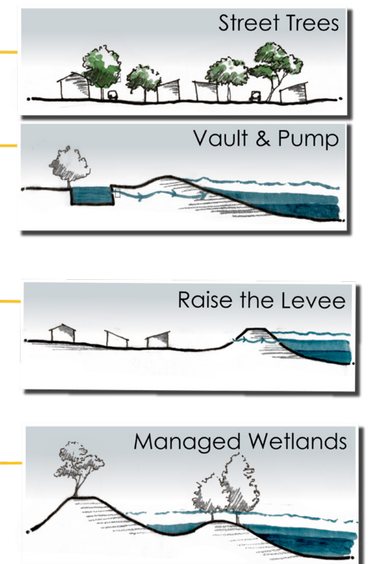


Figure 1.10
Hazards and key potential interventions within the study area. Complete map set found in Chapters 5 and 6.

What opportunities for flood mitigation emerge by mapping drivers of inundation and inundation controls?

Primary research question

2

HOW DOES WATER GET INTO DOWNTOWN COOS BAY CITY?


photo source: R. Ribe

2.1 Where will the water go?

What drives water into urban spaces? We pipe it into our communities. We also quickly pipe it out with sewer and stormwater infrastructure. We drain the water that falls as rain onto houses, businesses, and roads. Wetlands and rivers are prized recreational spaces. Our communities, coastal communities especially, have an interwoven relationship with water. In this era of sea level rise (SLR), building infrastructure that supports water-flow processes requires knowledge of water flows, where it flows, and when it may overflow. Sea level rise challenges the historic relationship coastal communities have to water-flow processes. This chapter will explore what drives water into the study site, downtown Coos Bay City, Oregon, defining where it flows and when it overflows.

To define and discuss "water depth" for land planning, we define it relative to a consistent and unchanging marker, some predetermined baseline, a "zero" that all heights are measured from. This vertical baseline is the tidal datum (Cornu & Souder, 2015, Chapter 7). The water levels in this project use the "North American Vertical Datum of 1988," a standardized vertical datum typical for mapping/planning in North America. All elevation, depths, water levels, and levee heights for this research are given in feet above NAVD88 (Figure 2.1).

2.2 How do these water flows work?

Tides

We know the study area is adjacent to tidally influenced waters (Chapter 1, Figure 1.4). What causes tides here and what might alter them? The tide pattern in the Coos Estuary is primarily controlled by the orbit of the moon, local climate, and coastal geography. The tidal range (height of lowest tide to highest tide) also decreases as one moves further up the bay from the ocean. To know flood risk, it is critical to use tide data specific to the site, to have knowledge of local tidal ranges, and to anticipate future changes in tidal depths.

Coos Bay has two mixed semi-diurnal tides per day, e.g. each day will typically have two high- and two low-tides of unequal heights. Water heights are often given as statistics, historically *mean sea level* or *mean high tide*, that are taken from local water level measurements. Local water levels for this research are taken from the closest tide station at Charleston, OR (documented in Figure 2.1). These statistics represent reliable trends in water levels but are not exact measurements or perfect predictions of this exceptionally complex set of processes. For this study, water level measurements include historic:

Mean Sea Level (MSL) - the hourly average tide-station water height at Charleston, OR.

Mean High Water (MHW) - the average height of all high tides.

Mean Higher High Water (MHHW) - the average water height of the higher of the two high tides.

Mean Lower Low Water (MLLW) - the average water height of the lower of the two low tides.

All inundation maps of tides with surge are represented at MHHW level (in feet above NAVD88) for this research. Because MHHW it is the highest tide per day, it is presented spatially (on a map as feet above NAVD88) and specifies how frequently it is likely to occur (once per day).

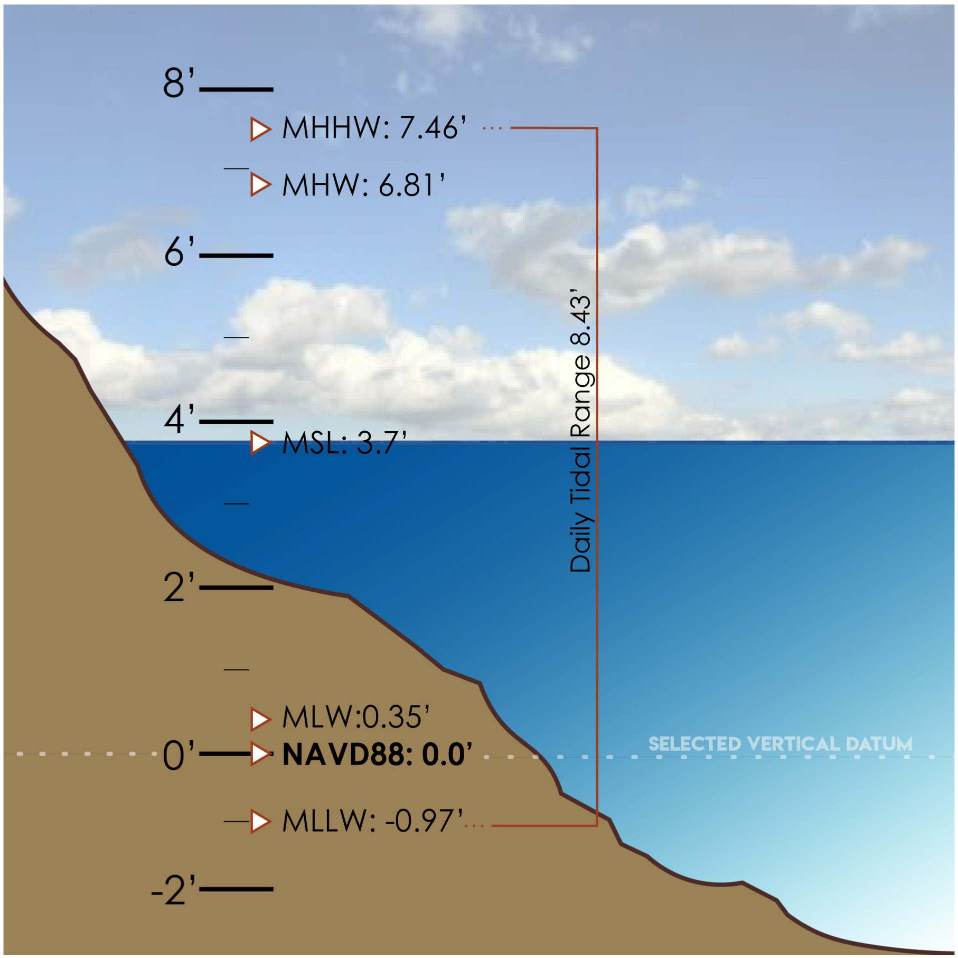


Figure 2.1
Vertical datums and depths for Coos Bay: Station 9432895 (NOAA Tides and Currents, 2009). Water levels for water navigation are typically given in reference to mean lower low water (MLLW). The selected vertical datum for this research is NAVD88 in alignment with similar research and studies.

mean higher high water: MHHW
mean high water: MHW
mean sea level: MSL
mean low water: MLW
vertical datum: NAVD88
mean lower low water: MLLW

All elevation, depths, water levels, and levee heights for this research are given in reference to NAVD88 (in feet).

Figure 2.2
Local SLR and tidal surge predictions (taken from Sepanik, Lanier, Dana, & Haddad, 2017, p. 173.)

	SLR	+ 2YR	+ 100YR
2019	0	2.46	3.74
2030	0.75	2.46	3.74
2050	1.57	2.46	3.74
2100	4.66	2.46	3.74

Surge

Surge data and sea level rise (SLR) are inseparable as they combine in the bay. Surge and SLR are, for this reason, mapped together in a map series (Figure 2.6). Water data from tide gauges allows researchers to isolate storm-surge events by probability. Surge levels are named for how often they statistically occur. If a surge is likely once every two years, each year has a 50% probability rate. This surge, a so-called 2-year surge event, has an annual likelihood of 50% (a 50/50 likelihood annually) and is statistically likely to occur every other year.

Sepanik, Lanier, Dana, & Haddad (2017) found that 2-year surge events raise typical water levels by 2.46 feet and 100-yr surge events raise typical water levels by 3.74 feet for all considered scenarios (Figure 2.2). Consequently, storm surge depths are added to predicted SLR (Figure 2.3). . A *2030 SLR + 2yr Surge* map represents MHHW plus 2030 SLR plus the designated storm surge (either a 2-yr or 100-yr surge). These two surge events represent two levels of inundation risk. 2-yr surge events offer data on events likely to occur often but with lower water levels. 100-yr surge events offer data on events likely to occur infrequently but with higher water levels.

Note that the daily tidal range offers a challenging "moving target" for regional planners. Landscapes and built structures in tidal environments have accommodated this historic, reliable cycle. With rising seas, the relationship between daily tides, infrequent surge, and coastal protections will need to be adaptable to continue to function.

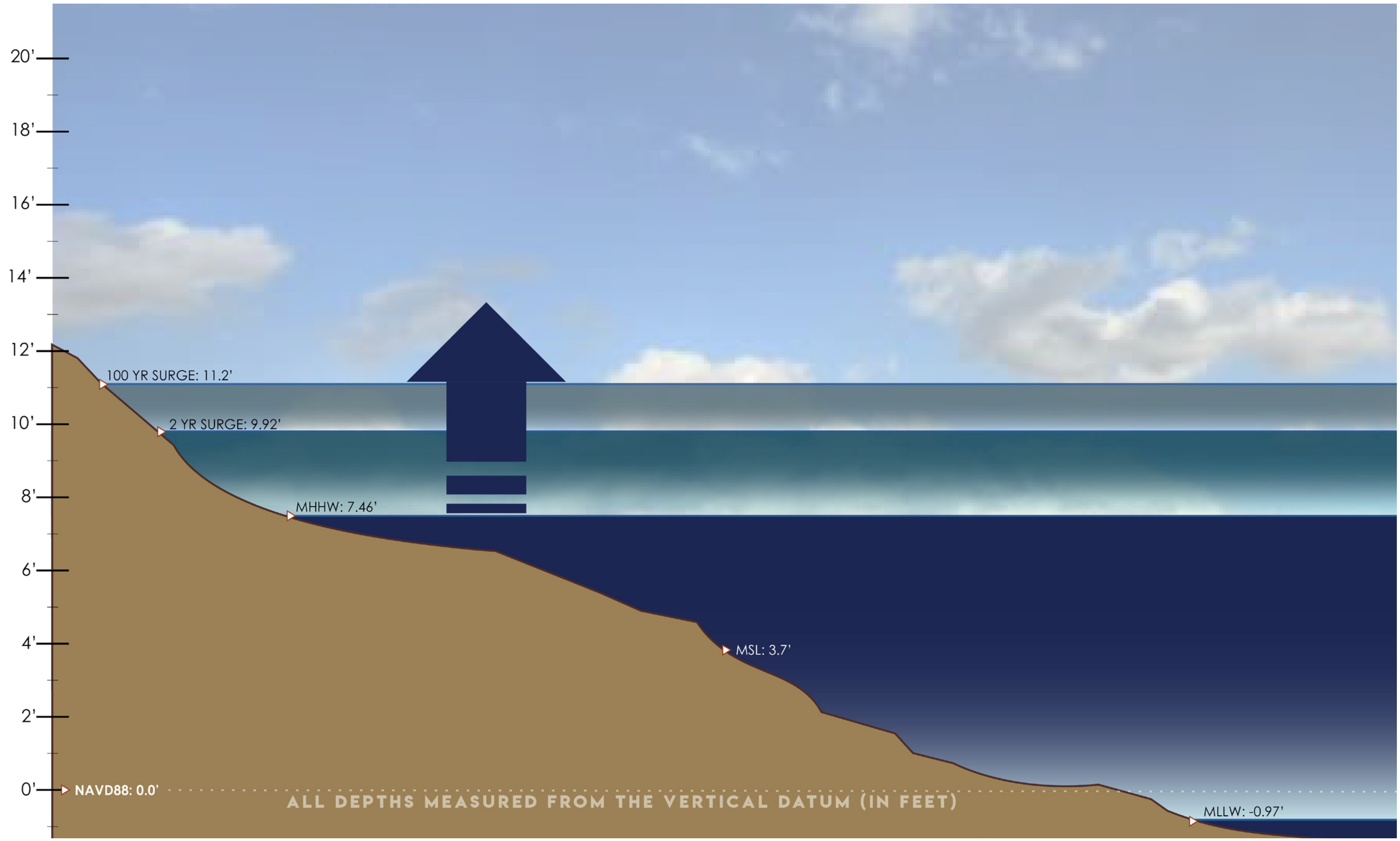


Figure 2.3
2-year and 100-year surge predictions (taken from Sepanik, Lanier, Dana, & Haddad, 2017, p. 173.) on top of local tide levels. Note that these water levels communicate not only depth but also a statistical rate of return. MHHW is likely to be experienced daily. 2-year storms are likely to be experienced every other year. 100-year storms occur, on average, once per century.

Sea Level Rise (SLR)

Tides push and pull ocean waters causing tidal fluctuation in estuary waters. SLR elevates the ocean surface which, in turn, elevates tide and surge heights. When the Intergovernmental Panel on Climate Change (IPCC) released its 2007 report, it summarized global climatic change and SLR. The global models incorporate huge amounts of data. With so much data input to generate global predictions, they cannot account for regional nuance and flux (National Research Council, 2012, p. 1).

Based on global projections released by the IPCC in 2007, Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future (National Research Council, 2012) adds regionally specific data to specify and quantify of local SLR and surge events for 2030, 2050, and 2100. The National Oceanic and Atmospheric Administration (NOAA) in turn used National Research Council's report to map SLR along the west coast (Sepanik, Lanier, Dana, & Haddad, 2017). NOAA's 2017 report, Sea Level Rise Exposure Inventory for Oregon's Estuaries, and associated online viewer are available at www.coastalatlas.net/index.php/tools/planners/68-slr. Included in the report (and viewer) are downloadable Graphic Information System (GIS) files for use with GIS software tools. Where specified in Appendix E, *SLR + Surge* maps are taken from this source. When not taken from this source, data were represented by the author using topography and known water levels (spatial data sources also in Appendix E). In alignment with previous studies, maps and data are for 2030, 2050, and 2100.

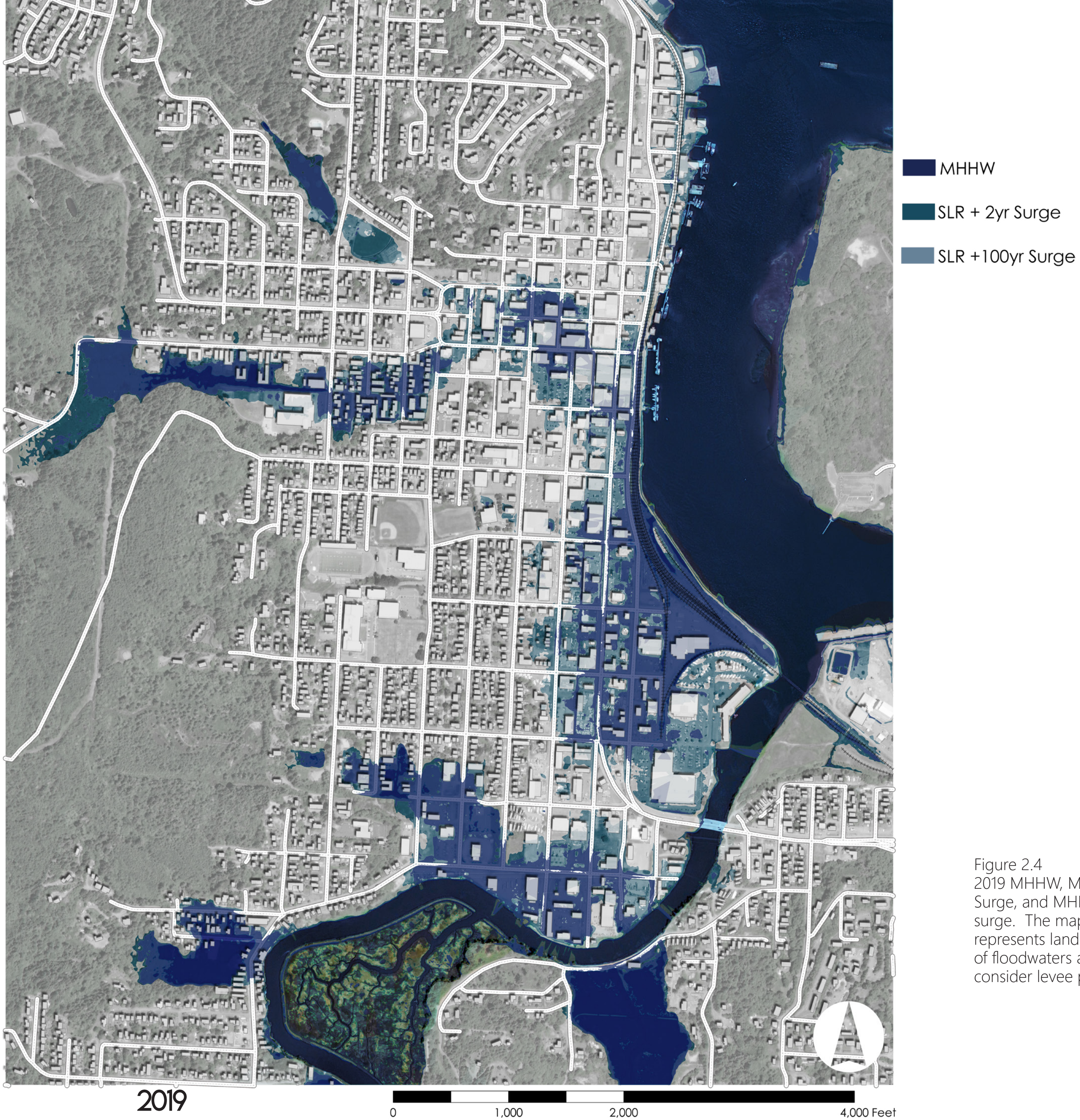


Figure 2.4
2019 MHHW, MHHW + 2yr Surge, and MHHW + 100 year surge. The mapped extent represents lands below the level of floodwaters and does not consider levee protected lands.

NOAA's regional predictions follow the "very likely" (90% probability range) global sea level projections (Figure 2.5) from the 2007 IPCC report. Of importance in quantifying SLR in Oregon is the tectonic movement of coastal land. Because oceans are rising, and in Oregon so is the land, we are likely to see smaller rises in sea-levels relative to the landscape (total relative SLR and storm surge data in (Figure 2.2). NOAA notes that scenarios do not factor in rail embankments, roads, culverts, tidegates, and levees (Sepanik, Lanier, Dana, & Haddad, 2017).

This inundation map series (Figure 2.6) visualized the range of events explored for this research. Each map includes three types of information. One, spatial data is provided by mapping extents for the selected site at Coos Bay. Two, temporal data are provided by identifying the year flooding is projected. This project considered 2019, 2030, 2050, and 2100 water levels. Three, frequency is designated in the label for MHHW (daily), 2-yr, or 100-yr event.

Inundation from tides and surge events are mapped together to provide a range of possible flood extents based on sea level by year and return rates (e.g. once per day for MHHW or every two years for 2-yr surge). Through mapping a range of scenarios and potential frequency, these maps inform decision-makers of the potential flood risk rather than strictly delineating "safe" or "at-risk "zones.

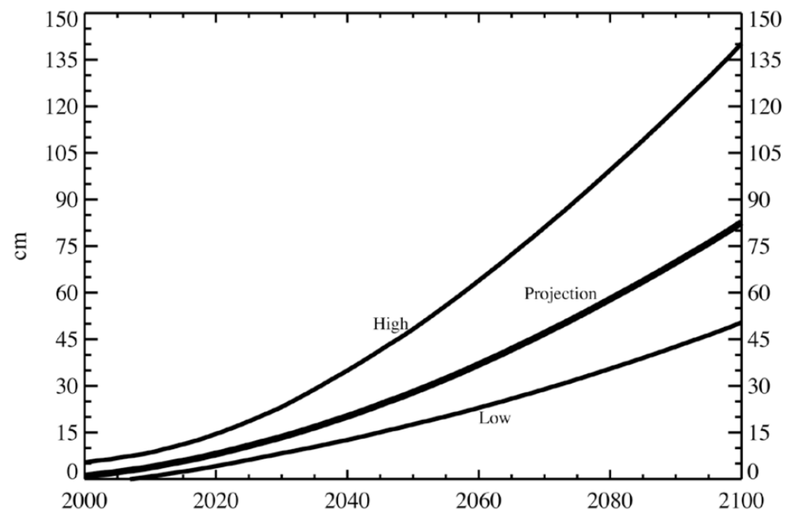
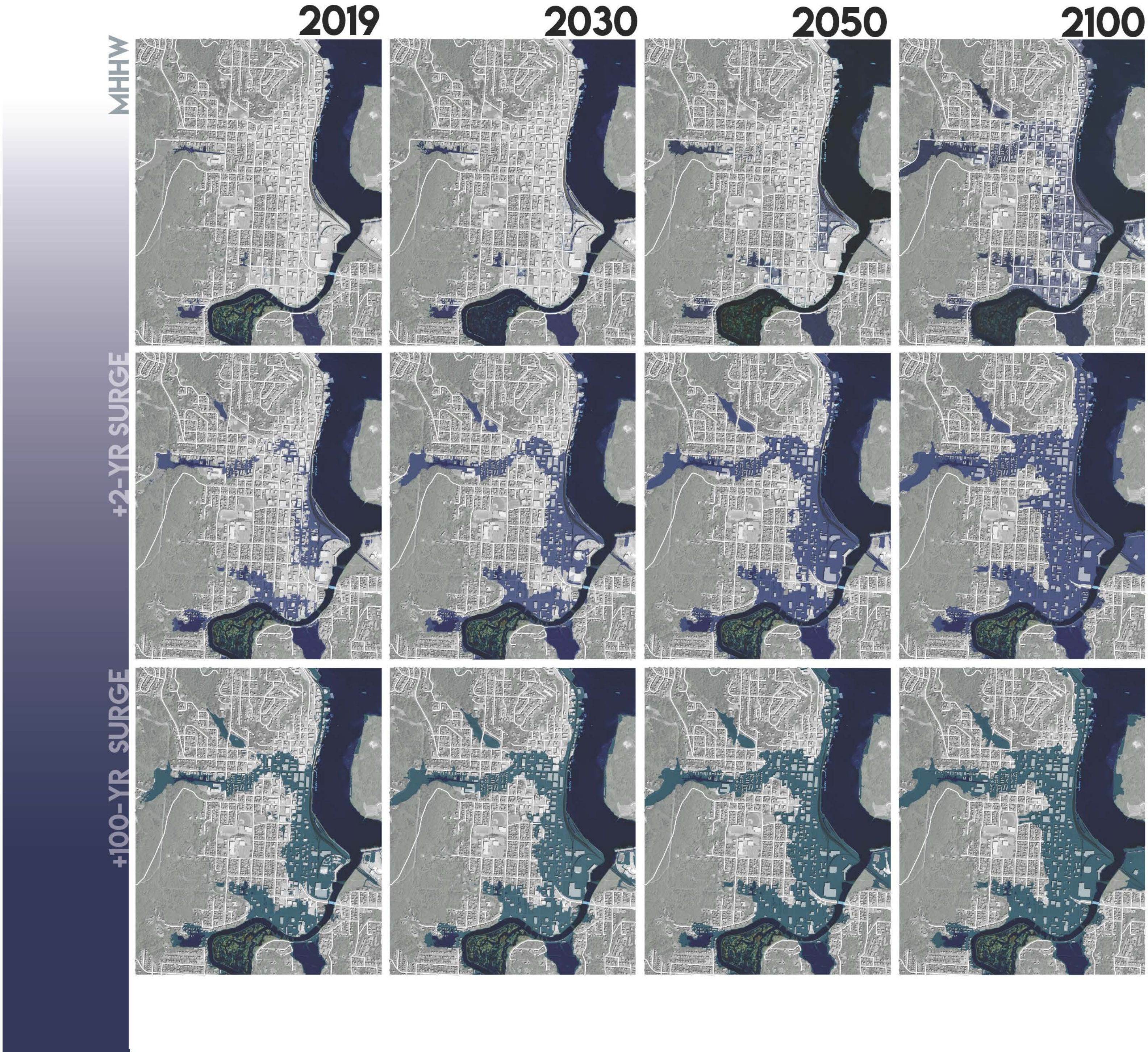


Figure 2.5
Global SLR trends and predictions (Dalton, Dello, Hawkins, Mote, & Rupp, 2017, p. 93)

Figure 2.6 (opposite)
2019 MHHW, MHHW + 2yr Surge, and MHHW + 100 year Surge. The mapped extent represents lands below the level of floodwaters and does not consider levee protected lands. Map data sources are available in Appendix E.


2019
2030
2050
2100
MHHW
+2-YR SURGE
+100-YR SURGE

Precipitation

Figure 2.6 shows a range of inundation scenarios from SLR and surge, however, *SLR + Surge* maps do not factor in overland flows, levees, or tidegates that can cause or contribute to urban stormwater floods (terms and coastal processes clarified in the Primer, pp. 20-23, of this report). Knowing rainfall in coastal cities can result in urban floods, it is clear precipitation needs to be explored as a possible inundation drivers for this project. Mapping stormwater flows allows a preliminary pass at understanding how *rainfall* will flow and accumulate in the landscape.

Precipitation that falls in developed areas is drained into stormwater pipes (the blue network of lines). The pipes drain to a tidegate (the red pentagons), and flow to the bay. During a, for-example, 2-year rain event, runoff flows are predictable. They can be reliably mapped and quantified. On Figure 2.7 you see the four major tidegates and the estimated volumes draining through, or possibly flooding behind, them. Labels indicate 2-yr rain event volumes (given first) in acre-feet, which is equal to one acre that is one foot deep. The red boxes to the right visualize the footprint these 2-yr rain events would occupy when surface waters are one foot deep.

Each selected tidegate (designated in red and numbered) controls drainage for a defined portion of the land (a sub-basin). The sub-basins were mapped to provide estimates of runoff volumes. Precipitation runoff volumes per sub-basin provided information about water flows to a (potentially closed or inundated) tidegate. This project provides volumetric estimations of runoff volumes flowing to tidegates (Figure 2.7) in 2-year and 100-year rain events. A detailed account of tidegate calculations is found in Appendix C.

Oregon's Climate Change Assessment cites the possibility that extreme rainfall events will become more intense and/or frequent over time (Dalton, Dello, Hawkins, Mote, & Rupp, 2017, p. 11). Regional predictions for future precipitation patterns are less clear and do not indicate large changes in the historic precipitation (rain and snow) patterns. With more extreme and/or frequent rain events predicted, the current 2-year rain event (2.46 inches over 24 hours) and/or 100-year rain event (3.46 inches over 24 hours) would occur more often than the specified recurrence. Using current rain predictions for all selected years provides a sufficient but conservative range for frequent, lower-volume events to infrequent, higher volume events.

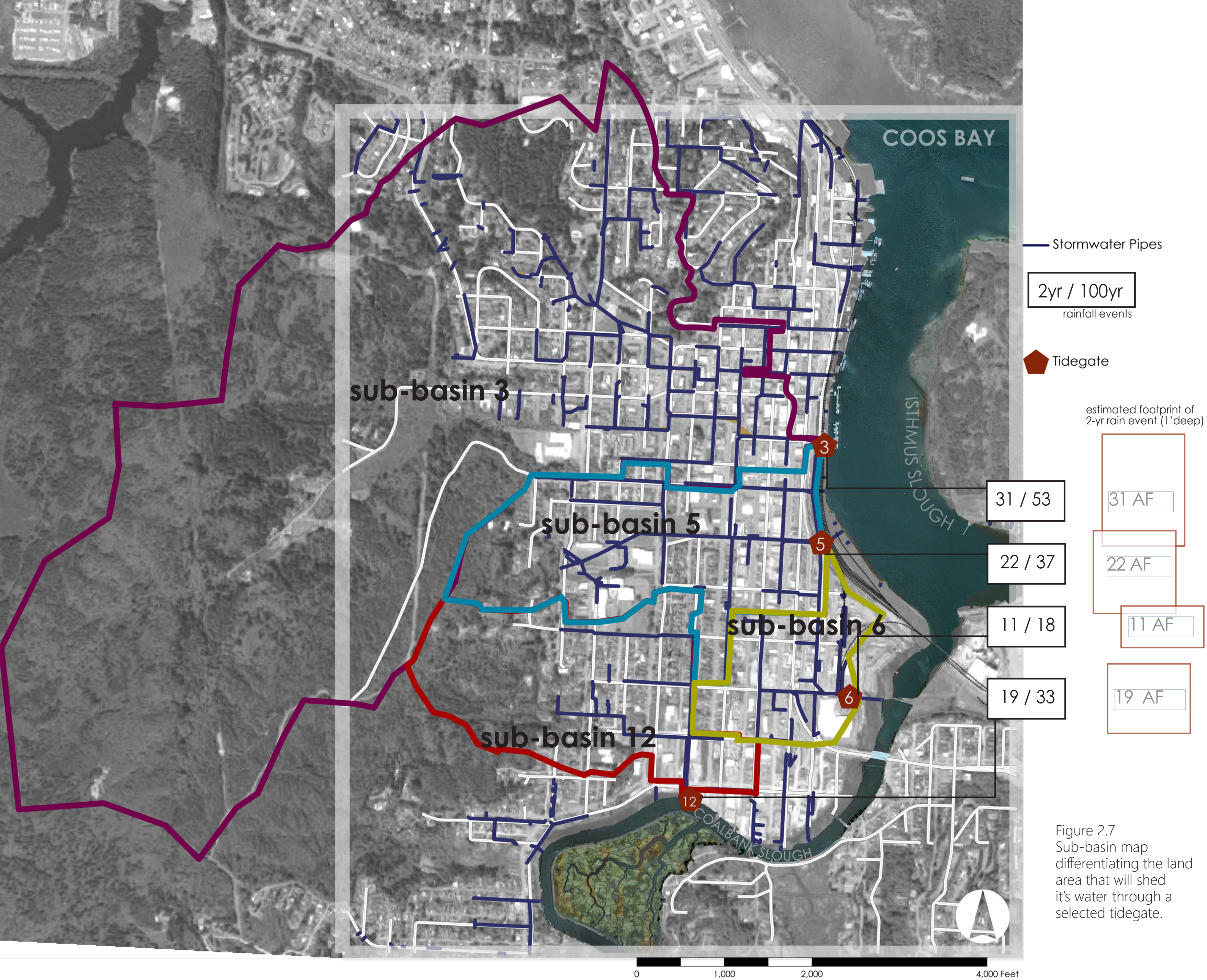


Figure 2.7
Sub-basin map differentiating the land area that will shed it's water through a selected tidegate.

Static protections cannot change with a changing climate. The dynamic processes of SLR redefine the relationship between inundation and inundation controls.

selected excerpt, p. 73

3

DON'T TIDEGATES AND LEVEES PROTECT DOWNTOWN COOS BAY CITY?


photo source: R. Ribe

3.1 How sufficiently are flood-prone areas protected via levees and tidegates?

This research has demonstrated where water would flow based on water level and topography. This research shows how those flows are projected change over time. At the study site in Coos Bay, levees and tidegates made development in the floodplain possible by building infrastructure that both drains and protects the land from tidal inundation (more on this in the included Primer, pp. x-xvii of this report). Without levees and tidegates to protect infrastructure here, Highway 101, public parks, the art museum, the Egyptian Theater will flood regularly by 2050 (Figure 4.6). We will explore the impacts of failing levees/tidegates in Chapter 4 but first we explore where and how these protections work.

3.2 How do these protections work?

Levees

Levees (raised embankments) offer a static protection from surge and sea-level. The yellow lines designate lands that currently function as levees (Figure 3.1). At the study area, many of the levees are topped with walking paths, a popular component of urban amenity along the waterfront.

The study area has almost 3.5 miles of levee with 1.2 miles protecting downtown Coos Bay (along the north bank of Coalbank Slough and the west bank of Isthmus Slough, Figure 3.1. These levees currently protect hundreds of acres of land within the study area. Structures at-risk are further explored in Chapter 4.

Topography that functions as levee provide a barrier to inundation. As seas rise, levee protections may need fortification to be effective. The levees between the slough and downtown range in elevation from approximately 9 feet to 11 feet at the low and high points, respectively. The relationship between predicted water levels, levee heights, and levee fortifications is detailed in Chapter 5, Figure 5.1.

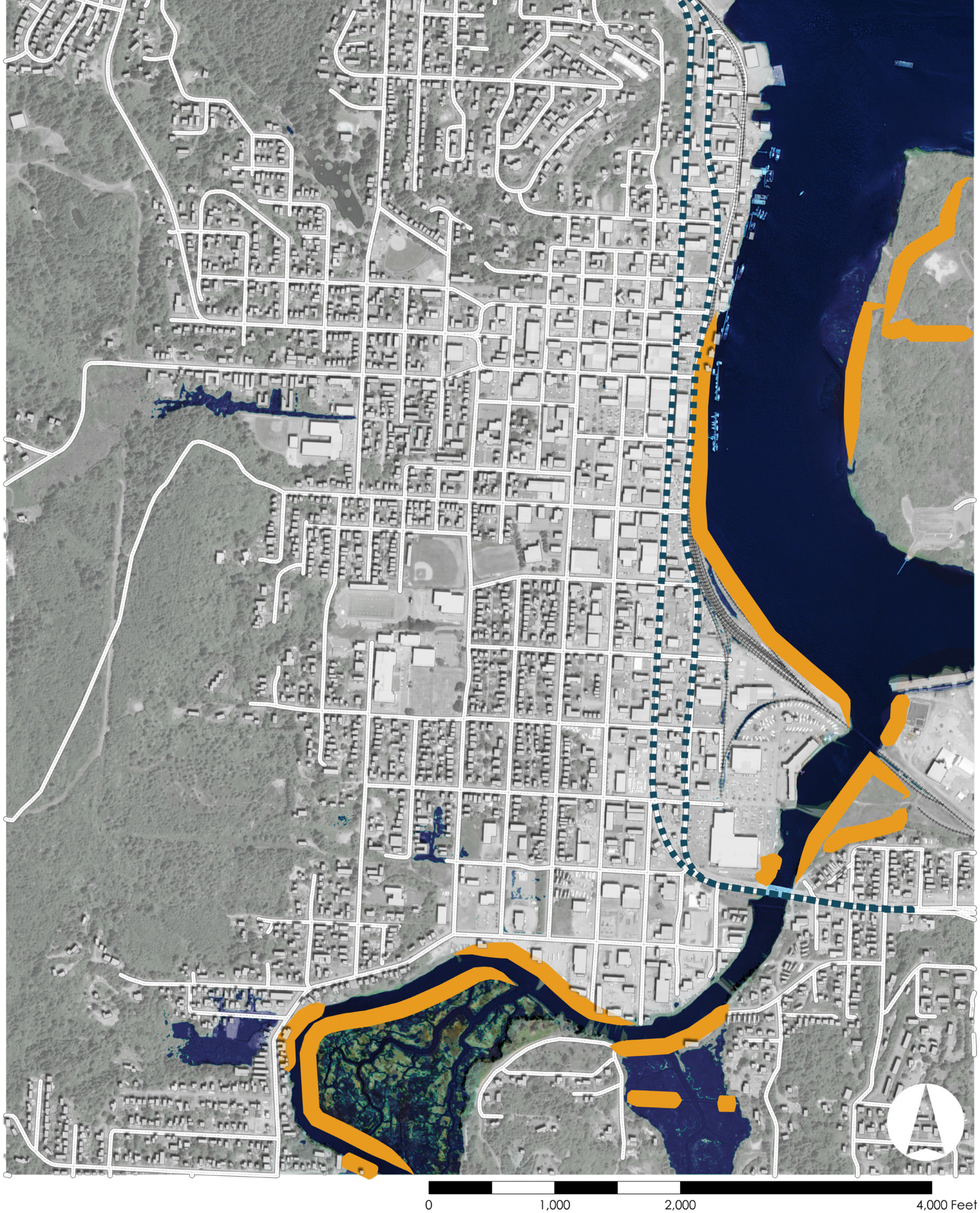


Figure 3.1
Topography that functions as levee, preventing water from flooding the city

Topography

Site topography prevents, directs, and channels water flow. It, therefore, defines flood extent and surface flows. Topography facilitated the mapping of sub-basins (Appendix C) and revealed stormwater flow. Topography defined where/when floodwater could breach levees. Additionally, as a tool for intervention options, incorporating natural/existing topography into planning can help avoid the expense of proposals that add or remove earth. It is easy to overlook that simply building at a higher elevation is itself a flood-protection strategy.

In this inset clip showing 2030 + Surges, Figure 3.2, one can see the relationship between topography as it defines the areas IN and OUT the floodplain.

Surface topography maps used here (Figure 3.3) are represented as one foot contours extracted from Oregon Department of Geology and Mineral Industries Bare Earth Lidar (2009). Detailed information on the creation of a one foot contour map is in Appendix A.

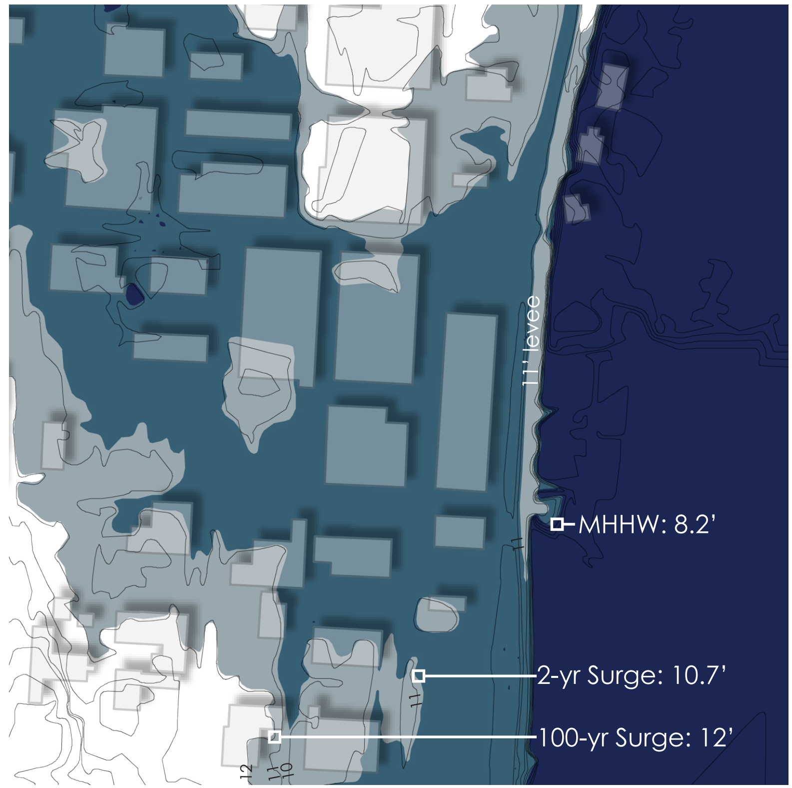


Figure 3.2
2030 + Surge inset demonstrating the relationship between one foot contours, the waterways, inundation levels, and the waterfront.

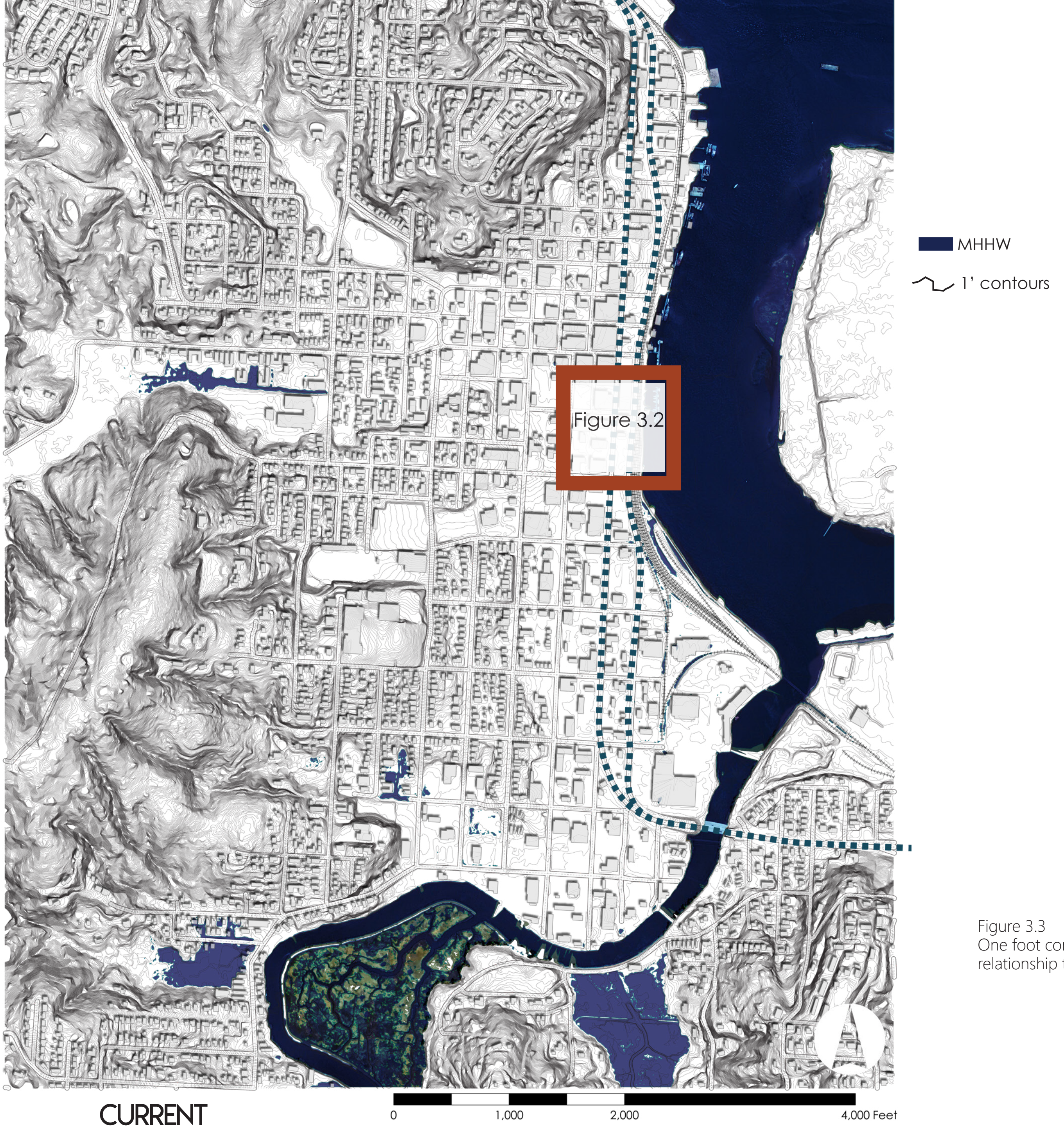


Figure 3.3
One foot contours and their relationship to the waterways

Stormwater + Tidegates

While the water flowing into stormwater pipes is a component of inundation, the pipes themselves are a protection tool. Current stormwater systems are sized for historic populations, historic rainfall rates, and historic sea level. In downtown Coos Bay, tidegates are embedded within levees or subsurface stormwater infrastructure.

Tidegates are a hinged cap that covers the end of a stormwater pipe. These gates are one-way valves that let stormwater drain at lower tides but prevent tidal waters from backflowing into the pipe. The tidegates found in the study area are "flap gates" that are hinged at the top and are forced open or held closed by water pressure. As demonstrated in the Primer (pp. x-xvii of this report), tidegates open when water pressure behind the gate is sufficient to force it open. This typically occurs when tides are low, creating greater pressure behind the gate, forcing it open. At high tide, the gate is held closed by the weight of tidal water pushing against it.

Under unprecedented but highly-predictable sea level rise, these tidegates eventually cease to function as estuary waters rise above the top of the tidegate. This condition is defined by a tidegate that is perpetually under the level of the tidal-waters. Under these conditions, tidal-water prevents tidegates from opening to drain urban stormwater. The result is rainfall that becomes a flood hazard as tidegates fail to function due to rising seas.

There are 16 tidegates within the study area. Tidegates with no number in the adjacent map, Figure 3.4, were excluded because of their location further from downtown and in proximity to a headland. The four tidegates that drain most of the study area, tidegates 3, 5, 6, and 12, were deliberately selected as posing the greatest future hazards and volumetric sub-basin analysis (mapped in Figure 2.7) were performed. The sub-basin map can be found in Chapter 2 and detailed process notes in Appendix C.

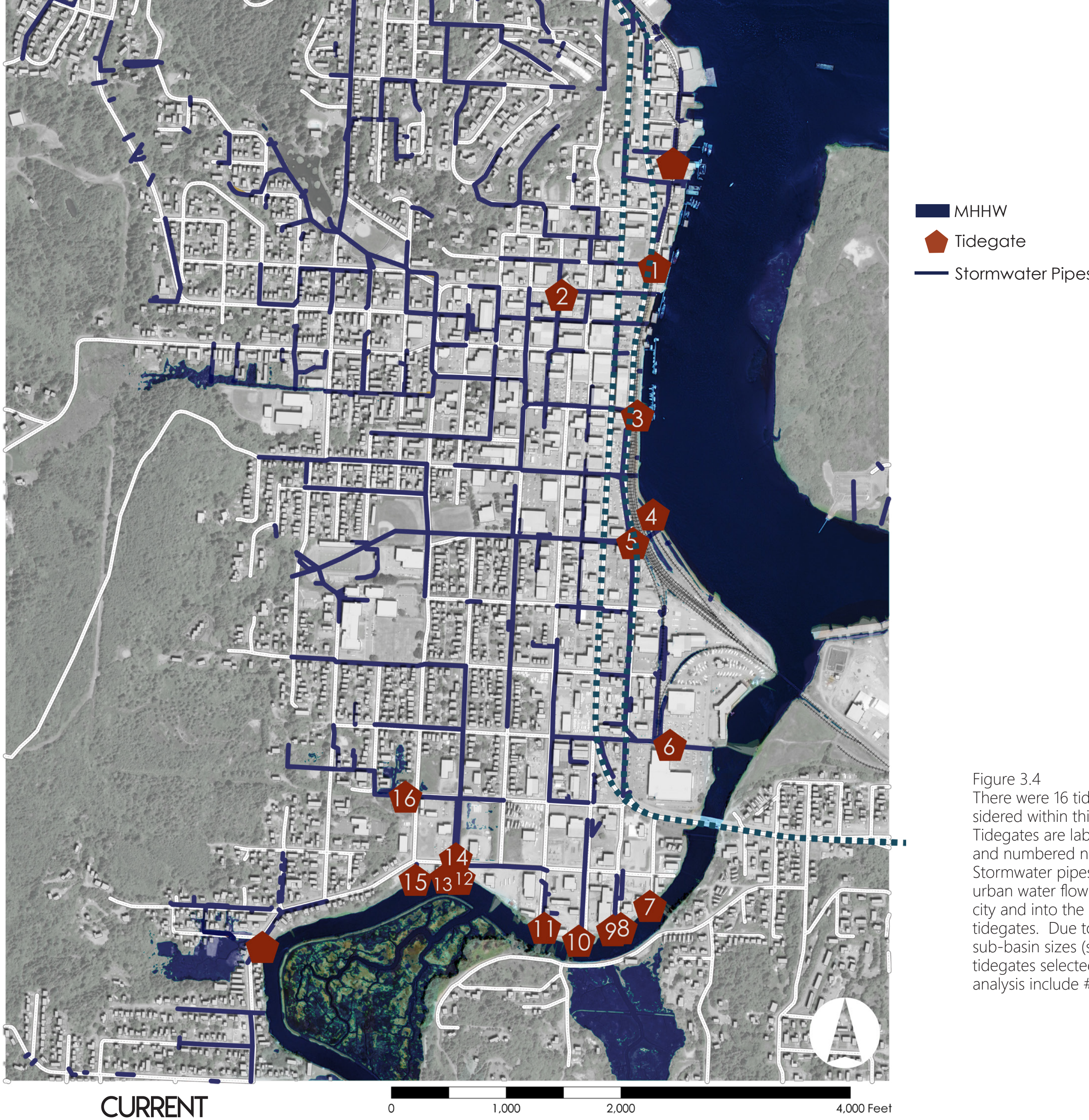


Figure 3.4
There were 16 tidegates considered within this study area. Tidegates are labeled in red and numbered north to south. Stormwater pipes (in blue) route urban water flows out of the city and into the bay through tidegates. Due to the large sub-basin sizes (see figure 2.7), tidegates selected for further analysis include #3, 5, 6, and 12.

We do not have *all* the answers,
however, we certainly have *enough* to begin the work.

selected excerpt, p.85

4

WHAT WILL BE FLOODED? FROM WHERE? WHEN? HOW OFTEN?

photo source: R. Ribe

4.1 What is the actual flood risk for downtown Coos Bay City?

We now have maps for inundation processes and structural protections that influence flooding for downtown Coos Bay City. So far, the maps have isolated a single process or structure. To map in context, components have to be combined and visualized to explore the relationship between inundation drivers, protections, and flood risks. Breaches and hazards emerge by analyzing the context maps. The following section will show the range of inundation risks under climate change by *combining* these data. The hazard maps in this chapter represent the spatial extent of probable flooding when including change through time, levee breaches, and tidegate failures. It, utilizing this information, then identifies infrastructure within inundation zones. Inundation thresholds (higher and lower water levels) are analyzed across a range of low-volume, frequent events to high-volume, infrequent events.

Providing a range of inundation scenarios follows the precedent set by current research for coastal planning (Nordenson, Nordenson, & Chapman, 2018). It provides a range of possible scenarios across a timeline rather than delineating "safe" vs. "at-risk" zones and puts local authorities in charge of decision-making. These data provide them information about how much risk applies to a city-scape. Mapping in this fashion reinforces the uncertainties of climate predictions and simultaneously visualizes the dynamism of water-flow processes and risks.

Static protections cannot change with a changing climate. With SLR, these static protections will have altered functionality as seas rise and protections fail. In Chapter 2, this research mapped inundation and its extents. Chapter 3 defined and mapped flood control structures. In this chapter, I combines inundation processes and protections to define hazards (unprotected structures) through time.

4.2 How will drivers and protections work through time?

Combining Data: Levee + SLR

Combining levee topography and inundation scenarios compares levee height to projected water height. Using the known levee heights (taken from topography data found in Chapter 3) and *SLR + Surge* maps, levee breach locations can be plotted. Predicted *SLR + Surge* offers probable water levels through time. Figure 4.1 summarizes tide, SLR, and surge event heights organized by water level. Each water level corresponds to the contour line that would breach under the specified event.

This map, Figure 4.2, identifies where levees heights are below water levels. In red are locations where levees are too short to protect against flooding for this inundation event. Note that when there is no map, there is no breach.

SLR + SURGE	water level (ft above datum)	breach height (topography elevation in ft)
2019 MHHW	7.5	7
2030 MHHW	8.2	8
2050 MHHW	9.0	9
2019 + 2 YR	9.9	9
2030 + 2 YR	10.7	10
2019 + 100YR	11.2	11
2050 + 2YR	11.5	11
2030 + 100YR	12.0	12
2100 MHHW	12.1	12
2050 + 100YR	12.8	12
2100 + 2YR	14.6	14
2100 + 100YR	15.9	15

Figure 4.1
By arranging surge events by the water level, the data allows an analysis of where levee heights are too short to protect the city-scape. All data measured from NAVD88 in feet.

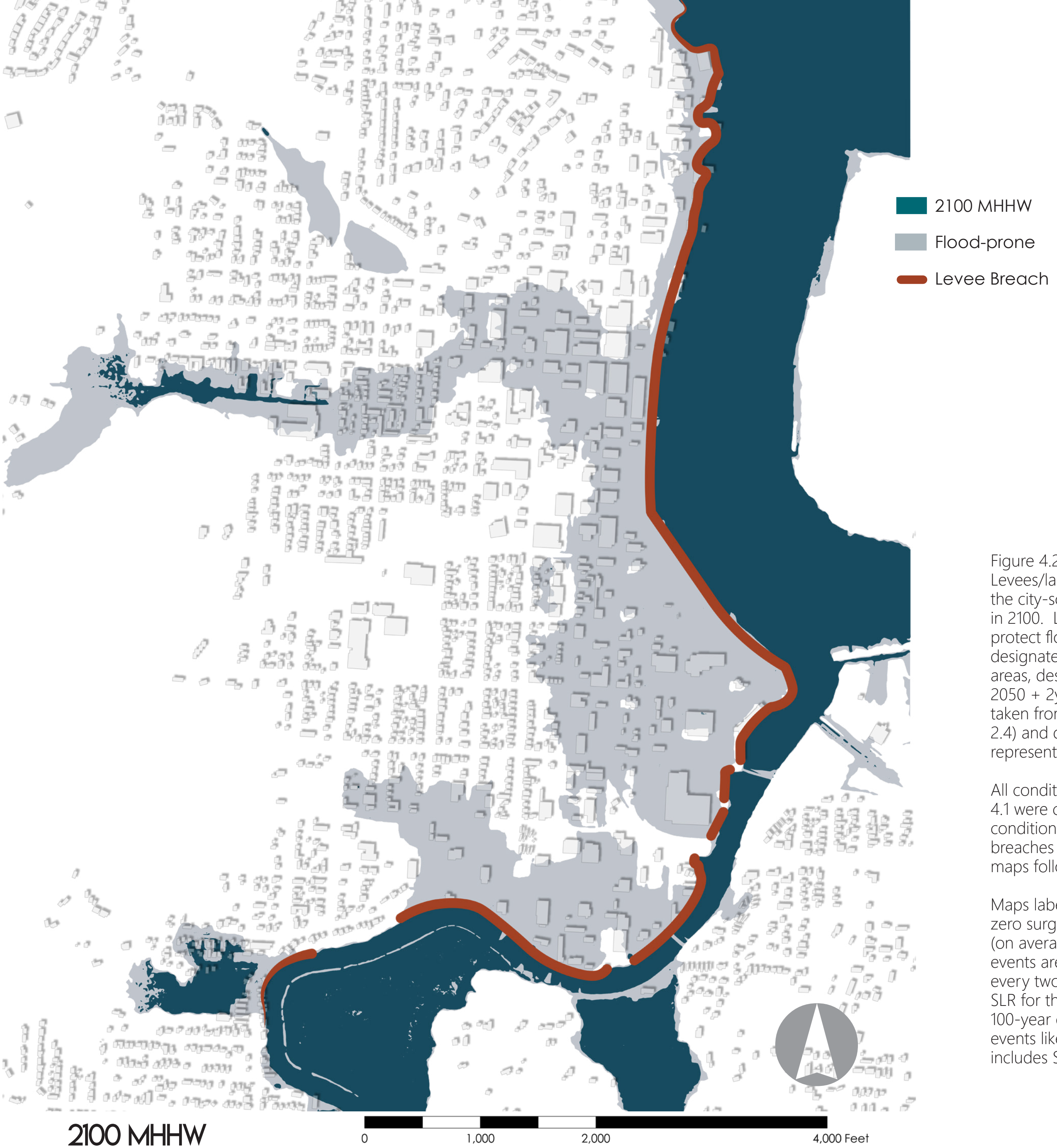
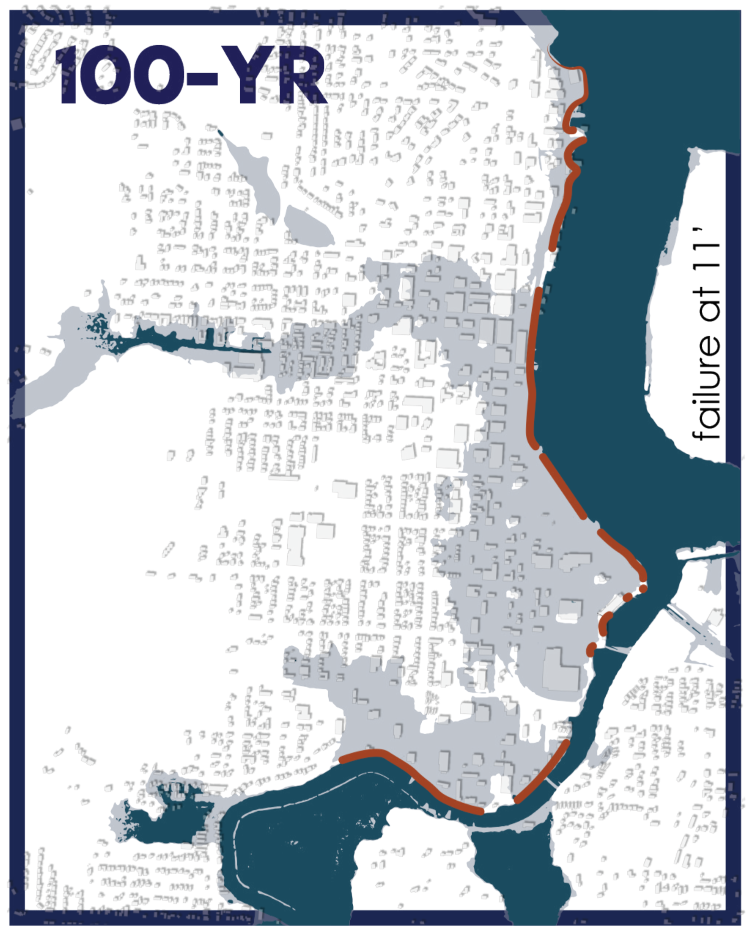


Figure 4.2
Levees/lands too low to protect the city-scape for MHHW in 2100. Levees too low to protect flood-prone areas are designated in red. Flood-prone areas, designated in gray, are 2050 + 2yr Surge extents (as taken from Chapter 2, Figure 2.4) and diagrammatically represents flood extents..

All conditions listed in Figure 4.1 were considered. Any conditions that resulted in breaches were mapped. These maps follow in figure 4.2.

Maps labeled MHHW include zero surge and will occur daily (on average). All listed 2-year events are surge events likely every two years and includes SLR for the given year. All 100-year events are surge events likely every century and includes SLR for the given year.

2019

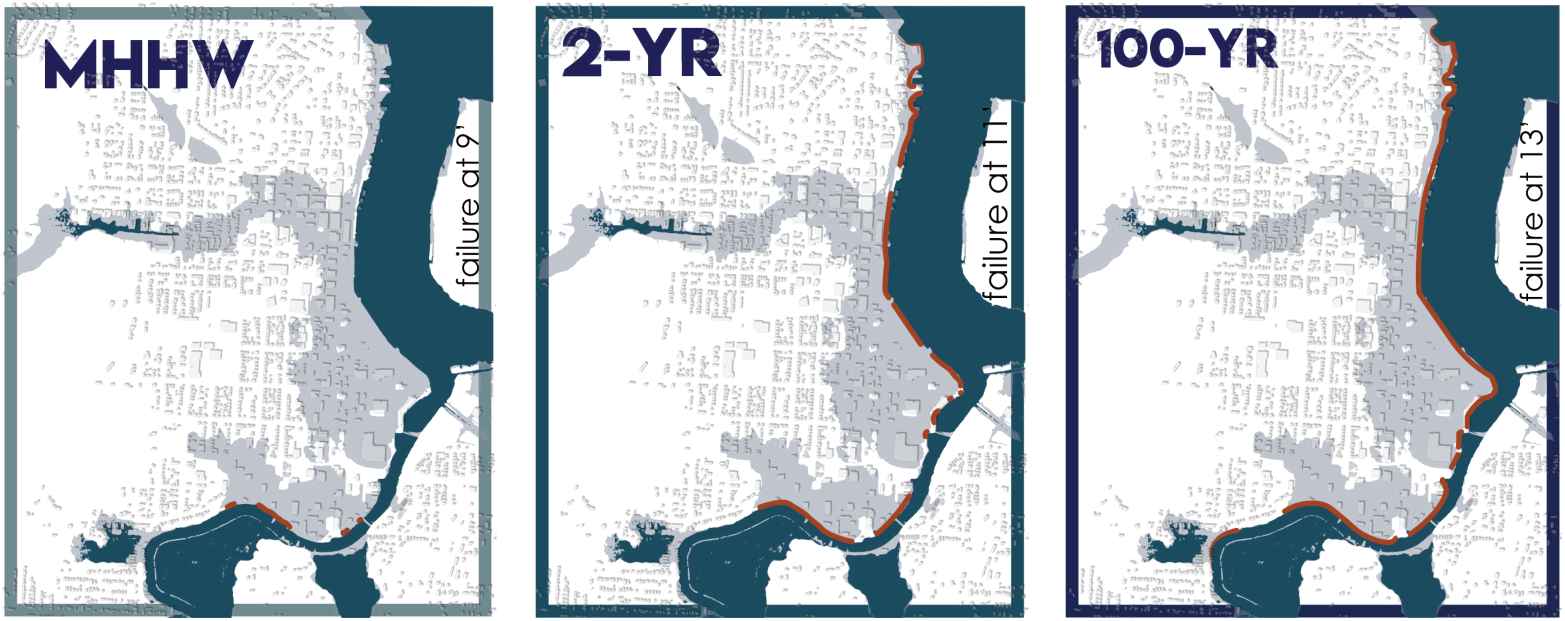


LEVEE BREACH TIMELINE

Figure 4.3
Levees too low to protect the flood-prone city-scape are designated in red. Diagrammatic floodplain where floodwater is likely to accumulate designated in gray. Each map is labeled with surge frequency (labeled on each map), extent of levee breaches (mapped in red), and plotted on a timeline (specified top left of each page). When there is no map, there is no breach.

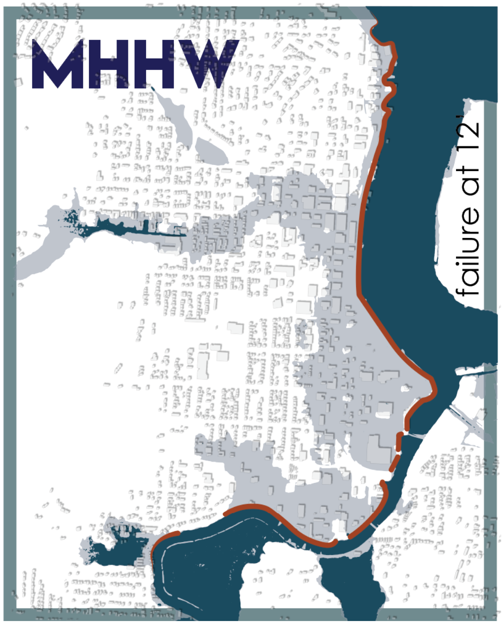
2030

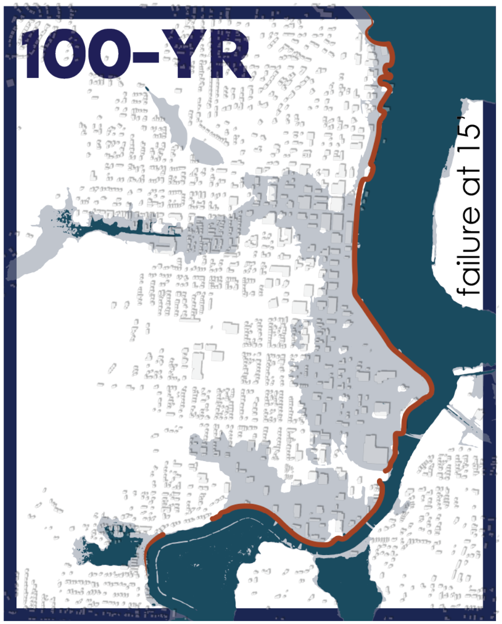
2050



LEVEE BREACH TIMELINE

2100





Combining Data: Tidegate + SLR

The previous Levee Breach Timeline in Figure 4.3 combined the spatial data of *SLR + Surge*, and levee heights. The combined map then defined where levee breaches occurred. In this section of the research, we combine the spatial data of SLR and tidegate function. When plotted together, tidegate depth, tidal fluctuation, and SLR clarify tidegate function through time. The following Tidegate Flow Timeline, Figure 4.5, defines where and when selected tidegates (#3, 5, 6, 12) may fail. While this series is unusual, the visualization process is effective and communicative.

A closed tidegate is unable to drain urban stormwater until enough pressure builds to push open the gate (details on this coastal interaction in the Primer, pp. x-xvii of this report). Wherever the tide is higher than the tidegate, the weight of the water holds it closed. Whenever this condition occurs, it is designated in red. So long as a tidegate drains at least once per day, it probably functions "well enough." When MLLW rises above the tidegate depth, it's perpetually closed and stops working.

The Tidegate Flow Timeline (Figure 4.5) plots tidal flux (blue line labeled "average tidal variation" in Figure 4.4) and the tidegate's top-of-pipe depth (horizontal red line). Figure 4.5 takes these data for selected tidegates and plots the interaction for one week (the x-axis) with depths in feet (the y-axis) for the selected tidegates. The purpose of this visualization process is to understand when the tidegate will be able to open and when it begins to fail. In the 2019 and 2030 scenarios, all selected tidegates are able to drain at least once per day (under typical conditions *with no surge*). By 2050, tidegates 5 and 12 are close to dysfunctional. By 2100, tidegate 3, 5, and 12 no longer operate or are close to being nonoperational.

Note that this Tidegate Flow Timeline *does not factor in surge*. This timeline accounts for daily tidal variation, tidegate depth, and SLR. These data clearly present functionality through time, allowing an analysis based on typical fluctuations.

This research assumed local tidal range will remain consistent through time. It is possible that an altered climate will change the projected timeline for inundation and tidegate failures though, to be clear, the failure is still highly probable but on an altered timeline. It should also be noted that tidegate aging and maintenance will play a significant role in tidegate function and longevity.

Based on data from Figure 4.5, it is clear that the city should target interventions at tidegate 5 and 12 because they are positioned to fail first. From this data a timeline emerges for intervention, as the overall duration of these failures show culmination around 2050. Finally, aging infrastructure is likely to play a major role in tidegate function by 2100 but these data also show ineffective tidegate function for three of the four major tidegates in this landscape.

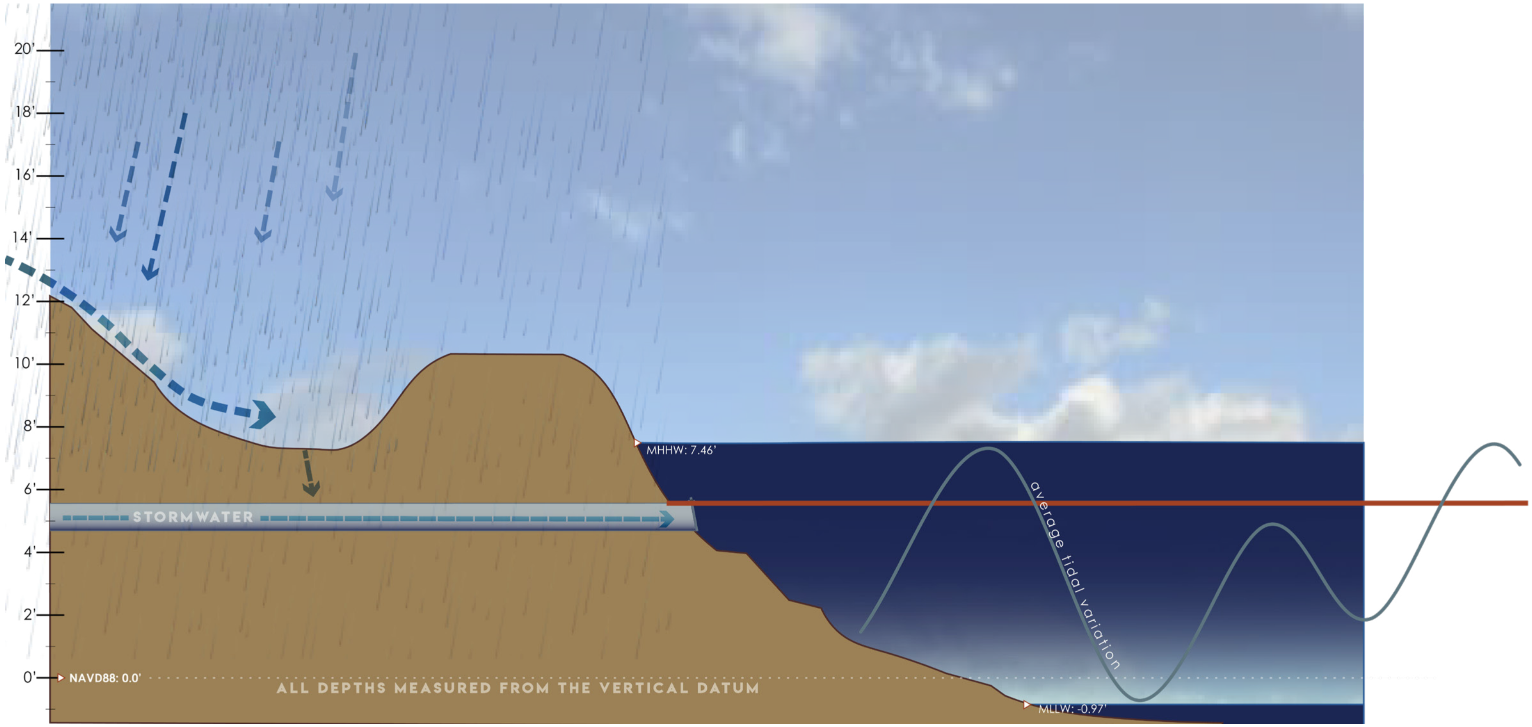
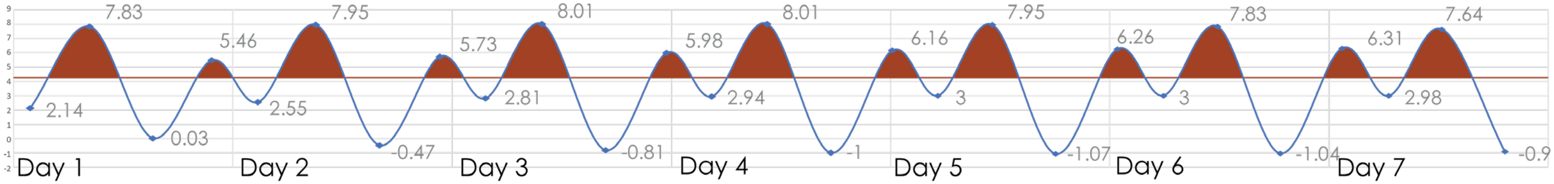


Figure 4.4
Tidegates open and can drain stormwater only when there is enough pressure to push it open. This can happen when tides are lower than the gate. The following visualization uses daily tidal fluctuation (the squiggly blue line) and the depth of the tidegate, the red horizontal line.

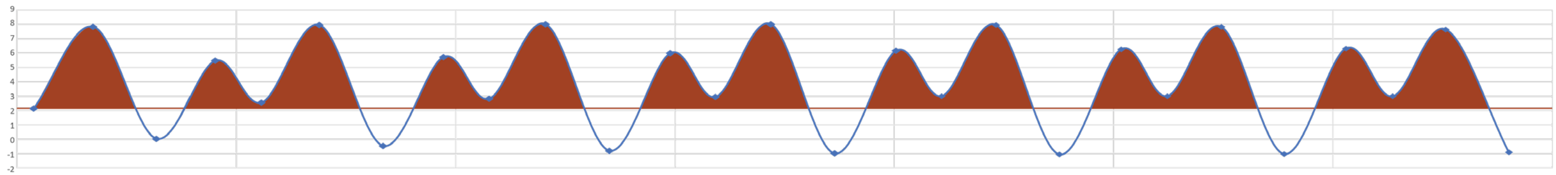
Figure 4.5 (subsequent pp. 69-71)
This Tidegate Flow Timeline Series combines data from tidal flows (in NAVD88 along the y-axis), tidegate depth, and SLR. Each year has four charts. Each of these charts shows the interaction between selected tidegates and water increases due to SLR. In each chart, the x-axis is one week of time. The specified tidegate top-of-pipe measurement is the horizontal red line. Tidally-influenced waters are designated by the curving blue line. Space filled in red represents times when a tidegate is likely to be held closed.

The amount of red correlates to the amount of time a tidegate is closed. As seas rise, stationary tidegates are held closed more often by higher bay-waters until they submerge (when top-of-pipe equals MLLW) and cease to function completely.

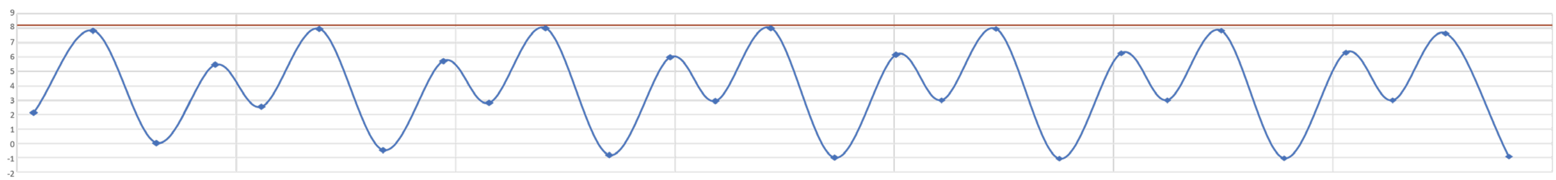
FLOW FOR TIDEGATE 3



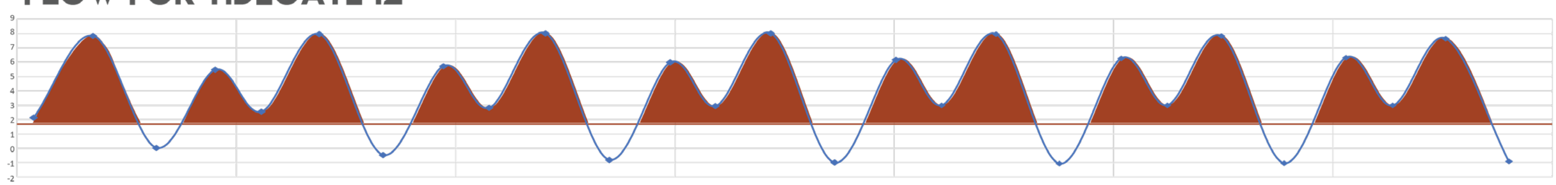
FLOW FOR TIDEGATE 5



FLOW FOR TIDEGATE 6

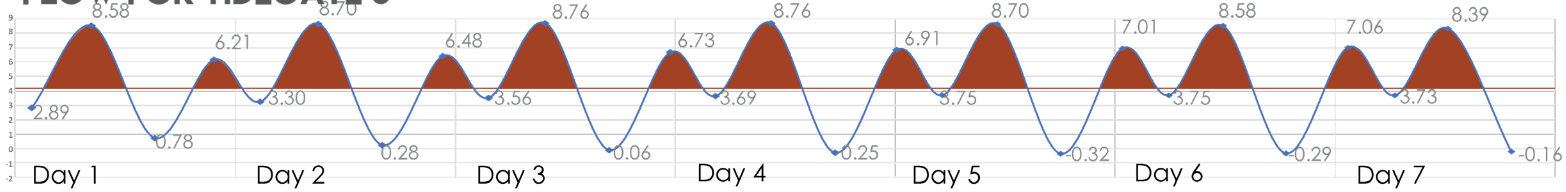


FLOW FOR TIDEGATE 12

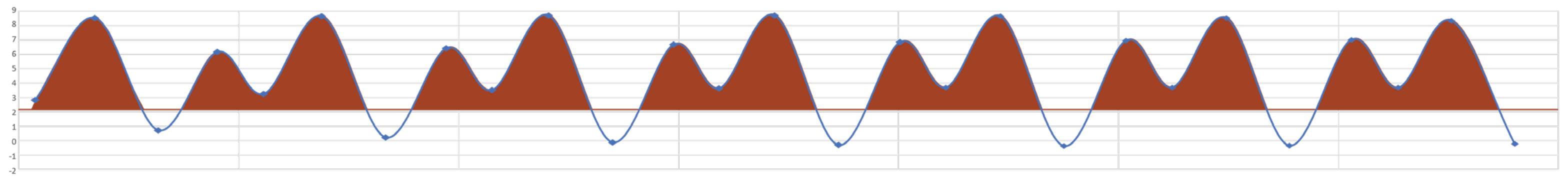


TIDEGATE FLOW TIMELINE: 2019

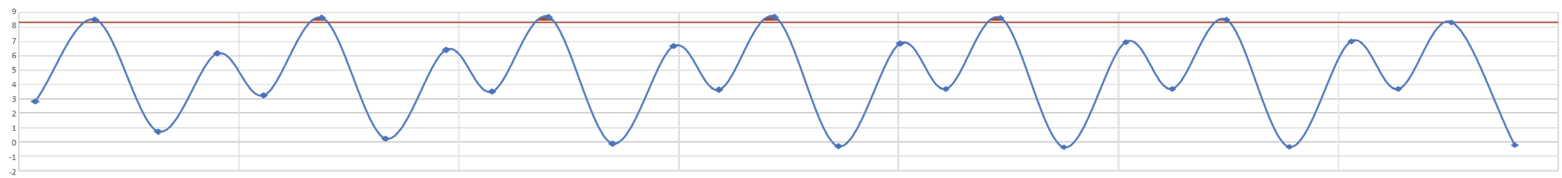
FLOW FOR TIDEGATE 3



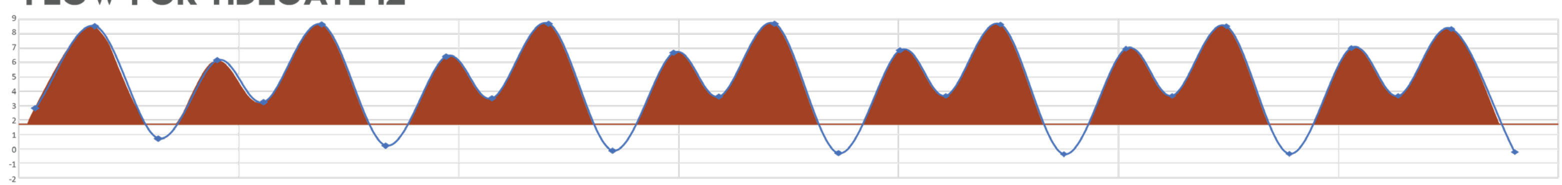
FLOW FOR TIDEGATE 5



FLOW FOR TIDEGATE 6

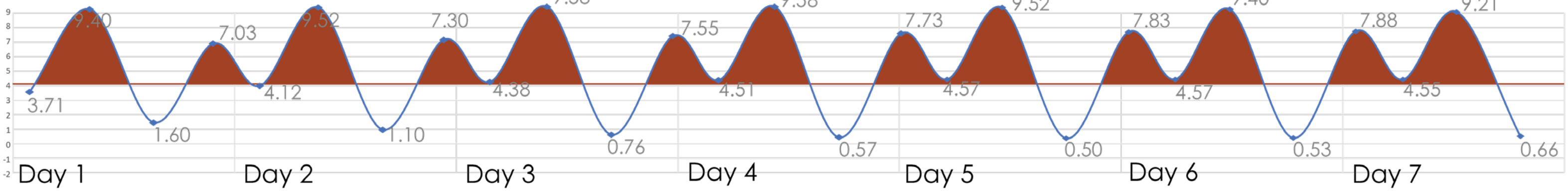


FLOW FOR TIDEGATE 12

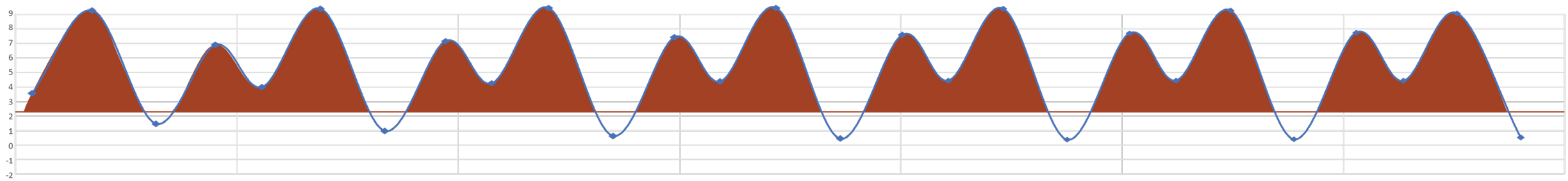


TIDEGATE FLOW TIMELINE: 2030

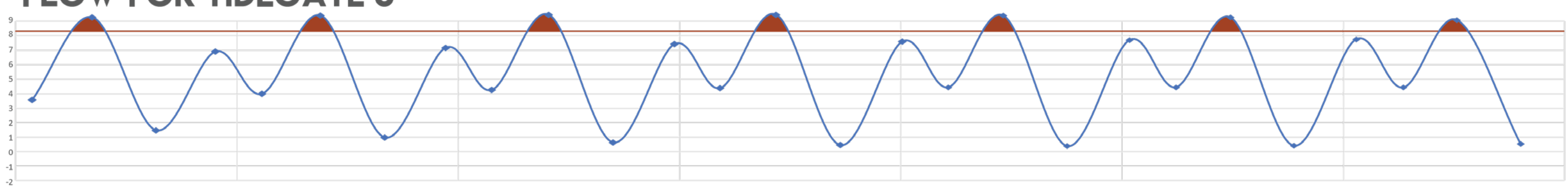
FLOW FOR TIDEGATE 3



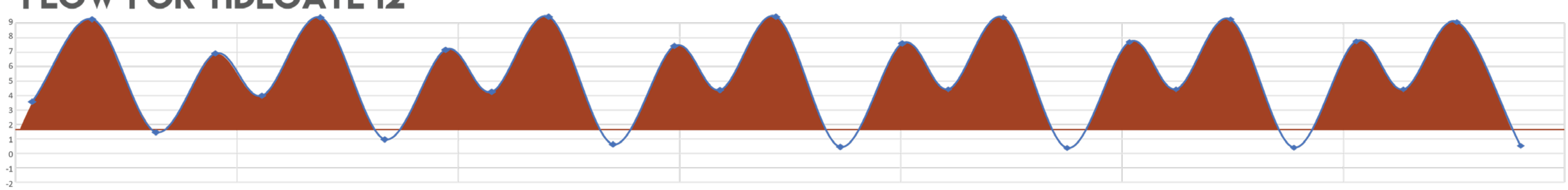
FLOW FOR TIDEGATE 5



FLOW FOR TIDEGATE 6

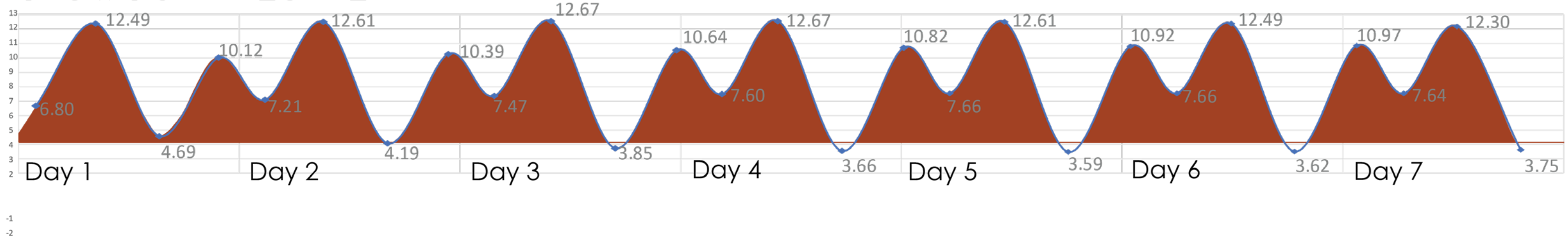


FLOW FOR TIDEGATE 12

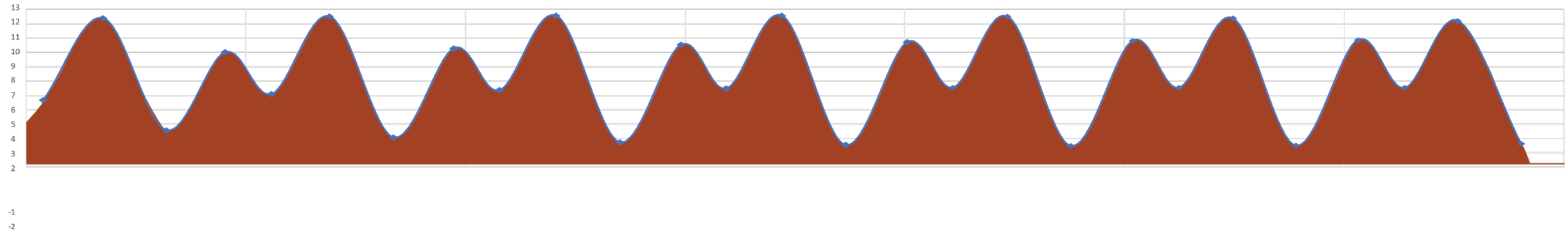


TIDEGATE FLOW TIMELINE: 2050

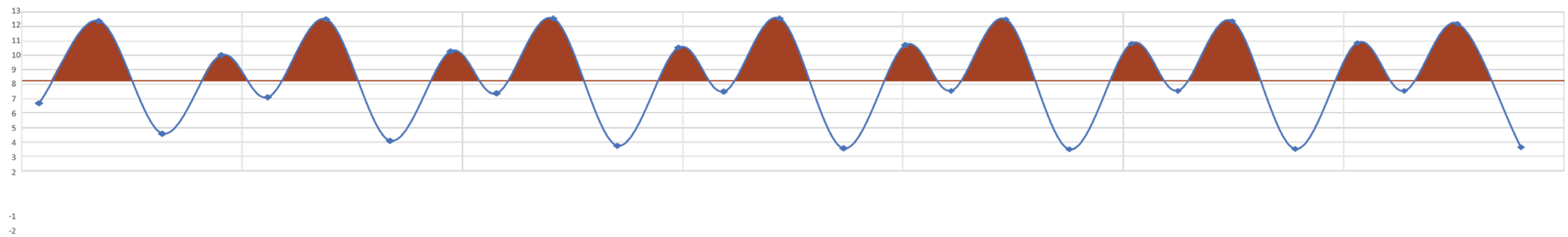
FLOW FOR TIDEGATE 3



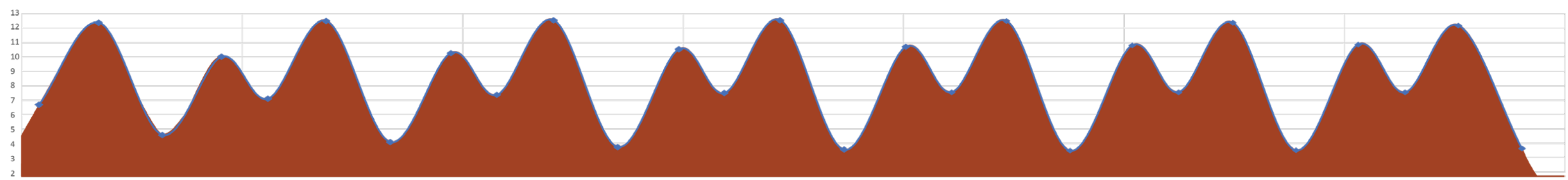
FLOW FOR TIDEGATE 5



FLOW FOR TIDEGATE 6



FLOW FOR TIDEGATE 12



TIDEGATE FLOW TIMELINE: 2100

Significant Structures

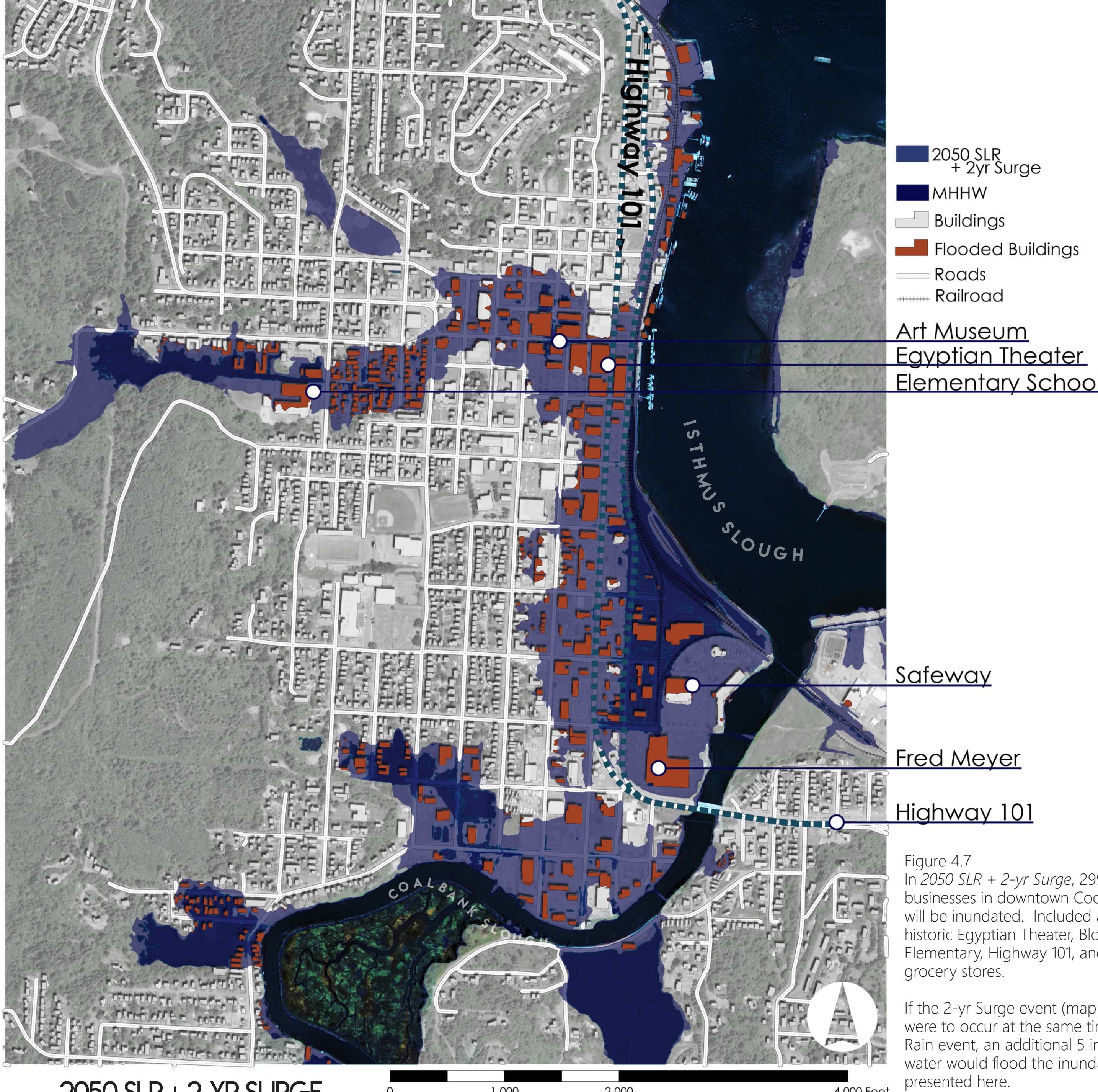
It is the protections for downtown, their interactions with inundation, and possible breaches that clarify when and how often structures are at risk of flooding. Knowing when and where inundation occurs allows an assessment of what is at-risk. Taken from the *2050SLR + 2yr Surge,* Figure 4.3 demonstrated that existing levees breach and flood low-lying areas across the waterfront. In this event, almost 300 buildings, several historic structures, major grocery centers, an elementary, and Highway 101 will flood (Figure 4.7).

Note that all significant structures occur within the northern area of inundation along Isthmus Slough and that the southern area along Coalbank Slough has fewer structures and is generally less dense. Using the levee timeline (Figure 4.3) and tidegate timeline (Figure 4.5), it is clear that under current conditions this landscape will experience 2-yr surge-events that overtop the levee by 2030, as well as rain-events that cause flooding behind tidegate 5 and 12 by 2050.

The at-risk infrastructure during 2030 SLR + Surge is summarized in Figure 4.6. Figure 4.7 visualizes the *2050 SLR + 2-yr Surge* event with its at-risk infrastructure.

Figure 4.6
Range of at-risk infrastructure for 2030 inundation extents.

INFRASTRUCTURE	2030 + 2YR	2030 + 100YR
Stormwater Pipes	6 miles	8 miles
Parks and Reserves	8.6 acres	8.6 acres
Buildings	298	416
Roads	6 miles	8.7 miles
Tidegates	16	18
Railroads	4 miles	4.8 miles
Total Acerage	213	305



2050 SLR + 2-YR SURGE

Figure 4.7
In *2050 SLR + 2-yr Surge*, 299 structures/ businesses in downtown Coos Bay City will be inundated. Included are the historic Egyptian Theater, Blossom Gulch Elementary, Highway 101, and two major grocery stores.

If the 2-yr Surge event (mapped here) were to occur at the same time as a 2-yr Rain event, an additional 5 inches of water would flood the inundation zone presented here.

Land Use

Along the waterfront, the site is dominated by industrial, business, and mixed-use zones (Figure 4.8). These land uses are disproportionately affected because they are in low-lying areas that were, in pre-development times, flooded by tides and/or storms. As above, there is slight increase in inundation extents with SLR and surge events over time because of their interaction with the topography. The reality of flood hazard correlates highly to placement, e.g. structures in low-lying areas adjacent to the water are at higher risk of flood. Levee/tidegate failures, if not adapted to changing water levels, will heavily impact these spaces (Figure 4.9)

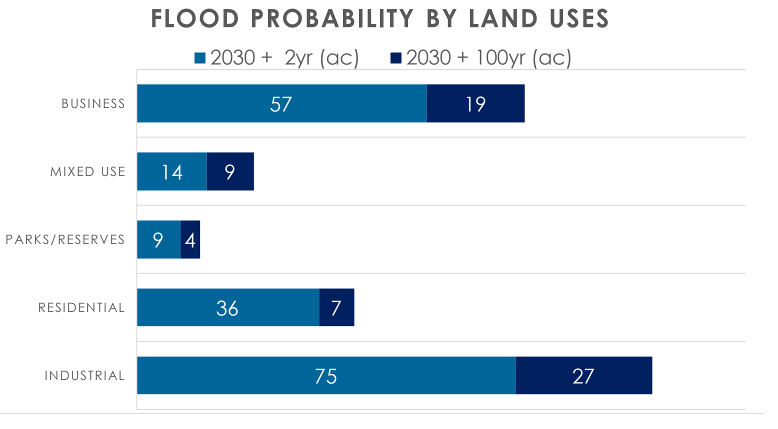
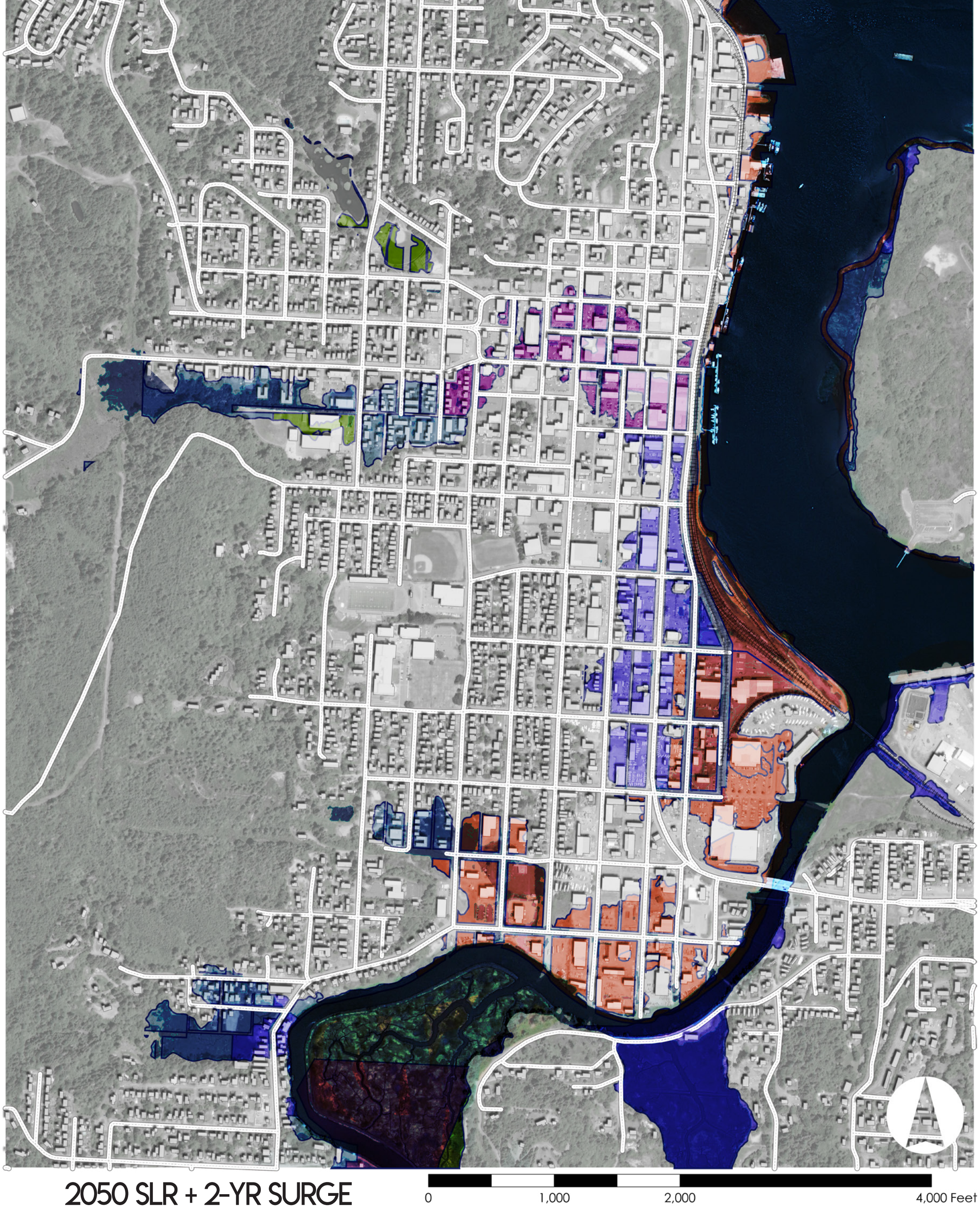


Figure 4.8 Acres flooded by land use types in a 2030 + 2yr event.



2050 SLR + 2-YR SURGE

- Business
- Industrial
- Mixed-Use
- Parks & Reserves
- Residential, Low Density
- Residential, Medium Density

Figure 4.9
All flood extents primarily affect the Industrial, business, and mixed uses adjacent to the waterfront.

Roads + Railways

Worthy of note for transportation infrastructure is that the major route in and out of downtown on Highway 101 (Figure 4.11) is at risk of inundation. There are alternate routes out of the city but a simple, clear evacuation route is necessary in emergencies. If improvements to levees and stormwater management are not made, an alternate evacuation route may be required. As is, clear access to essentials, available at Safeway or Fred Meyer (mapped in Figure 4.7) could be imperiled.

It is notable that the streets are 50' wide or more with little urban forest (typical aerial image in Figure 4.10).

Figure 4.10
Typical block surrounding the historic Egyptian Theater. Note the lack of street trees, wide streets, and parking area.

Figure 4.11
While transportation processes across the site may seem intuitive, street density is notable on two counts. One, identifying the major route (101 for this study site) is an essential component of coastal evacuation routes.

Two, given the density of road infrastructure in the study area, any resilient interventions to road infrastructure can spread along this dense network by updating specified construction standards.

“There is no bigger challenge today than the management of coastal ecologies.”

(Kimmelman, 2017, pg x)

5

HOW DO WE PREVENT FLOODING IN DOWNTOWN COOS BAY?


photo source: R. Ribe

5.1 Where and when are the targets for intervention?

It is the process of mapping, of defining the temporal and spatial contexts for each component, that builds an understanding of how each inundation process functions in the landscape. Based on topography and water levels, Chapter 2 contains mapped spatial extents of flooding for the selected test case in Coos Bay City. Chapter 3 defined what protections are at work and their spatial extents. These processes are each complex and dynamic, therefore, each factor must be defined, understood, and mapped within its unique landscape.

In Chapter 4, combining inundation and protection maps can allow this research to isolate at-risk infrastructure, physical points of failure, and project dates when interventions are needed. In this chapter, I define spatial and temporal points of intervention that emerge by evaluating the mapped data. From these data, I will offer possible intervention options that prioritize resilient, climate-ready landscapes and are uniquely targeted to the specific conditions of each emergent intervention site.

5.2 Critical points in space through time

Through the context maps, breaches and hazards are already emerging from the data. In 2030 with 2yr surge, there are a set of smaller breaches (designated with yellow boxes in Figure 5.2). By 2050, levee breaches require further fortification. The analysis within this report estimates that tidegates 5 and 12 begin to fail by 2050. By 2100, tidegates 5, 12 *and* 3 are failing and levee fortifications east of 101, to keep up with rising seas, must be raised 4 feet along its entire length.

Levee fortifiation lengths are specified on the maps in Figure 4.3 but the process of raising levee height poses an additional analysis opportunity. To fortify levees sufficiently in given scenarios requires existing heights and projected water levels. The required fortification height provides valuable information for selecting pragmatic interventions and alternatives. Estimates for levee fortifications are summarized in Figure 5.1. Note that levees east of 101 are already higher (typical base height of 11 feet), while levees west of 101 are currently lower (typical base height of 9 feet), and are treated separately (Figure 5.1).

5.3 Defining goals and options

It is clear interventions are necessary but what can be done about these hazards? What interventions make sense? Which interventions are responsible ones? Interventions proposed in this report are options that mitigate flooding conditions defined by this research data. They do not represent ALL options available but are a first-cut set of diverse options meant to support a resilient city-scape and healthy water-scape. This researcher would like to recognize that intervention implementation will be part of a larger, complex planning process undertaken by the city, county, stakeholders, and community members. This research aims to support that process by offering SLR risk maps along with pragmatic, functional, and resilient options.

Chapter 1 summarized goals selected from the EPA's suggestions for climate-ready estuaries (p. 11 of this report). I select interventions that are being implemented (or plan to be implemented) in other cities striving for resilience worldwide that meet these goals. This research completes two of the stated goals through the research itself: 1, plan and design for SLR; 2, define predicted flood zones. The selected interventions will meet the additional goals that include removing impervious surfaces, raising levees to accommodate rising seas, possibly managing retreats from floodplains, and prioritizing wetland protection and restoration.

To identify interventions from resilient cities, I looked at precedents taken from *Adapting Cities to Sea Level Rise* (2018). Options are noted in Figure 1.6. This is by no means an exhaustive list. It is, in fact, a short list that is, hopefully, perpetually expanding as we learn from existing interventions, develop new strategies, and redefine resilient infrastructure. The options in the following maps function to

SLR + SURGE	water level (ft above datum)	breach height (topography elevation in ft)	req'd fortification to water height: south of 101	req'd fortification to water height: east of 101
2019 MHHW	7.5	7	none	none
2030 MHHW	8.2	8	none	none
2050 MHHW	9.0	9	< 1'	< 1'
2019 + 2 YR	9.9	9	1'	< 1' (limited extent)
2030 + 2 YR	10.7	10	1' 8"	< 1' (limited extent)
2019 + 100YR	11.2	11	2' 3"	< 1'
2050 + 2YR	11.5	11	2' 6"	< 1'
2030 + 100YR	12.0	12	3' 0"	1'
2100 MHHW	12.1	12	3' 1"	1' 1"
2050 + 100YR	12.8	12	3' 10"	1' 10"
2100 + 2YR	14.6	14	5' 7"	3' 7"
2100 + 100YR	15.9	15	6' 11"	4' 11"

Figure 5.1
Water levels for SLR and surge scenarios, breach heights, and estimated additional height required to keep levees functioning under each scenario. Fortifications are separated by Highway 101 due to differing existing conditions and separation of inundation zone.

mitigate specific, targeted conditions but remain adaptable to future conditions. They maximize performance or functions (layering multiple-uses on one piece of infrastructure) over the life of the intervention and can be adaptable to future conditions.

In the next section, this research explores what intervention options match emergent targets. These offer resilient possibilities as planners and residents decide what to do as historically terrestrial landscapes become tidal water-scapes. These are a first-cut series of options relevant for this study area that meet the stated goals for estuaries that are climate-ready, pragmatic, functional, and resilient. Let's look at how these unfold through time and how planners can potentially intervene.

5.4 Targeted intervention options

Reducing impervious surfaces and providing stormwater detention/treatment supports a more climate-ready landscape (EPA, 2009). While it may currently be a daunting option, reclaiming parking lots for stormwater infrastructure and adding street trees accomplishes multiple goals simultaneously. It supports resilient design through adaptive green infrastructure, a climate-ready estuary by impervious surface reduction, and begins redefining a healthier urban relationship to the estuary *in collaboration* with climate change. These strategies can be employed across the study area as generalized resilient interventions. They can also function as targeted interventions that address localized flooding behind a particular tidegate.

2030

As explored in Chapter 4, levee breach timeline data suggests current levee heights suffice as flood protection under daily conditions (for daily tides in 2019 and 2030) but are insufficient for surge events analyzed (2-yr and 100-yr surge). Under current conditions through 2030, levee breaches occur on-average every two years and, consequently, pose a regular and debilitating hazard for businesses, industries, and residents within flood extents.

Analysis of Figure 4.3, the Levee Breach Timeline, reveals locations where levees require fortification and are identified in Figure 5.2. The largest target (southernmost) encompasses the extensive levee failures and connects to the inundation south/west of 101, whereas breaches east of 101 are small and protect a dense portion of business, industrial, and residential areas (refer to Chapter 4). Because the inundation areas are separate, they can be treated separately, a strategy that takes advantage of topography as a protection.

Given that regular 2030 breaches north of 101 can be prevented with relatively small levee fortifications and because these levees protect dense infrastructure, it follows that this site could maintain its protections. Additionally, by adding one foot of additional height (above mapped 2-yr breaches) to all levees east of Highway 101, this section of downtown is protected from up to 100-year surge events. These levee fortifications disconnect tidal waters from the northern inundation zone and prevent flooding due to surge.

For the large breaches along the south edge of the study area, this seems a site well-suited for returning to the floodplain. By managing a retreat here, the city could avoid fortification costs and choose to support resilience by removing impervious surfaces, restoring naturally occurring wetlands, and accommodating surge volumes.

In a precedent from “Water Proving Ground” (a project from P. Lewis, M. Tsurumaki, and D. Lewis), low-lying land that is regularly flooded due to SLR could be converted into a meandering waterfront with urban amenities that supports tourism, aquaculture, recreation, or wetlands. Through the removal of impervious surface and a cut/fill strategy, the city could dramatically increase the length of accessible waterfront, restore wetlands, provide a public connection to local waters, and support flood mitigation off-site. This approach begins with a planned retreat that moves at-risk structures away from the floodplain.

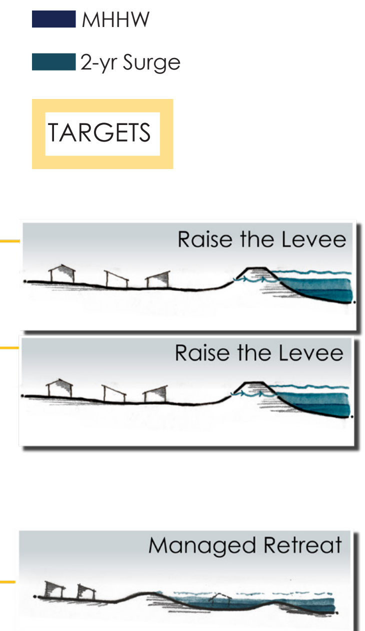


Figure 5.2
Levee targets for *2030 SLR + 2-yr Surge* intervention and possible intervention options that support goals stated in Chapter 1.

2050

The data in Chapter 4 also suggest current stormwater and tidegate infrastructure will be sufficient for most 2019 and 2030 rain/surge events. In 2050, the *Tidegate* Flow Timeline (Figure 4.5) identified Tidegate 5 and 12 failures by 2050. At this time urban stormwater may begin to frequently accumulate behind these tidegates, especially when surge events are added to the analysis (which this research *did not* include). Surge events occurring at the same time as rain events obviously being most problematic.

Figure 5.3 summarizes the targeted interventions for 2050 with specific focus on regular (2-yr rain and surge) events. To intervene in tidegate failures, I propose greening the street network by narrowing connector roads and adding a network of street trees. There is almost no urban canopy currently (Figure 4.10). Street trees intercept rain and decrease stormwater volumes. They are quickly being recognized as a vibrant component of resilient stormwater systems, but also support a diverse urban ecology, thriving economies, and social spaces. Street trees here could strategically be incorporated along drainage routes to tidegate 5, but would be an asset as a generalized layer of resilience throughout the city.

Additionally for tidegate 5, creating vault storage that can be pumped to the bay, prevents inundation in the shorter-term, could decrease urban sediment pollution in the bay, and affords the city time for long-range planning and/or code updates.

To address tidegate 12 in conjunction with the southern levee breaches, the managed retreat option could be phased to address hazards as they change through time. Early phases of the managed retreat could include constructed wetlands that manage stormwater runoff, ideally infiltrating rain-events on-site. This phased process involves a slow transition from current uses toward a crenelated waterfront and inundation zone taken from the precedent "Water Proving Ground" (discussed above). The transition could move forward with managed urban rezoning (2030), constructed wetlands (2050), recreation (2030 and beyond), industrial uses (current and continued), and/or aquaculture (2050). This slow transition is likely a longer-term option aiming for completion by 2050 (or later).

2-yr surges require eastern levees to be raised another foot of elevation (above *2030 SLR + 2-yr Surge* levels). Alternatively, protecting from 100-yr Surge requires about two feet (above *2030 SLR + 2-yr Surge* levels).

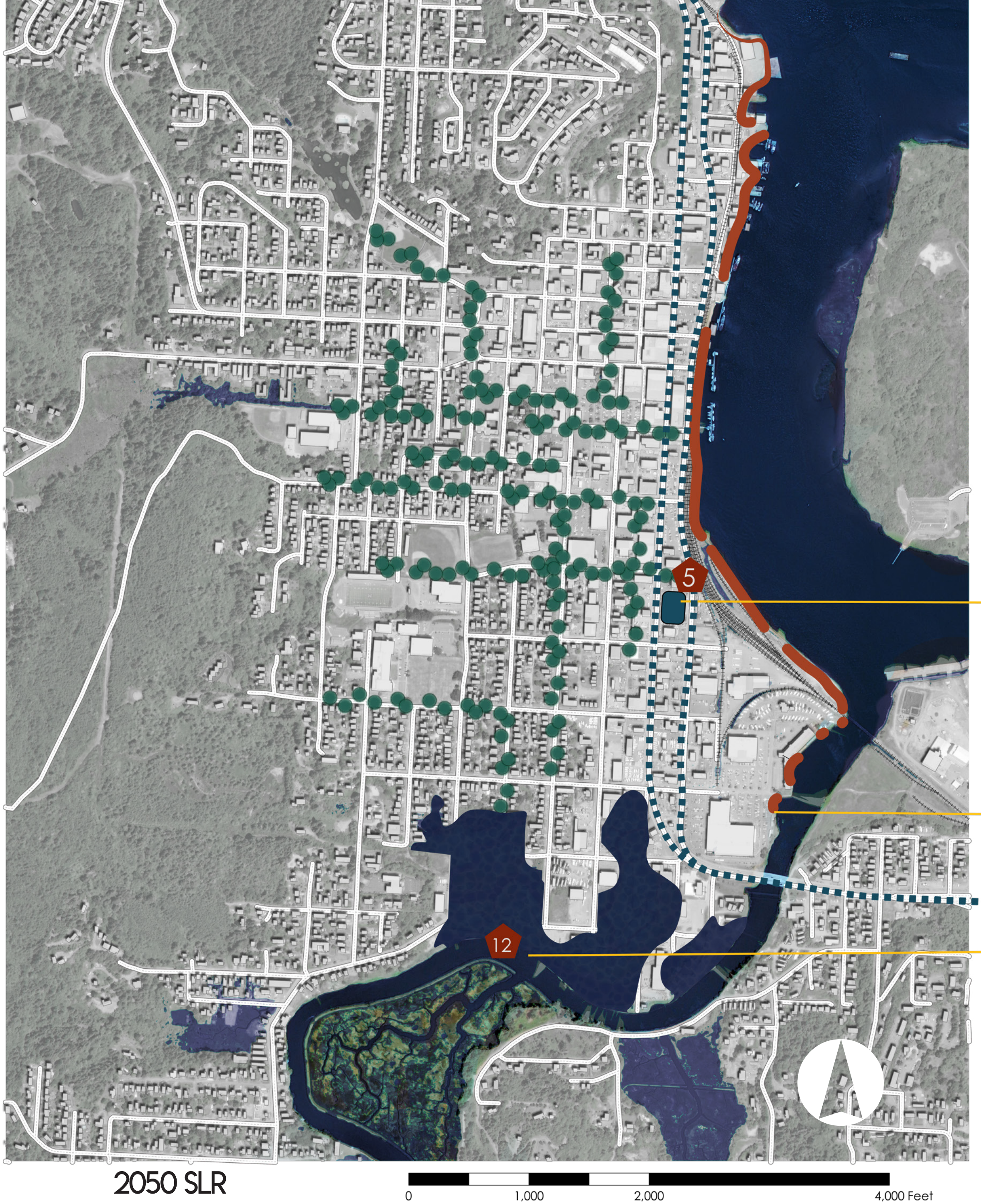


Figure 5.3
In 2050 flooding can be addressed with a pump to handle stormwater in rain and surge events. Levees east of 101 will need to be raised another foot above 2030 levels.. Managed retreat along the southern edge as this space is transitioned into a waterfront with wetlands as urban amenity.

Tidegate

Trees

Storage facilities

Levee Fortification

2100: Fortified Levee

Tidegates 5, 12 *and 3* are failing, a reality that requires expanded stormwater storage. Tidegate 5 and 3's sub-basin houses more intense uses and many significant structures. Accommodating and infiltrating the 2-year rainfall event (a volume of 22 acre·feet) requires a large detention footprint within the urban fabric. Precedents offer many potential options for where storage could go. Underground storage, surface storage, floodable parks, or wetlands are options.

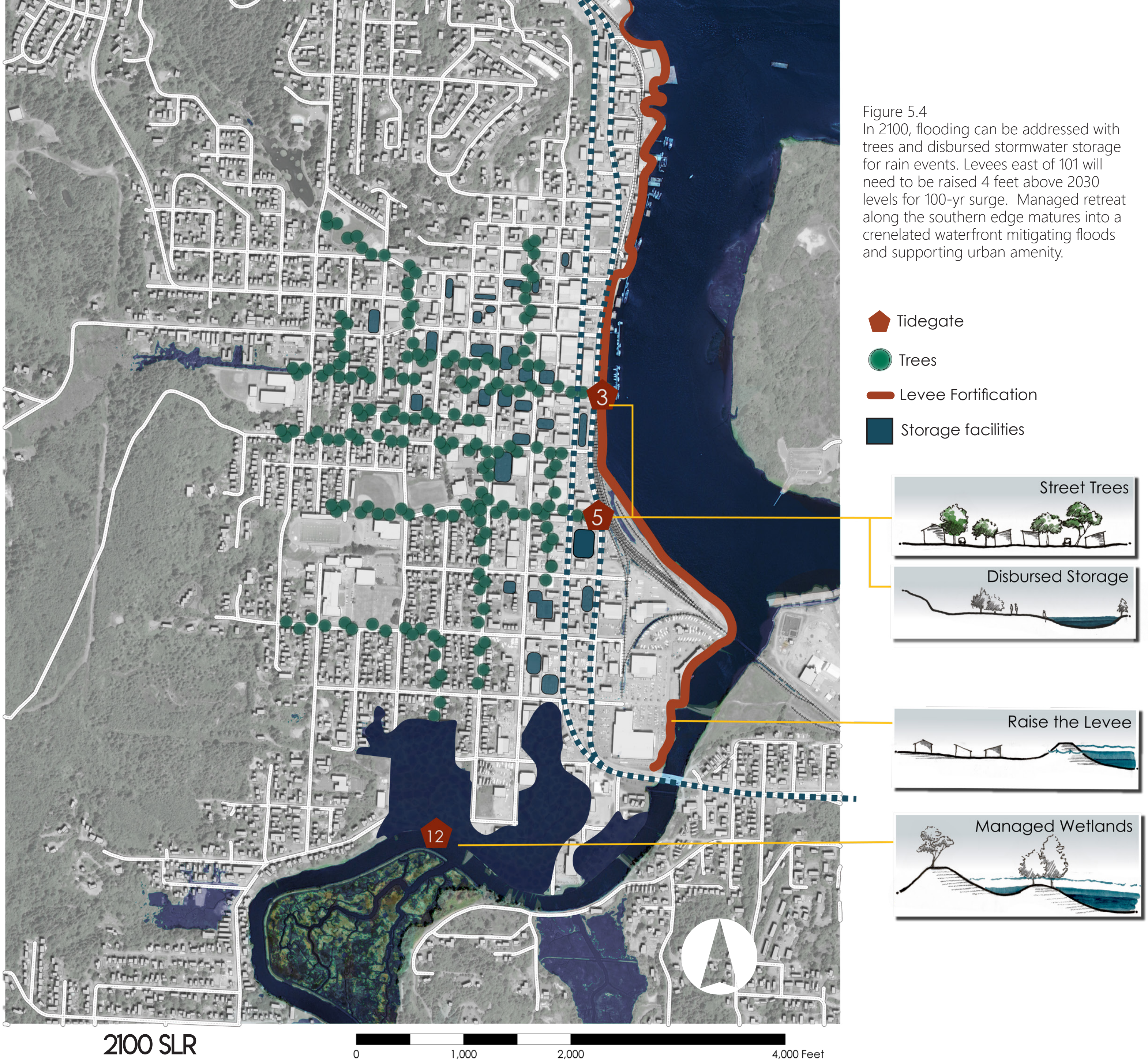
For this city-scape, planning to reclaim parking lots could provide enough square footage for a series of detention facilities (Figure 5.4). This process seems best suited for longer-term redevelopment codes, aiming for long-range planning beyond 2050. Within business and mixed use areas, selected sites would depave parking lots, converting them into stormwater storage that could double as urban greenspace, plazas, or walkways. Integrated stormwater systems slow and clean stormwater before being released to the slough. Walkways and greenspace with these new facilities support a vibrant cityscape and, hopefully, community planning could shape the forms Coos Bay chooses to implement.

At this time, street trees (if implemented to address 2050 stormwater volumes) are at maturity and continue decreasing runoff volumes. With the addition of disbursed storage facilities, most rain events should be infiltrated on-site. Larger rain events, like a 100-yr rain, would slowly percolate through this resilient system, overflow to the existing vault (seen in Figure 5.3), and finally be pumped to the bay.

Presuming levees east of 101 were raised to meet *2050 SLR + 2-yr Surge* requirements, fortifications east of 101, to keep up with rising seas, must be raised an additional three feet along its entire length for 2-yr surges. 100-yr surge protections require an additional 4 feet of fortification.

Is there an alternative to a 4 foot levee fortification? In alignment with the goals stated in Section 5.3, this project would like to consider an alternative strategy for 2100. In this next section, an exploration of ways to use pragmatic, functional, and resilient interventions increases the layers of levee function through time.

Figure 5.4
In 2100, flooding can be addressed with trees and disbursed stormwater storage for rain events. Levees east of 101 will need to be raised 4 feet above 2030 levels for 100-yr surge. Managed retreat along the southern edge matures into a crenelated waterfront mitigating floods and supporting urban amenity.



2100: Levee as Highway 101

The selected strategies in this alternative (Figure 5.5) support the same tailored approach that addresses the unique challenges of each intervention site. Emergent hazards continue to be paired with resilient interventions specific to the site's needs. This alternative brings the potential of decreased maintenance and infrastructure costs as two pieces of urban infrastructure (levee and highway) merge into one.

As road infrastructure ages and Highway 101 inevitably requires maintenance, it can strategically be elevated to function as the levee. If these two elements, levee and 101, are combined maintenance is required for one piece of infrastructure, rather than two. Elevating 101 facilitates tsunami evacuation routes and also allows uninterrupted emergency access to and from downtown during surge events. This option does involve managed retreat for the lands east of 101 and potential brownfield remediation. Beginning now allows planners time to develop a strategy for engagement, incentivizing, and/or zoning this space.

Previously mentioned interventions for tidegate failures in 2100 are still supported by this alternative that redefines Highway 101 as the levee.

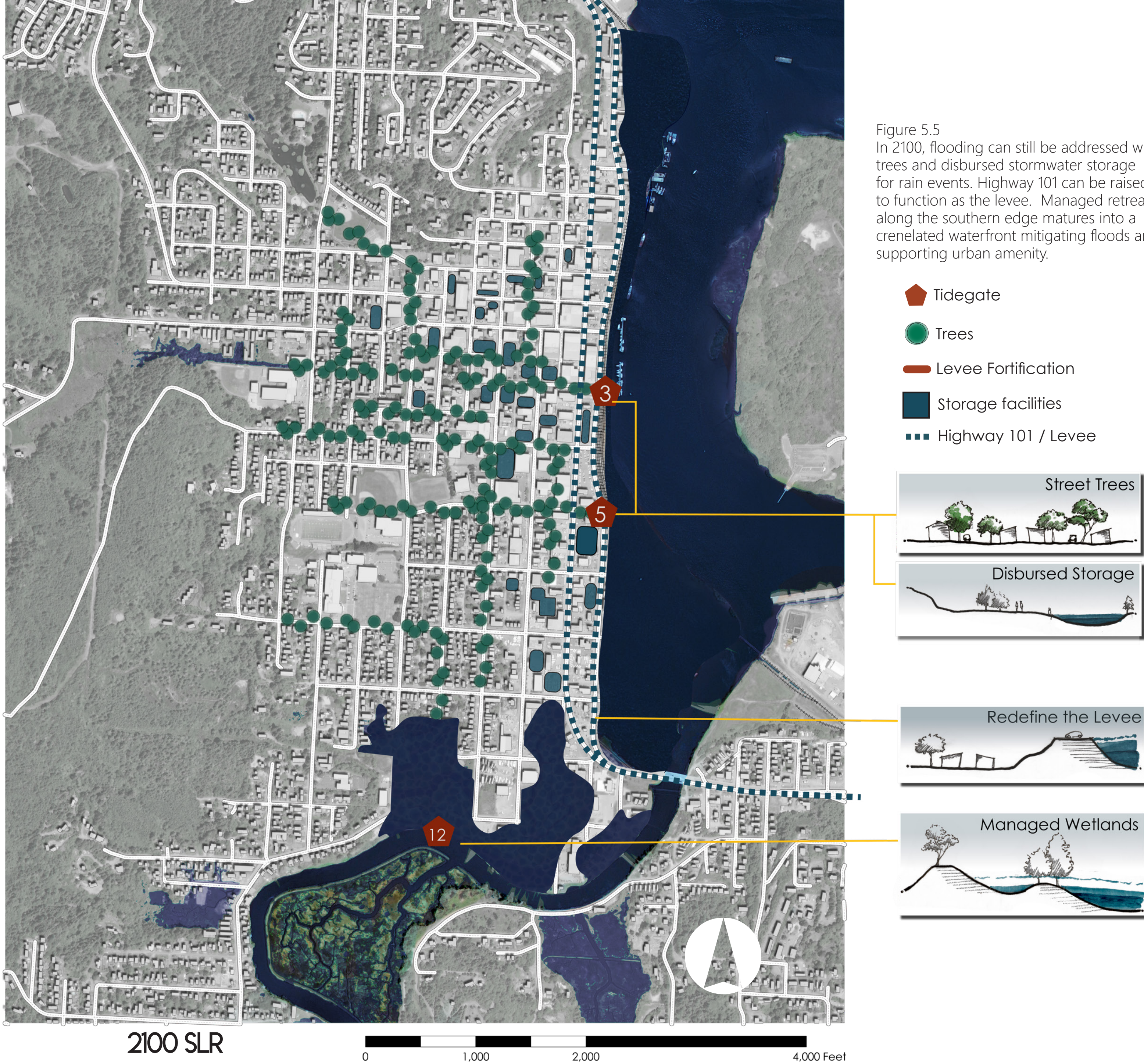


Figure 5.5
In 2100, flooding can still be addressed with trees and disbursed stormwater storage for rain events. Highway 101 can be raised to function as the levee. Managed retreat along the southern edge matures into a crenelated waterfront mitigating floods and supporting urban amenity.

6

DISCUSSION

What opportunities emerge for flood mitigation through mapping drivers of inundation and inundation controls? The framework for this research, at its core, uncovered the local complexities of urban flooding and flood processes. It is not always clear what drives inundation or when and where protections will fail. Following this project's framework at Coos Bay uncovered specific results for this particular location and reinforces the challenges of coastal urban planning. What is effective for one population at one time for a specific place will be a unique flashbulb in their shared history.

It is the mapping process that makes reoccurring challenges more obvious and opens a path toward targeted and pragmatic design options. By exploring inundation processes through mapping, opportunities to address hazards/breaches emerge from the spatial data. Each of these intervention sites then offers an opportunity to prevent urban coastal flooding on a timeline specific to that place. When maps explore how inundation drivers change alongside their associated static protections, there are emergent targets which highlight those intervention opportunities.

The framework presented here is very open-ended. My results and maps were guided by the unique landscape at Coos Bay as well as my own ideology, limitations, knowledge, curiosities... Nevertheless, I see this as an adaptable framework that is able to support hazard mapping and intervention options for other small coastal communities who may be resource-limited. Given my own constraints and the results that came from this work, I think the presented framework is an especially useful tool for under-resourced rural communities that still have to face the challenges of rising seas.

It is clear that this framework, specifically addressing inundation, may not be sufficient for other coastal locations. Many coastal cities are faced with critical challenges related to sedimentation, coastal erosion, and river migration. Modifying this framework such that additional sub-questions are addressed, such as questions of wave run-up or sedimentation, could generate a new series of targeted maps, hazards, and intervention options relevant for a new place.

It is clear that with additional components, the step of generating context maps becomes more complicated. To systematize the process of context mapping, a map of how components are interconnected could clarify the process.

Defining the interactions between each process by visualizing (mapping) it will clarify which processes relate to each other, how they relate, and will isolate which context maps are needed for a study site.

This work also served to remind me that when protections are static, it is critical to consider their lifespan. Where will they be in 20 years? In 80 years? Is is appropriate for future generations to bear the cost or ecological burdens of out-dated infrastructure? Are there infrastructure options that bring vibrancy and health to future human and non-human communities? It is notable that resilient infrastructure is adaptable, non-static, and evolves *with* the changing climate. It, by definition, anticipates, prepares, and adapts to changing conditions, functioning from construction to retrofit.

Following this mapping framework for Coos Bay also draws attention to a stark reality. This is not a challenge that will resolve with time. The reality of rising seas is that problems compound. The hazards begin affecting more people, more often, more frequently. Honestly, we simply do not have all the answers we need to address anticipated hazards.

That is true. We do not have *all* the answers. However, we certainly have *enough* to begin the work. We know resilient designs adapt with changing conditions. We know the pricetag of interventions today will support more resilient infrastructure for future generations and landscapes. Future communities are going to be part of a world where climate change is a reality, where communities live with the compounding realities of sea level rise, aging infrastructure, and coastal flooding. We are currently making decisions that impact how large those climate challenges will be.

I admit that this project has been an eye-opening experience for me. I admit that not everyone will dedicate a year of work and research to dwelling on resilient coastal design. I admit that this work is difficult and complicated and ever-changing. I also know that there are others who are passionate about bringing good, equitable, vibrant systems into the world. To them I say, "thank you for your work." I look forward to seeing you engage with your own communities. You are the supports that will shape the infrastructures of the futurev and the systems that bind us together.

APPENDICES

APPENDIX A: GIS PROCESS

Projection

Aligns with Regional SLR research.

All maps are in/using:

NAD 1983 OR Statewide Lambert Feet International

Datum: D_North_America_1983

Vertical Datum:

NAVD88

Contour Extraction (1 ft contours) from Digital Elevation Model (DOGAMI 2009

Toolbox

>3D Analyst

>>Raster Surface

>>>Contour (in be42134c2, out contour_1, int 1 (ft), base 0, Z 1)

Smooth contours

Toolbox

>Cartography Tools

>>Generalization

>>>Smooth Line (in contour_1, out contour_Sm1, alg Pael, Tol 20)

Simplify contours

Toolbox

>Cartography Tools

>>Generalization

>>>Simplify Line (in topoSm_1, out topo_1 (N or S), alg Bend_simplify, tol 20)

Manually deleted contours <200’ in length.

Manually deleted small enclosed, “noisy” contour lines for clarity (~200 ft2 or less).

Clips:

Maps are clipped using border4

Border 4 manually generated to enclose the selected study area

Clip representative example:

outfall_exhibit_pt reprojected as outfall_CB, outfall_CB clipped as outfall)

Generated Inundation Maps

Including: 2019 MHHW

2030 MHHW

2019 Sea Level + 2-yr Storm Surge

2019 Sea Level + 100-yr Storm Surge

Data from OR_MFR_slr_data_dist using the DEM (be43124c2).

Example: 2030 MHHW

Tool box

>spatial analyst

>>reclass (Reclass 0 - 7.46 -> 1, all others NoData)

Yield: mhhwRECL

From Raster to Polygon

conversion Tools

>From Raster

>>Raster to Polygon (In mhhwRECL, Value 1, out MHHWpoly, simplify ON.)

Smooth Polygon

>Cartography Tools

>>Generalization

>>>Smooth Polygon (in MHHWpoly, out MHHW2030, Alg Paek, tol 20)

Manual delete of all polygons less than 200 ft2

APPENDIX B: TIDEGATE CALCULATION

Tidegate Depth

This research generated tidegate inverts (the elevation of the bottom of the pipe) by measuring them in the field and/or extrapolating tidegate depths from outfall inverts when necessary. Where tidegates were accessible, the invert depths were measured directly (as specified in Figure B.1 below) by this method. Using the 1-foot contour map that was extracted from a DOGAMI digital elevation model (DOGAMI, 2009), surface elevations are drawn. These surface elevations function as reference elevations. From the reference elevation, a laser level drew a level horizontal line to a tape measure or surveying rod set at invert depth. The tape/rod measurement is subtracted from the surface elevation to determine invert elevation. Measurements were taken to the nearest inch with estimations to the nearest foot, so that the inverts' significant digits correlate to the reference topography, thus representing a more appropriate margin of error.

TIDEGATE #	Type	Diameter (ft)	invert NAVD88	top of pipe	Measured
1	flap	4	3	7	directly
2	flap	3	2.84	5.84	outfall
3	timber flap	9' x 6'	-1.75	4.25	directly
4	ND	ND	ND		ND
5	ND	4	-1.9	2.1	outfall
6	ND	5	3.235	8.235	outfall
7	ND	ND	ND		ND
8	ND	ND	ND		ND
9	ND	ND	ND		ND
10	ND	ND	ND		ND
11	ND	ND	ND		ND
12	flap	2	-0.25	1.75	directly
13	flap	3	-1.46	1.54	directly
14	ND	ND	ND		ND
15	ND	ND	ND		ND
16	ND	ND	ND		ND

Figure B.1
Invert depths (in NAVD88, feet) are the bottom of the tidegate depth. Top-of-pipe measures are generated by adding the diameter (or height for tidegate 3) to the invert depth.

Tidegate numbers correlate to Figure 3.4.
*ND = no data

Many tidegates were under steel plates, were situated underneath roadways, or were otherwise inaccessible. Indirect measurements were taken for these stormwater outfall inverts were taken at the slough or bay (specified "outfall" in the Collected Tidegate Data Figure). Using the outfall invert depth (measured), diameter (observed), distance from outfall to tidegate (via Google Maps), and the recommended slope (figure B.2, taken from the Stormwater Master Plan design specifications for the City of Coos Bay), the presumed tidegate depth can be calculated (in feet) as follows:

Slope = (tidegate invert – outfall invert) / (Distance from tidegate to outfall)

Table 7.1.2 – Recommended Slopes for Storm Drains (ft/f
(Based on a Manning's 'n' of 0.013)

Nominal Pipe Diameter (in)	Minimum Slope (2 fps)	Recommended Slope (3 fps)
10	0.0025	0.0055
12	0.0019	0.0044
15	0.0014	0.0032
18	0.0011	0.0025
21	0.0009	0.0021
24	0.0008	0.0017
27	0.0007	0.0015
30	0.0006	0.0013
36	0.0004	0.0010
42	0.0004	0.0008
48	0.0003	0.0007
60	0.0002	0.0005

Figure B.2.
(Source: City of Coos Bay Stormwater Master Plan, pg 7-3)

Tidegate Flow Timeline

To generate data about tidegate flow failures plotted along a timeline, I began with selecting a representative sample size of one week. This is sufficient to provide some variation and visualize the trend but also of reasonable scope for master's work. Here is the selection process and reasoning following the research Q&A format.

Q: When are tides highest for Coos Bay?

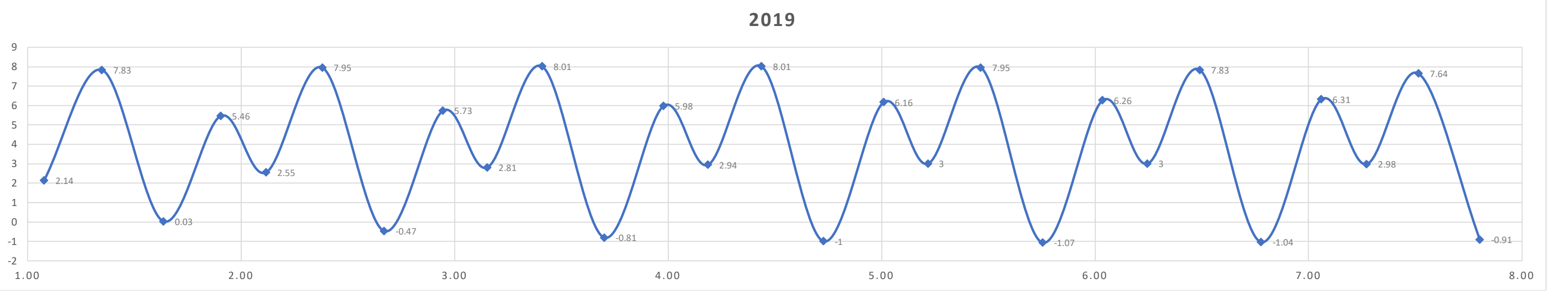
A: January (Figure B.3, taken from https://www.tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9432780)

Q: Does this date align with high seasonal precipitation (e.g. the need for tidegate drainage)?

A: Mostly: highest precipitation months are November, December, and January (figure B.4)

Q: For a one week sample in January, what does tide fluctuation look like?

A: (data taken from https://tidesandcurrents.noaa.gov/noaatidepredictions.html?id=9432780)



Q: How much will SLR increase tidal depths?

A:

	SLR
2019	0
2030	0.75
2050	1.57
2100	4.66

Using the tide levels from NOAA (tidesandcurrents.noaa.gov/noaatidepredictions.html?id=9432780, 2019), top-of-pipe depths, and predicted SLR, Figure 4.5 summarized the interaction of these features for 2019, 2030, 2050, and 2100. The x-axis designates depth in NAVD88 plus appropriate SLR through time. The y-axis is plotted for one week, labeled by day. Areas marked in red represent points where the tidal water prevents the tidegate from opening. This occurs when the water level is at or above the top-of-tidegate depth. The upper boundary for each graph is tide water depth. The lower boundary is the top-of-tidegate depth (figure B.1).

Readers should note that portions of the chart marked in red, e.g. times the tidegate is closed, is a conservative measure.

It is highly likely the tidegates will remain closed for longer periods even before water levels reach the top-of-gate depth. Greater specificity will depend on the volume of stormwater behind the gate, the depth of tidal water, the weight of the gate itself, and the friction of gate hinges. Future research and modeling to determine basin-specific flows will be invaluable in site-scale design.

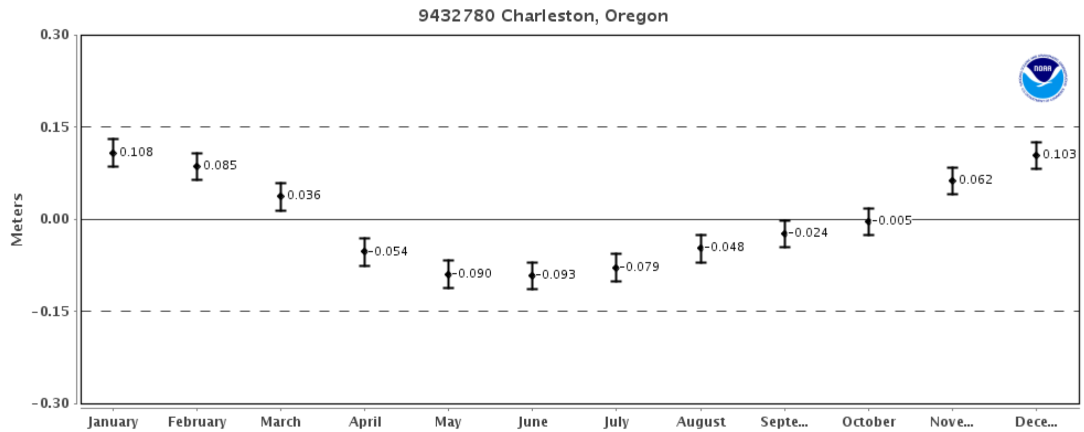


Figure B.3.
Seasonal Mean Sea Level the mouth of the Coos Estuary (from https://www.tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9432780)

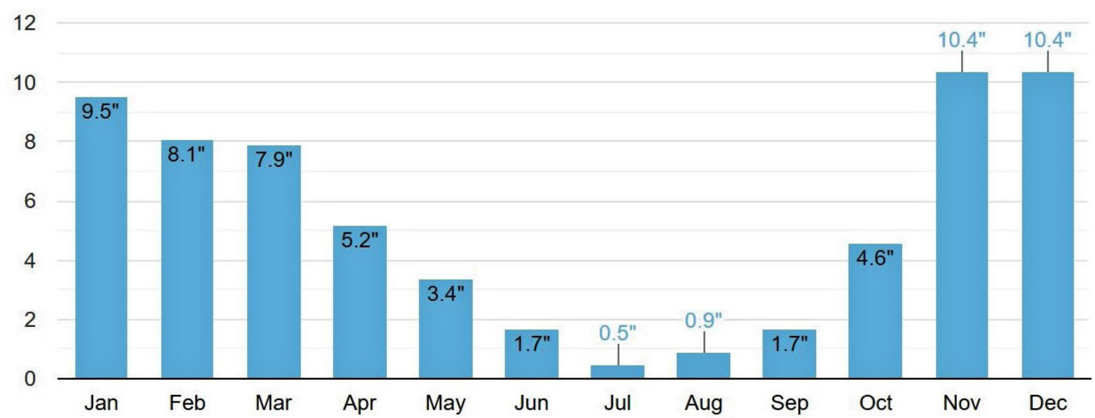


Figure B.4.
Monthly average rainfall for Coos Bay, OR (from https://www.weather-us.com/en/oregon-usa/coos-bay-climate, accessed 02 Apr 2019)

APPENDIX C: STORMWATER VOLUME

Four tidegate-basins were selected (basins draining through tidegate 3, 5, 6, 12) because they drain a respectively large portion of downtown. The goal of sub-basin boundary mapping was to define what lands will drain through a selected tidegate and the subsequent flood hazard IF a tidegate ceases to function. This research presumes seasonal rainfall rates will change only slightly due to climate change. Current projections support this assessment for seasonal rain/snowfall trends (Figure C.1), thus, current rainfall rates are sufficient to provide a conservative estimate of runoff for all rainfall predictions.

Sub-basin boundaries define the area where runoff will be generated behind the selected tidegate. To calculate volume, the sub-basin area provides the two-dimensional measurement but requires a depth to define the volume. Once the sub-basin (the defined drainage area) is known, the rainfall rates provide water depth. This allows stormwater volumes to be calculated for each sub-basin. Volumes were calculated by the following formulas and then summed to yield total volume per basin. The selected sub-basin boundaries (Figure 2.7), runoff coefficients (figure C.2), and rainfall rates (documented in the following).

Each Basin is the sum of:

Volume per Business Land Use = (Land Use Acres)*(Runoff Coefficient)*(Storm Depth)
Volume per Mid Density Residential = (Land Use Acres)*(Runoff Coefficient)*(Storm Depth)
Volume per Low Density Residential = (Land Use Acres)*(Runoff Coefficient)*(Storm Depth)
Volume per Industrial Land Use = (Land Use Acres)*(Runoff Coefficient)*(Storm Depth)
Volume per Mixed-Use Areas = (Land Use Acres)*(Runoff Coefficient)*(Storm Depth)
Volume per Open Space Land Use = (Land Use Acres)*(Runoff Coefficient)*(Storm Depth)
Volume per Road Land Use = (Land Use Acres)*(Runoff Coefficient)*(Storm Depth)

Quantifying Acreage (1, 2, & 3), Coefficients (4), and Storm Depth (5)

1. The sub-basin boundary map and volumetric flow totals are found in Figure 2.7. Sub-basin boundaries were determined manually using the extracted 1-foot contour map (DOGAMI 2009) and a USGS 7.5-minute topoquad (2017). Delineations were made based on apparent water flows from higher to lower elevations.

2. Using GIS, sub-basins were divided into their respective land uses and acreages documented. Except for roads, all land use

determinations were taken from the DLCD (all sources are available in Appendix E) .

3. Road acreage was determined using the length of roadway (given by ODOT, sources in Appendix E) multiplied by 50' wide paved travel lanes (50' minimum right of way taken from the City of Coos Bay Design Standards, 2016, pg 19).

4. Not ALL water that falls on landscapes becomes runoff. Much is slowed by vegetation/textures and absorbed by the land. Runoff coefficients temper water volumes based on how much a surface will slow and absorb water. Coefficients were taken from the Rational Method, a standard engineering strategy for assessing water flow volumes over time in the landscape (Figure C.2). Where the coefficients offer a range of values, the mid-range value is used.

5. Storm Depths are not specified in the Coos Bay Stormwater Manual but were available for Florence, Oregon. Florence specified rainfall rates:

    2- year is 3.46" in 24-hours
    10-year is 4.48" in 24-hours
    25-year is 5.06" in 24-hours
    100-year is 5.95" in 24-hours

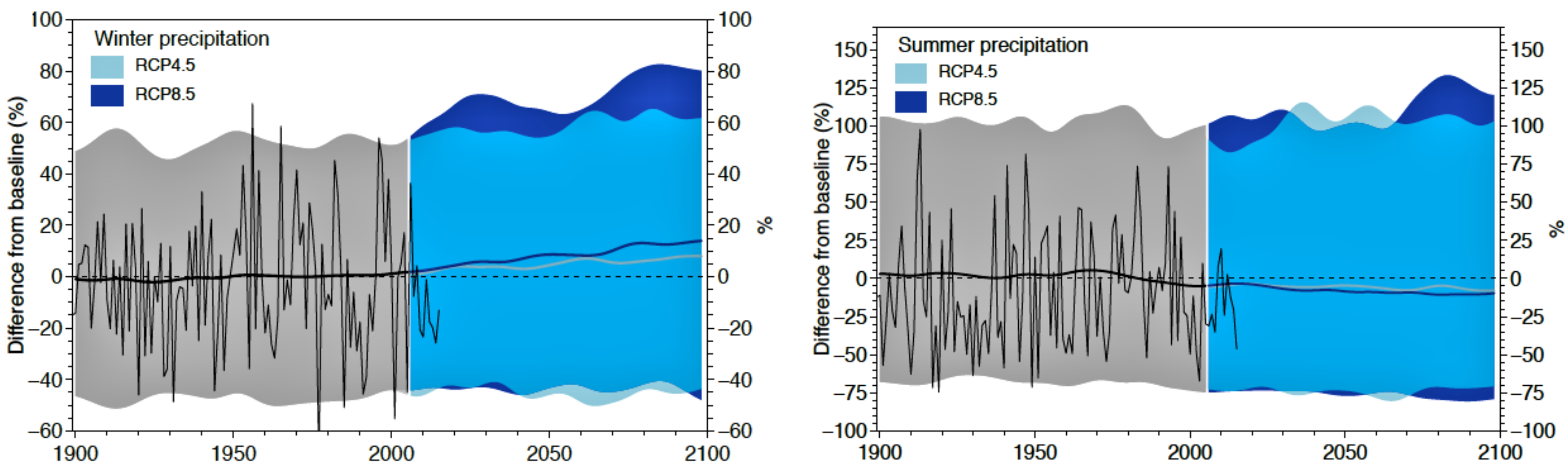


Figure C.1
Projected change in Oregon precipitation by percent (winter and summer under RCP 4.5 and RCP 8.5, Rupp et al., 2016 as cited in Dalton, Dello, Hawkins, Mote, & Rupp, 2017)

Sub-basin 3 was further divided based on the location of Mingus Lake. The upper reaches of the sub-basin were removed from tidegate 3's volume. Naturally occurring wetlands and waterways provide a variety of ecosystem services including the ability to slow, filter, and infiltrate water flows. The upland portion of sub-basin 3 flows into Mingus Lake. These waters are excluded from flood assessments because they are already part of a more resilient stormwater system, naturally occurring waterways and preserved greenspace. These waters are specified subbasin 3-up. They were tallied and subtracted from the basin 3 total volume. All stormwater that is not flowing into the lake is said to flow to tidegate 3. The waters specified as flowing through tidegate 3 are designated subbasin 3-down.

Land Use	C	Land Use	C
Business:		***Lawns:***	
Downtown areas	0.70 - 0.95	Sandy soil, flat, 2%	0.05 - 0.10
Neighborhood areas	0.50 - 0.70	Sandy soil, avg., 2-7%	0.10 - 0.15
		Sandy soil, steep, 7%	0.15 - 0.20
		Heavy soil, flat, 2%	0.13 - 0.17
		Heavy soil, avg., 2-7%	0.18 - 0.22
		Heavy soil, steep, 7%	0.25 - 0.35
Residential:		***Agricultural land:***	
Single-family areas	0.30 - 0.50	*Bare packed soil*	
Multi units, detached	0.40 - 0.60	*Smooth	0.30 - 0.60
Munti units, attached	0.60 - 0.75	*Rough	0.20 - 0.50
Suburban	0.25 - 0.40	*Cultivated rows*	
		*Heavy soil, no crop	0.30 - 0.60
		*Heavy soil, with crop	0.20 - 0.50
		*Sandy soil, no crop	0.20 - 0.40
		*Sandy soil, with crop	0.10 - 0.25
		Pasture	
		*Heavy soil	0.15 - 0.45
		*Sandy soil	0.05 - 0.25
		Woodlands	0.05 - 0.25
Industrial:		*Streets:*	
Light areas	0.50 - 0.80	Asphaltic	0.70 - 0.95
Heavy areas	0.60 - 0.90	Concrete	0.80 - 0.95
		Brick	0.70 - 0.85
Parks, cemeteries	0.10 - 0.25	Unimproved areas	0.10 - 0.30
Playgrounds	0.20 - 0.35	Drives and walks	0.75 - 0.85
Railroad yard areas	0.20 - 0.40	Roofs	0.75 - 0.95

Figure C.2
Rational Method Coefficients

BASIN 3	Acres	Runoff Coefficient	Acres x Coefficient (ac)	2-yr Storm (AF)	100-yr Storm (AF)
Business	4.7	0.7	3.29	0.95	1.63
Residential, Medium Density	340	0.5	170	49.02	84.29
Residential, Low Density	9.4	0.325	3.055	0.88	1.51
Industrial	0	0.7	0	0.00	0.00
Mixed-Use	40	0.725	29	8.36	14.38
Open Space	250	0.175	43.75	12.61	21.69
Roads	65	0.825	53.625	15.46	26.59
TOTAL				87.28	150.10
SUBBASIN 3-UP				56.59	97.31
SUBBASIN 3-DOWN				30.70	52.79

BASIN 3-UP	Acres	Runoff Coefficient	Acres x Coefficient (ac)	2-yr Storm (AF)	100-yr Storm (AF)
Business	0	0.7	0	0.00	0.00
Residential, Medium Density	248	0.5	124	35.75	61.48
Residential, Low Density	6	0.325	1.95	0.56	0.97
Industrial	0	0.7	0	0.00	0.00
Mixed-Use	40	0.725	29	8.36	14.38
Open Space	236	0.175	41.3	11.91	20.48
Roads	0	0.825	0	0.00	0.00
TOTAL				56.59	97.31

Figure C.3
Sub-basin Volumes

BASIN 3-DOWN	Acres	Runoff Coefficient	Acres x Coefficient (ac)	2-yr Storm (AF)	100-yr Storm (AF)
TOTAL BASIN 3	NA	NA	NA	87.28	150.10
Minus 3-UP	NA	NA	NA	56.59	97.31
				30.70	52.79

BASIN 5	Acres	Runoff Coefficient	Acres x Coefficient (ac)	2-yr Storm (AF)	100-yr Storm (AF)
Business	27	0.7	18.9	5.45	9.37
Residential, Medium Density	49	0.5	24.5	7.06	12.15
Residential, Low Density	0	0.325	0	0.00	0.00
Industrial	0.7	0.7	0.49	0.14	0.24
Mixed-Use	6.7	0.725	4.8575	1.40	2.41
Open Space	25	0.175	4.375	1.26	2.17
Roads	27	0.825	22.275	6.42	11.04
TOTAL				21.74	37.38

BASIN 6	Acres	Runoff Coefficient	Acres x Coefficient (ac)	2-yr Storm (AF)	100-yr Storm (AF)
Business	11	0.7	7.7	2.22	3.82
Residential, Medium Density	0.7	0.5	0.35	0.10	0.17
Residential, Low Density	0	0.325	0	0.00	0.00
Industrial	22.6	0.7	15.82	4.56	7.84
Mixed-Use	4.6	0.725	3.335	0.96	1.65
Open Space	0	0.175	0	0.00	0.00
Roads	12	0.825	9.9	2.85	4.91
				10.70	18.40

BASIN 12	Acres	Runoff Coefficient	Acres x Coefficient (ac)	2-yr Storm (AF)	100-yr Storm (AF)
Business	0	0.7	0	0.00	0.00
Residential, Medium Density	86.9	0.5	43.45	12.53	21.54
Residential, Low Density	0	0.325	0	0.00	0.00
Industrial	12.7	0.7	8.89	2.56	4.41
Mixed-Use	0.06	0.725	0.0435	0.01	0.02
Open Space	3.8	0.175	0.665	0.19	0.33
Roads	17	0.825	14.025	4.04	6.95
				19.34	33.26

APPENDIX D: LEVEE MAPPING

Generating levee breach data required arranging water depths, including predicted SLR (by year) and surge event (2-yr and 100-yr). By arranging the water levels by height (figure D.1), the pattern of frequency and spatial levee breaches emerges. Levee breaches, designated in red on the maps (Figure 4.3), were manually drawn from the topography (data sources available in Appendix E) in any location where waters would flood beyond 100 feet of the existing MHHW line. The maps show levee breach spatial extents, their timeline, and their recurrence rates.

SLR + SURGE	water level (ft above datum)	breach height (topography elevation in ft)	req'd fortification to water height: south of 101	east of 101
2019 MHHW	7.5	7	none	none
2030 MHHW	8.2	8	none	none
2050 MHHW	9.0	9	< 1'	< 1'
2019 + 2 YR	9.9	9	1'	< 1' (limited extent)
2030 + 2 YR	10.7	10	1' 8"	< 1' (limited extent)
2019 + 100YR	11.2	11	2' 3"	< 1'
2050 + 2YR	11.5	11	2' 6"	< 1'
2030 + 100YR	12.0	12	3' 0"	1'
2100 MHHW	12.1	12	3' 1"	1' 1"
2050 + 100YR	12.8	12	3' 10"	1' 10"
2100 + 2YR	14.6	14	5' 7"	3' 7"
2100 + 100YR	15.9	15	6' 11"	4' 11"

Figure D.1
Water heights, the correlated levee breach height, difference from levee elevation to water level by location. South of 101, the lowest levee elevations are 9 feet. East of 101, the lowest elevations are 11 feet.

APPENDIX E: SPATIAL DATA SOURCES

DATA COLLECTED FROM EXISTING RESEARCH:	source	date
2030, 2050, 2100 SLR + Storm Surge	Sea Level Rise Exposure Inventory for Oregon's Estuaries	2017
Levee	Department of Land Conservation and Development (DLCD)	2011
Stormwater Infrastructure	City of Coos Bay	2019
Tidegate locations	City of Coos Bay	2005
Stormwater Pipe Diameter	City of Coos Bay	2019
Land Use	Department of Land Conservation and Development (DLCD)	2017
Stormwater Pipe Location	City of Coos Bay	2019
Business and Industry ID	Google Maps	2019
Building Footprints	City of Coos Bay	2019
Railroads	Oregon Department of Transportation (ODOT)	2015
Roads	Oregon Department of Transportation (ODOT)	2017
Digital Elevation Model	Department of Geology and Mineral Industries (DOGAMI)	2009

EXISTING DATA SPATIALLY •RE•PRESENTED:	original representation	date
Topography	from Digital elevation Model	2009
MHHW 2019, 2030, 2050, 2100	from Tides & Currents: Datums for 9432895	2004
2019 + Storm Surge	MHHW + Storm Surge	2004 2017

DATA GENERATED FOR THIS REPORT:	process-details documentation
Tidegate Depths	Appendix C
Tidegate Flow Timelines	Appendix C
Sub-basins	Appendix B
Sub-basin Volumes 2-yr rainfall	Appendix B
Sub-basin Volumes 100-yr rainfall	Appendix B
Levee Breach Timeline	Appendix D

original source

DOGAMI
National Oceanic and Atmospheric Administration (NOAA)
NOAA (for current MHHW)
Sea Level Rise

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