# Anticipating Sea Level Rise Response in Puget Sound

Alexander W. Petersen

A thesis
submitted in partial fulfillment of the
requirements for the degree of

MASTER OF MARINE AFFAIRS

University of Washington

2007

Program Authorized to Offer Degree:
School of Marine Affairs

University of Washington
Graduate School

This is to certify that I have examined this copy of a master's thesis by

Alexander W. Petersen

and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

Committee Members:

_______________________________________________
Edward L. Miles

_______________________________________________
Thomas M. Leschine

_______________________________________________
Douglas J. Canning

Date: ____________________

University of Washington

**Abstract**

Anticipating Sea Level Rise Response in Puget Sound

Alexander W. Petersen

Chair of the Supervisory Committee:
Professor Edward L. Miles
School of Marine Affairs

When faced with the issues of climate change and sea level rise, decision-makers are unable to wait for scientific uncertainties to be resolved before taking action. Sea level rise predictions are complicated by the complex non-linear nature of the climate system and long-term dependence on human choices. This study analyzes the regulatory and institutional structure surrounding coastal zone management in Puget Sound, Washington, in order to identify barriers to and opportunities for sea level rise response.

Viewing the problem from a resilience perspective proves valuable as it builds off the social-ecological system concept, embraces change, and attempts to find ways to co-exist with uncertainty. The selection of non-catastrophic sea level rise scenarios and the creation of a variety of high-resolution, location specific, inundation maps are used to identify areas of vulnerability.

Focusing on local government, four potential sea level rise response options are identified along with associated barriers. *1)* Increase the update frequency for floodplain maps to more accurately reflect environmental changes. *2)* Include consideration of a dynamic shoreline when making shoreline armoring, cumulative impacts, and no net loss of ecological function determinations. *3)* Use shoreline designations in the Shoreline Management Act to tailor responses to the coastal environment. *4)* Leverage the Federal

Consistency and funding provisions of the Coastal Zone Management Act to enhance response options.

The long-term nature of the sea level rise issue provides response opportunities not available in other arenas. By using the tools currently available, local decision-makers can limit the response costs and create a more robust policy framework capable of incorporating uncertainty and adapting to sea level rise.

# Table of Contents

Page

## List of Figures

# List of Tables

## Glossary

| | |
|---|---|
| ACOE | Army Corps of Engineers |
| CAO | Critical Areas Ordinance |
| CFR | Code of Federal Regulations |
| CIG | Climate Impacts Group |
| CWA | Clean Water Act |
| CZMA | Coastal Zone Management Act |
| CZMP | Coastal Zone Management Program |
| DEM | Digital Elevation Map |
| DOE | Department of Ecology |
| DNR | Department of Natural Resources |
| EPA | Environmental Protection Agency |
| FEMA | Federal Emergency Management Agency |
| FIRM | Flood Insurance Rate Map |
| GMA | Growth Management Act |
| HPA | Hydraulic Project Approval |
| IPCC | Intergovernmental Panel on Climate Change |
| JISAO | Joint Institute for the Study of the Atmosphere and Ocean |
| LIDAR | Light Detection and Ranging |
| OHW | Ordinary High Water |
| MHW | Mean High Water |
| MHHW | Mean Higher High Water |
| MLW | Mean Low Water |
| NFIP | National Flood Insurance Program |
| NOAA | National Oceanic and Atmospheric Administration |
| RWC | Revised Code of Washington |
| SMA | Shoreline Management Act |
| SMC | Seattle Municipal Code |
| SMP | Shoreline Master Program |
| WAC | Washington Administrative Code |
| WDFW | Washington State Department of Fish and Wildlife |
| USC | United States Code |

## Acknowledgements

This research was supported by the Climate Impacts Group (CIG) and funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under National Oceanic and Atmospheric Administration (NOAA) cooperative agreement no. NA17RJ1232.
I would like to thank Professor Edward L. Miles, Professor Thomas M. Leschine, and Douglas J. Canning for their insights, knowledge, guidance, and support throughout the process. The City of Seattle, particularly Miles Mayhew and Brenndon Staley, and King County, particularly Jill Moe and Sally Abella, deserve recognition for their willing collaboration and efforts to begin addressing sea level rise and climate change in their planning processes. I would also like to thank Rob Norheim and Hugh Shipman for guidance on cartography and geology respectively. Many others contributed to the success of this project. I am ever grateful to Elizabeth Rohlich and my family for their love and support and my friends and colleagues at the School of Marine Affairs.

# **1.0 Introduction**

Global climate change is an intricate and multi-faceted issue that will affect many aspects of social-ecological systems throughout the world (IPCC 2007b). Addressing the issue of climate change will require a suite of responses utilizing both market and non-market mechanisms; focusing on both mitigation and adaptation; and addressing both public and private interests.

Public interest and awareness of climate change has been steadily increasing over the last few years. This can be seen in the proliferation of news articles such as the recent cover story in *Time* magazine (Kluger 2007), movies such as *An Inconvenient Truth* (2006), and political discussions such as the one between Kerry and Gingrich (Milbank 2007) on the issue. Increasing public awareness has opened a policy window and a new opportunity exists for policy entrepreneurs (Fiorino 1995) to develop responses to climate change and sea level rise.

Within the Pacific Northwest, the salience of the climate change issue has already triggered some action. A planning group for the City Council of Olympia recently completed an update to a 1993 study (Craig 1993) on the impacts of sea level rise. They recommended modifying the architectural plans for the new city hall and elevating the building an additional foot in preparation for expected increases in sea level (Mucha &

Hoey 2007). In addition, through the mandatory Shoreline Master Program (SMP)[1] update process, King County has started to consider the potential impacts of climate change and sea level rise (King County 2006). These actions highlight the desire of the public and local government officials to address climate change and sea level rise in the planning processes.

Addressing climate change will not be easy. The climate change issue is rife with uncertainties. These uncertainties arise from the long time scales, inherent variability, and embedded non-linear responses, in both the human and natural subsets of the integrated social-ecological system. Specific to sea level rise, there are fundamental uncertainties in the magnitude and rate of future increases.

Decision-makers need techniques and tools that incorporate uncertainties into the decision making process. At all levels of government, and in the private sector, decision-makers cannot wait for the uncertainties to be resolved. They are required to take action in this uncertain environment and the choices they make will ultimately determine the economic and social impacts of climate change. The path to a solution is long and varied. This study provides a step along that path as it explores the value of using the concepts of social-ecological resilience to develop a sea level rise response strategy.

[1] Shoreline Master Programs are required by the Shoreline Management Act (RCW 90.58). They are created by local governments to provide coordinated and consistent land use planning within 200 feet of marine and freshwater shorelines.

# 2.0 Focus of the Study

## 2.1 Research Questions

This study is designed to answer the following research questions:

1) *What are the key regulatory and institutional barriers to incorporating sea level rise science and its associated uncertainty into decision making?*

2) *How can these impediments be overcome in order to develop a policy framework that can effectively incorporate consideration of the uncertainty associated with sea level rise?*

## 2.2 Scope of Study

This study tests the applicability of using the social-ecological resilience framework to analyze and respond to sea level rise. In order to be effective, it focuses on a topical and geographic subset of the sea level rise issue. The goal is to provide a detailed evaluation of the impediments and opportunities for sea level rise response in the context of public institutions in Washington State. Limiting the scope of this study is not intended to ignore or dismiss the other relevant, inter-related, and intriguing aspects of climate change. When appropriate, important connections to other sectors, industries, and topics are illustrated.

The geographic scope of the study is restricted to Puget Sound. The chosen locations test the analytical framework and procedures used in the study. Ultimately, the process developed in this study can be generalized and applied in other contexts.

**2.3 Mitigation vs. Adaptation**

In general, there are two major categories of response to climate change: *mitigation* and *adaptation*. In this context, *mitigation* refers to reduction in greenhouse gas emissions that will decrease the magnitude of the long-term changes in the climate system. *Adaptation* refers to actions taken (proactively or reactively) to respond to climate change and decrease local impacts[2]. Proactive adaptation decreases the system's sensitivity to climate change stressors while reactive adaptation limits the negative outcomes of those stressors.

These categories are by no means mutually exclusive and, in the long-term, mitigation actions increase resilience by decreasing exposure to climate stressors. This study focuses on adaptation (sensitivity and adaptive capacity) and not mitigation for two reasons. First, the long atmospheric residence time of $CO_2$ and other greenhouse gases and inertia in the climate system mean the current emissions commitment will dominate impacts for the next few decades (Meehl et al. 2005, Wigley 2005). Second, mitigation is tied to global actions and is thus connected to regional, national and multi-national efforts (Tol 2005, Füssel & Klein 2006). Adaptation, on the other hand, is naturally more local (or regional) in scale (Tol 2005, Füssel & Klein 2006) and can be effectively pursued by local governments and institutions.

---

[2] These two terms can have substantially different meanings in non-climate change contexts. For example, *mitigation* has a long history in land use planning and restoration. In that context, *mitigation* (or compensatory mitigation) refers to response actions taken by developers to offset the impacts of new construction. Filling wetlands for development will frequently require preservation or creation of wetlands in other areas (33 U.S.C. 1344).

**2.4 Public Institutions**

*Social-ecological systems*[3] are complex and even with a focus on sea level rise and resilience there are a variety of avenues to explore (such as focusing on the use of market-based incentives or the role of the re-insurance industry). These potential avenues are interesting and analysis in each area could provide valuable insights into the dynamics of the system. This study focuses on identifying barriers to and opportunities for developing sea level rise response within the public institutional context and governance structure. Limiting the research questions to this context is valuable for a number of reasons.

In Puget Sound, local governments and institutions are showing interest in addressing the realities of sea level rise. Local governments frequently have long-term planning horizons that facilitate consideration of sea level rise; where private individuals (primarily shoreline property owners) may not be as attuned to such long-term impacts. Thus, governmental institutions will likely be the early adopters of sea level rise response. Successful adaptation also requires leadership, and through their customary role in land use management, local governments have the opportunity to provide that leadership. Their actions will set the stage for future developments.

[3] Here the term *social-ecological system* acknowledges the complex interconnections and coupling between the human and natural sub-systems.

# 3.0 Methodology

## 3.1 Major Components

The first component is the selection of a theoretical foundation by focusing on the peer reviewed scientific basis for sea level rise and the principles of resilience theory (Sections 4, 5, & 6).

The creation of high-resolution inundation maps (Section 7), based on the developed sea level rise scenarios, is the second component of the study.

The final component is the application of this information in the current legal, regulatory and institutional context within Puget Sound in order to identify key impediments and opportunities for local sea level rise response (Section 8).

## 3.2 Scenario Development

The use of scenarios is particularly valuable when dealing with futures that involve human action and human choices. Humans are uniquely able to respond to their environment, make changes, and adapt. Human adaptation (either proactive or reactive) will influence the trajectory and end state of the social-ecological system. Instead of trying to predict the future, scenarios "…begin by explicitly acknowledging the indeterminacy of future change" (Berkhout et al. 2001, pg 8). Therefore, scenarios fit well with the resilience framework, climate change, and potential non-linear threshold responses.

Scenario planning has been used on a large scale by the Intergovernmental Panel on Climate Change (IPCC) to explore the potential climate effects of a suite of worldwide social-economic development paths (IPCC 2000). It has also been proposed as a conservation management tool for addressing problems with substantial uncertainty (Peterson et al. 2003). In this study, the set of sea level rise scenarios focus on potential physical changes and use high-resolution elevation data to explore the sensitivity of the social-ecological system to non-catastrophic increases in sea level. This set of scenarios is not exhaustive, but illustrative, and is used to test the value of this approach.

### 3.3 Generalizing this Approach

One goal of this study is to create an approach that can be generalized and applied in a variety of contexts. Modifications based on the physical and social realities will be necessary in order to develop realistic local sea level rise scenarios for other locations.

# 4.0 Climate Change and Sea Level Rise Science

## 4.1 The Global Climate System

The Earth's climate system is highly nonlinear with dynamics governed by abrupt changes, multiple equilibria, and thresholds (Rial et al. 2004). Positive feedbacks in the climate system play a key role in determining nonlinear climate response (Rial et al. 2004). These nonlinearities are apparent in the natural climate system as well as the social system and the combined social-ecological system (Folke et al. 2002). Rapid threshold responses in regional ecosystems increase the complexity and difficulty of responding to climate change (Burkett et al. 2005).

## 4.2 Sea Level Rise

Sea level rise is one of many key results of global climate change. The IPCC's Working Group I "Summary for Policy Makers" issued in February of 2007 states that:

> Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level. (IPCC 2007a, pg 5)

Global sea levels have been rising since the last glacial maximum (~ 21,000 years ago) though the rate of rise has been variable with peak rates twice potentially exceeding 50 mm/yr, 19,000 and 14,500 years ago (Alley et al. 2005).

Thermal expansion due to ocean temperature increases and mass input from melting glaciers and ice sheets are the primary components responsible for sea level rise. Both of these inputs are driven by increases in atmospheric greenhouse gas concentrations, the resultant Earth energy imbalance and subsequent warming (IPCC 2007a). During the last 50 years, the oceans have warmed significantly "…absorbing more than 80% of the heat added to the climate system" (IPCC 2007a, pg 4). Thermal expansion has contributed about 0.4 mm/yr to global sea level rise over the last 50 years. However, this rate has increased to between 1.2 mm/yr and 1.8 mm/yr over the 1993-2003 period (Nerem et al. 2006). Over the same period, ice-melt contributions from glaciers and ice sheets are estimated to have contributed between 1.0 mm/yr and 1.2 mm/yr to global sea level (Nerem et al. 2006). Rates of sea level rise vary on many different spatial and temporal scales (Church et al. 2004). The long-term average, based on tide gauge records over the last 50 years, is 1.8 $\pm$ 0.3 mm/yr (Nerem et al. 2006). However, this rate has accelerated and the TOPEX/Poseidon and Jason 1 satellite measurements from 1993-2003 provide a value of 3.1 $\pm$ 0.4 mm/yr (IPCC 2007a, Nerem et al. 2006). It is not yet clear whether this acceleration reflects a long-term change or decadal variability (IPCC 2007a, Nerem et al. 2006).

### 4.3 Global Sea Level Rise Predictions

The accuracy and availability of data have increased since the IPCC Third Assessment Report (2001) and subsequently for some aspects of sea level rise uncertainty has decreased. The projected increase in global sea level ranges from 0.18 m to 0.59 m by 2099 (IPCC 2007a). However, these model projections do not:

> …include the full effects of changes in ice sheet flow, because a basis in published literature is lacking. […] Larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise. (IPCC 2007a, pp 14-15)

The physical processes which determine the rates of Greenland ice loss and Antarctic ice sheet melting are not completely understood and have not been adequately modeled (Alley et al. 2005). This means that current model predictions are limited and may not be entirely accurate (Howat et al. 2007, Rahmstorf 2007). Evidence from paleoclimatic warming events suggests that future rates of melting could be more rapid than current expectations (Overpeck et al. 2006). Acceleration in Greenland ice sheet melt rates comes from increases in glacial velocities (Rignot & Kanagaratnam 2006, Chen et al. 2006), which also show substantial short-term variability (Howat et al. 2007). In response to model uncertainty, Rahmstorf (2007) proposed the use of a semi-empirical model that, when applied to the IPCC Third Assessment Report emission scenarios, predicts between 0.5 m and 1.4 m of sea level rise by 2100.

### 4.4 Regional Scale Sea Level Rise Predictions

Scaling down global climate predictions to the regional level is a key aspect of current research. Efforts have begun to investigate regional differences in sea level rise (Church et al. 2004). At the regional and local level, relative rates of sea level rise are influenced not only by regional ocean basin differences but also by local vertical land movements. Key processes affecting vertical land movements are glacial isostatic adjustment (Miller & Douglas 2006) and crustal deformation (Verdonck 2006).

In addition to regional differences, the likelihood of future events may not be accurately predicted by probabilities derived from the past. The current techniques developed for dealing with uncertainty and natural variability will not necessarily be effective when faced with future changes. For example, the Federal Emergency Management Agency (FEMA) uses historic analysis to create floodplain maps and determine base flood elevations representative of the 100-year floodplain. These maps do not reflect how hydrological regimes will be affected by future climate change. Factors such as increasing sea levels, along with changes in precipitation and snow pack, will affect the flood zones. These factors will need to be considered for FEMA maps to be accurate (Hudgens 1999).

### 4.5 Sea Level Rise Uncertainty

The exact rate or magnitude of future sea level rise is nearly impossible to specify. This is partially because of the uncertainties associated with the potentially non-linear dynamics of ice sheet response to warming temperatures. This uncertainty is complicated by natural variability. Sea levels vary on many temporal scales from hours to centuries (Nerem et al. 2006, Subbotina et al. 2001). In addition, future long-term changes in sea level are dependent on human response to the climate change issue as well as other factors such as economic growth, population increases, or the development of new technologies. Uncertainty based on human choices is irreducible and not easily determined. The IPCC uses socio-economic scenarios (IPCC 2000) to explore different potential future development paths based on human choices. Each choice leads to a different emission scenario, temperature increase, and subsequently affects the magnitude of sea level rise.  All of these factors mean that exact predictions of future sea level rise are not currently possible and that regional policy makers are forced to make choices in an uncertain environment.

# 5.0 Resilience Framework

## 5.1 Resilience Theory

The concept of resilience has evolved beyond the confines of ecological systems where it was first introduced to describe multiple stable state behavior (Holling 1973). Resilience is defined as:

> ...the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks. (Walker et al. 2004 pg 6)

In this context, "system" can refer to ecological systems, social systems (Adger 2000), or combined social-ecological systems (Carpenter et al. 2001). The resilience framework, based on multiple *basins of attraction*, is a departure from the earlier single stable state theory and has broad implications for management (Folke 2006). A *basin of attraction* describes one of the multiple domains of stability in which the system can reside (Holling 1973). A system can move between basins of attraction (stable states) in one of two ways. Either the system can move across the boundary between the basins or the boundary itself can shift. Figure 1, below, provides a graphical depiction of these basins of attraction.

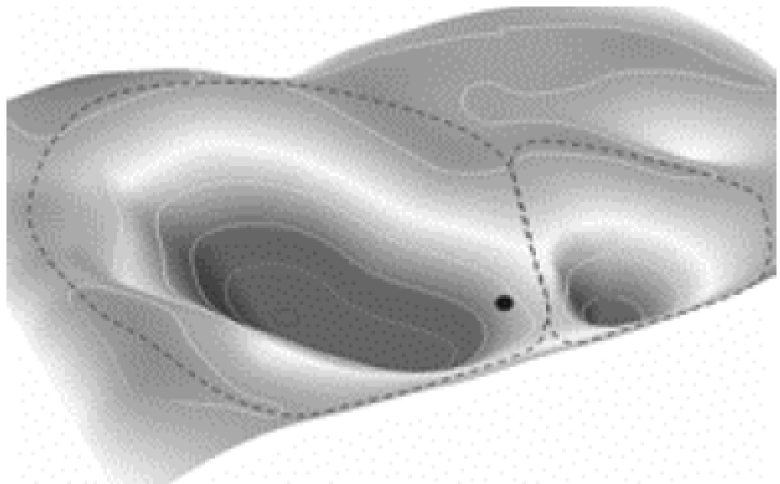

**Figure 1: Resilience landscape**

Adapted from Walker et al. (2004), this figure represents a three-dimensional stability landscape with two distinct basins of attraction. The dashed lines are the boundaries between the basins and the black dot is the current location of a social-ecological system within the landscape.

The resilience perspective is well suited for approaching complex social-ecological systems characterized by non-linear dynamics, thresholds, uncertainty and surprises across a variety of spatial and temporal scales (Folke 2006).

Focusing on resilience does not attempt to eliminate uncertainty but to develop better ways to co-exist with inherent and irreducible uncertainties (Klinke & Renn 2002). This makes resilience a particularly relevant framework for addressing climate related issues.

### 5.2 Fast and Slow Variables

The linkages between social and ecological systems are influenced by a combination of fast and slow variables (or stressors) acting to affect the system (Carpenter et al. 2001). Similarly, cross-scale vertical linkages between local, regional and global dynamics are also governed by both fast and slow variables. Selection of the scale under consideration is important, as the ability of the system to respond to a disturbance will be influenced by its connections with systems at different temporal and spatial scales (Folke 2006). The interaction between social and ecological pressures on multiple temporal and spatial scales determines the system dynamics and can lead to non-linear responses (Chapin et al. 2006a). Slow variables control the location of basin boundaries (dashed lines in Figure 1 above) and thus determine which acute events (fast variables) are capable of moving the system (black dot in Figure 1 above) across the boundary between basins of attraction and into a new, and potentially less desirable, stable state (Carpenter et al. 2001).

### 5.3 Non-linear Response

The potential for non-linear responses is not limited to the climate system. Social-ecological systems are just as likely to demonstrate non-linear threshold responses as physical systems. In natural systems, these changes tend to be driven by slowly changing variables (Walker et al. 2006) (*e.g.*, soil resources, sea level rise, gradual shifts in storm frequency and/or orientation). Similar slow variables can affect social systems (*e.g.*, increasing public awareness of climate change). These changes act to shift the boundary between basins of attraction. Frequently, negative feedbacks act to maintain the system structure even as key slow variables change. However, once a threshold is crossed, the system has the potential for rapid transformation (Chapin et al. 2006b). Pressures can also be exerted by fast variables in the physical system (major storms) or the social system (changes in population densities or community income) (Chapin et al. 2006a). These disturbances can catalyze transformation in a system (Chapin et al. 2006b). It is the combination of the short and long-term changes, fast and slow variables, that gives rise to potential non-linear responses in the social-ecological system.

### 5.4 Thresholds

Thresholds are a primary component of non-linear systems and resilience theory. Changes may occur gradually until a threshold is reached and the system suddenly shifts into a new basin of attraction. Such thresholds are relatively easy to examine and discuss after the transition has occurred and far more difficult to predict. There are many examples of thresholds in ecological systems. Alaskan boreal forests' response to increasing temperatures and melting permafrost is one example (Chapin et al. 2006b). Depending on topography, thawing permafrost can result in either: a well-drained area with productive broad leaf trees in the uplands; or a poorly drained high moisture boggy environment in the lowlands (Chapin et al. 2006b). Another example is the potential synergistic affect of human and natural disturbances that catalyzed the transformation of Caribbean coral reefs from hard coral to fleshy algae dominance (Nyström et al. 2000) [4].

### 5.5 Exposure, Sensitivity, and Adaptive Capacity

Classically, risk is defined as the probability of an event occurring multiplied by the consequences of that event (Schneider 2002). This risk-based approach can be successful

[4] See Folke et al. 2002 or the Resilience Alliance's "Thresholds and Alternate States in Ecological and Social-Ecological Systems" Database (http://www.resalliance.org/185.php) for additional examples.

in responding to events with well-defined probabilities. However, it is not as effective in addressing non-linear systems where stochastic events, natural variability, and dependence on human choices make it difficult to assign probabilities (Sarewitz et al. 2003). Decreasing system vulnerability (increasing resilience) is not dependent on accurate determination of the probability of extreme events (Sarewitz et al. 2003). The resilience of a social-ecological system is determined by the exposure to stressors, the system's sensitivity to those stressors, and the adaptive capacity of the system (Nicholls & Hoozemans 2002, Klein et al. 2003, McCarthy et al. 2001). The potential for adaptation is based on the adaptive capacity of the system, which varies depending on the time scale considered (Brooks et al. 2005). To be more specific, the adaptive capacity of a system is tied to the system's ability to self-organize and learn from experience (Folke 2006). Adaptive capacity depends on social capital, institutions, and resources as well as resource distribution (Tompkins & Adger 2004). With increasing adaptive capacity comes the potential for increasing resilience (Füssel & Klein 2006). The resilience of a system determines the system's ability to cope with non-linear surprises (Folke et al. 2002). Resilience can be increased in one of three ways: 1) *decreasing exposure*, 2) *decreasing sensitivity*, or 3) *increasing adaptive capacity*.

In the case of climate change and sea level rise, *decreasing exposure* is tied to mitigation actions that limit the long-term effects of climate change and lower the amount of sea level rise. *Decreasing sensitivity* is one type of adaptation and tied to actions taken in the coastal zone (land use planning, building codes…etc.) that provide short and long-term protection to current infrastructure or ecosystems. Finally, *increasing adaptive capacity* allows the social-ecological system to respond to stressors, deal with surprises, and increase adaptation. Implementing flexible learning-based management strategies (Tompkins & Adger 2004) can avoid limiting the response paths available and can increase the system's adaptive response capability.

# 6.0 Application of Resilience to Sea Level Rise

## 6.1 Focusing on Resilience

The resilience framework provides three key insights that are particularly valuable when developing responses to sea level rise and other climate issues. First, resilience highlights consideration of complex social-ecological systems in which human and natural systems are explicitly interconnected. With this view, humans are part of, and not separate from, the surrounding environment. Resilience supports realization of the reciprocal nature of social-ecological relationships and how the two sub-systems influence each other.

Second, resilience accepts uncertainty and does not attempt to eliminate it. This provides a framework for acknowledging uncertainty and working to reduce it with the understanding that decisions, especially those related to climate change, must be made in the face of this uncertainty.

Finally, a focus on social-ecological resilience requires accepting change (Berkes et al. 2003). This comes with accepting that human and natural systems change over time and that humans must be prepared to respond to those changes.

> In operationalizing this view of resilience, managing for sustainability in social-economic systems means not pushing the system to its limits but maintaining diversity and variability, leaving some slack and flexibility… (Berkes et al. 2003, pg 15)

Looking through the lens of resilience at sea level rise response in Puget Sound provides a valuable framework that can describe system dynamics, highlight barriers, and identify opportunities.

The resilience framework has even been heralded as the potential future management paradigm for complex social-ecological systems (Anderies et al. 2006). The ideas of resilience can be used to explain the past behavior of complex social-economic systems. Resilience has been applied in this way to a variety of case studies: the Alaskan Bristol Bay salmon fishery (Robards & Greenberg 2007), Alaskan boreal forests (Chapin et al. 2006b), and Coastal Mega Cities (Klein et al. 2003) are a few examples. It is more difficult to look to the future, attempt to identify thresholds before they are crossed, and create proactive response strategies based on the concept of resilience.

### 6.2 Fast and Slow Variables

Sea level rise is a slow physical variable (occurring on decade and century time scales). Major storms, with their associated storm surge, flooding, and sudden erosion events are fast variables (occurring on hourly to daily time scales). The tidal height at the time of a storm is a key factor in determining the inundation and impact of that storm.

For example, current levels of coastal protection may be designed to enhance social-ecological resilience to a tidal and storm surge stressor two feet above the current high water mark. The physical impacts of this storm will not cause the system to cross the boundary between basins of attraction. After the storm, the system will remain in the same basin and return to its original state. Increasing sea level by one foot effectively moves the basin boundary closer to the system. In this new configuration, a two-foot storm surge will actually be three feet above the original high water mark and may have substantially greater impacts. If the impacts are large enough, the system will move across the boundary into a new basin of stability and not automatically return to its original state. This discussion highlights how the combination of fast and slow sea level rise variables can create non-linear responses within the social-ecological system.

Fast and slow variables also influence social-ecological adaptation. In general, actors (humans and institutions) are geared to respond to the fast variables and are not always aware of the long-term consequences of their actions.

> In other words, people and institutions tend to manage resources based on changes in fast variables rather than the slow variables that ultimately control long-term changes in social-ecological systems. (Chapin et al. 2006b, pg S43)

This can be seen in the institutional response to coastal hazards. Acute storm effects (storm surge, flooding and sudden coastal erosion) receive far more attention than the underlying slowly changing variable of sea level. The fact that flood response is addressed at a variety of scales and levels of government (Section 8.3) provides evidence that management responses are tuned to deal with these fast variables.

# 7.0 Puget Sound Sea Level Rise Scenarios

## 7.1 Areas Mapped

This study selected three areas for detailed mapping: Harbor Island in Seattle; Quartermaster Harbor between Vashon and Maury Islands; and downtown Olympia. The three areas identified represent a variety of shoreline types in Puget Sound and are shown in Figure 2 below.

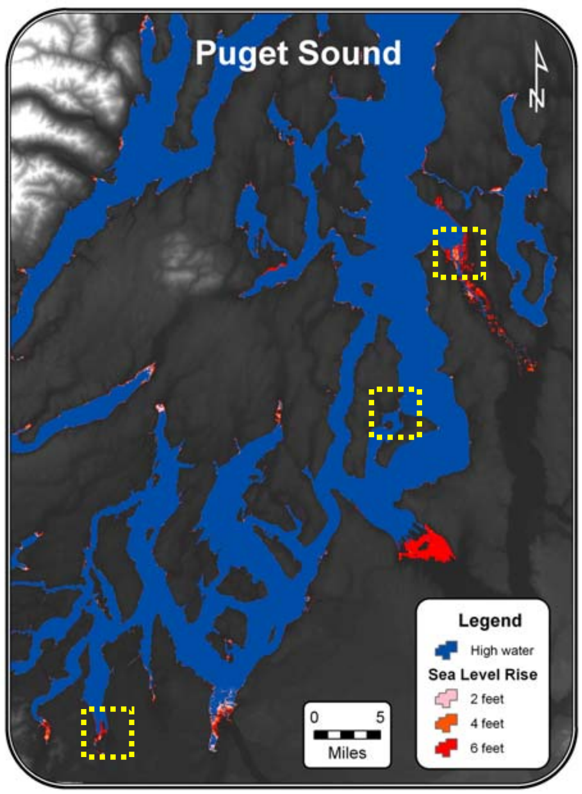


**Figure 2: Sea level rise map locations**

Location of mapped areas within Puget Sound. Mapped areas are outlined with dashed yellow squares. From top to bottom, they are: Harbor Island, Seattle; Quartermaster Harbor, Vashon and Maury Islands; and downtown Olympia.

The Seattle waterfront, and in particular Harbor Island, is an example of an industrialized urban waterfront. Sea level rise has been part of the conversation for replacement of the Alaskan Way seawall (Cohen 2005) and the forthcoming updates to Seattle's Shoreline Master Program (SMP). Built on fill, this area has little or no natural shoreline and, at low elevation, is vulnerable to inundation. Vashon and Maury Islands include the only unincorporated marine shorelines within King County[5] and represent the naturally occurring bluff backed beaches common in Puget Sound. Finally, downtown Olympia provides an example of a waterfront city with multiple shoreline uses and a good comparison to a previous sea level rise study (Craig 1993).

### 7.2 Mapping Methodology

A geographic information system (ArcGIS) was used to map potential sea level rise scenarios. These maps provide an important tool for qualitatively highlighting coastal vulnerability associated with future changes in sea level. The maps generated in this process have also proven extremely useful in communicating the potential impacts of sea level rise and initiating policy discussions with decision-makers. A detailed description of map creation is provided in Appendix A. In this section, discussion will be limited to the key topics of vertical land movement and map resolution.

---

[5] For the King County SMP update, all incorporated cities with populations greater than 10,000 people are required to develop their own SMPs by Dec. 1, 2009 (RCW 90.58.80). The county is only responsible for unincorporated shorelines. This includes Vashon and Maury Islands and a portion of the lower Duwamish waterway.

### *7.2.1 Vertical Land Movements*

Relative rates of sea level rise depend on both global and regional changes as well as local vertical land movements. A literature review was used to determine the appropriate value for vertical land movements in Puget Sound. Three studies are particularly relevant in this region (Holdahl et al. 1989, Mitchell et al. 1994, Verdonck 2006). All three cover slightly different geographic areas and make use of data from different periods. Though the broad picture is relatively consistent, these studies reveal varying magnitudes and directions of change in Puget Sound, raising the issue of whether local vertical land movements in western Washington are linear and/or consistent over time. In contrast to Holdahl's (1989) finding that much of central and southern Puget Sound was subsiding at about 2 mm/yr, the most recent study (Verdonck 2006) shows little or no vertical movement in the same area. Because of the varied results from the different studies and the resolution of the digital elevation map (DEM), vertical land movements have not been used to modify global sea level rise predictions for Puget Sound.

### *7.2.2 Horizontal and Vertical Accuracy*

The horizontal and vertical accuracy of the following maps is based on the accuracy of the underlying data sets used in their creation. Of primary concern is the vertical accuracy of the DEM. All of the maps created in this study are based on the Puget Sound DEM[6] created by Finlayson (2005). That elevation map was derived from a variety of

[6]Horizontal coordinate system: Lambert Conformal Conic, North American Datum of 1983. Vertical coordinate system: North American Vertical Datum of 1988

data sources, each with its own vertical resolution. For the areas mapped, the majority of the data comes from the Puget Sound LIDAR (Light Detection and Ranging) Consortium. In its original 6 ft. grid cell form, the vertical accuracy of LIDAR data is $\pm$ 30 cm on flat open ground, but will be much less in highly sloped areas. Thus, the vertical accuracy depends on the topography and varies between locations. Due to resizing (averaging within 30 ft. grid cells) and processing (mosaicing and blending), the vertical error of the selected areas is estimated to be less than two feet (Finlayson 2005). The raster data set is also stored in integer format, thus elevation changes in fractions of a foot are not represented. A future study could improve the resolution and vertical accuracy of the maps by working on a smaller spatial scale and recreating the DEM with the use of only the original high quality LIDAR data.

The maps created in this study are designed to identify areas of potential vulnerability. They should not be used for specific site planning, construction decisions or high precision planning. The maps are a valuable aid to local decision-makers and planners in the development of non-catastrophic sea level rise response options.

**7.3 Inundation Scenarios**

Given the scientific uncertainty associated with sea level rise predictions (discussed in Section 4) and the vertical resolution of the data set, two-foot, four-foot, and six-foot inundation scenarios were chosen. The scenarios are distinct and reflect the previously stated purpose of increasing awareness and identifying areas of vulnerability. These maps do not attempt to predict the amount of sea level rise by a certain date. When a given amount of sea level rise occurs, the maps depict the associated inundation. Inundation maps based solely on elevation do not model dynamic processes such as erosion and do not attempt to determine areas of increased vulnerability due to geological characteristics, longer fetch, or increased wave energy. The maps are based on the current (2005) shoreline as defined by the ordinary high water mark (OHW)[7]. They do not identify potential shoreline changes based on likely human responses such as protection, accommodation, or retreat. Future studies could model these dynamic processes and include potential responses within the human system. These more detailed scenarios could then be used to explore the impacts of a range of human adaptation responses.

### 7.4 Scenarios and Increased Learning

One value of scenarios not fully utilized in this study is their ability to help stakeholders and communities learn. When applied to issues with a diverse group of stakeholders, scenario planning provides a forum for discussion and consideration of a variety of viewpoints (Berkhout et al. 2001). Local stakeholder groups work together to define and develop the scenarios they find most meaningful for their area. This is a valuable part of the process and can help build consensus and identify areas of concern (Berkhout et al. 2001). Thus, it is not only the result that is valuable, but also the process. Scenario

[7] The "'Ordinary high water mark' on all lakes, streams, and tidal water is that mark that will be found by examining the bed and banks and ascertaining where the presence and action of waters are so common and usual, and so long continued in all ordinary years, as to mark upon the soil a character distinct from that of the abutting upland, in respect to vegetation…" (Shoreline Management Act, RCW 90.58.30 2b).

planning can increase the adaptive capacity of a community by helping stakeholders consider and prepare for a variety of potential futures.

### 7.5 Sea Level Rise Inundation Maps

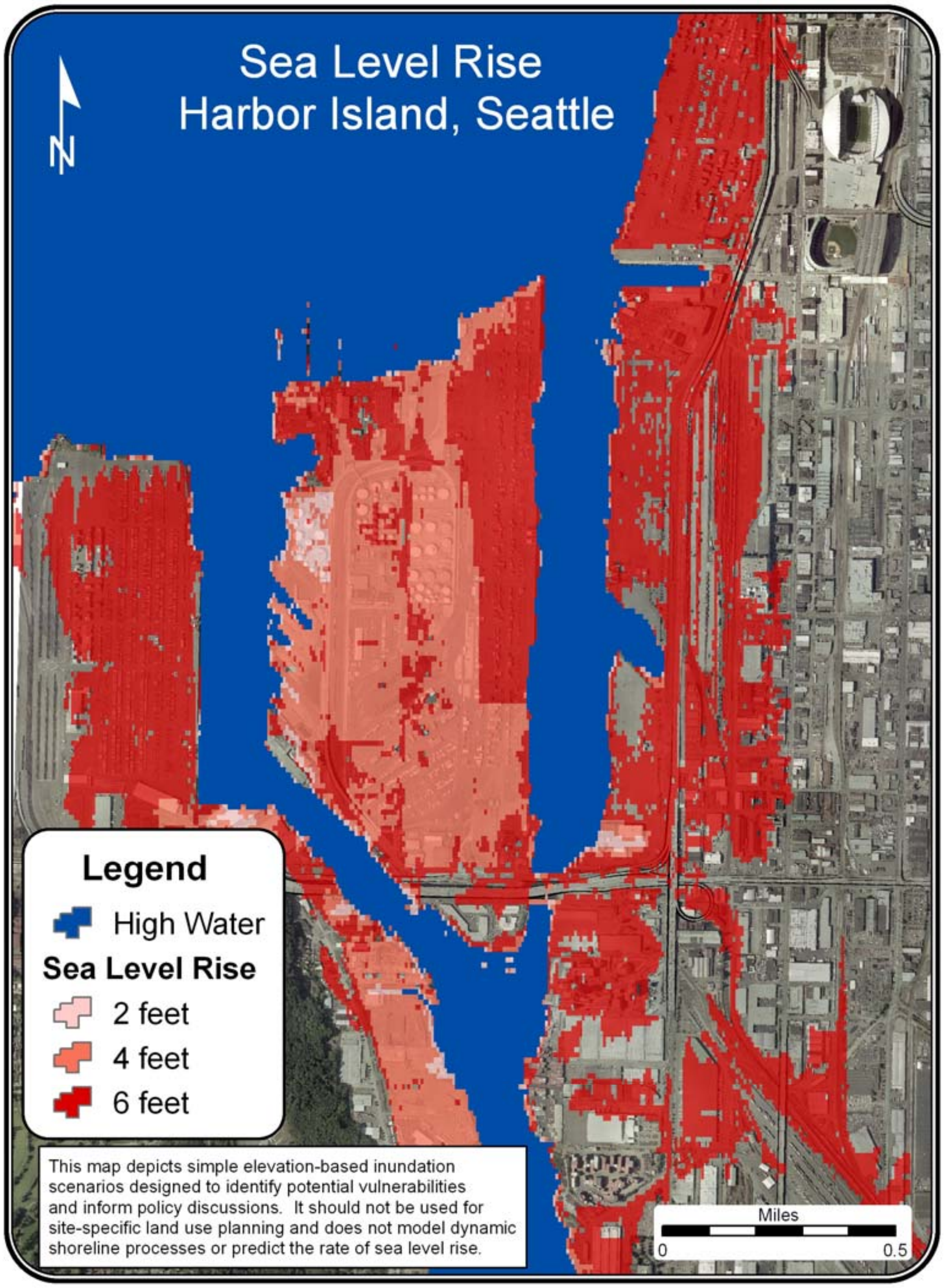


**Figure 3: Harbor Island inundation map**

Sea level rise inundation scenarios (two-feet, four-feet, and six-feet) for Harbor Island, Seattle

The aerial photography overlay helps identify areas of vulnerability and potential infrastructure risks. Possibly an effect of processing, a portion of the West Seattle Bridge is not shown. It appears that Harbor Island is not connected to the western shoreline, when in reality it is. The Seattle waterfront consists of a highly modified shoreline and the two-foot sea level rise scenario would have limited direct impact (light pink areas). Harbor Island, which is built on fill, is all low elevation and thus particularly vulnerable to changes in sea levels. Given the high economic value of the Port of Seattle facilities, the sports stadiums (shown in the upper right corner of the map), transportation facilities, office buildings and other infrastructure, it is likely that the benefits of protection will justify the costs. Actions, such as elevating the land, building sea walls, or other defenses, are potential responses to preserve this valuable land.

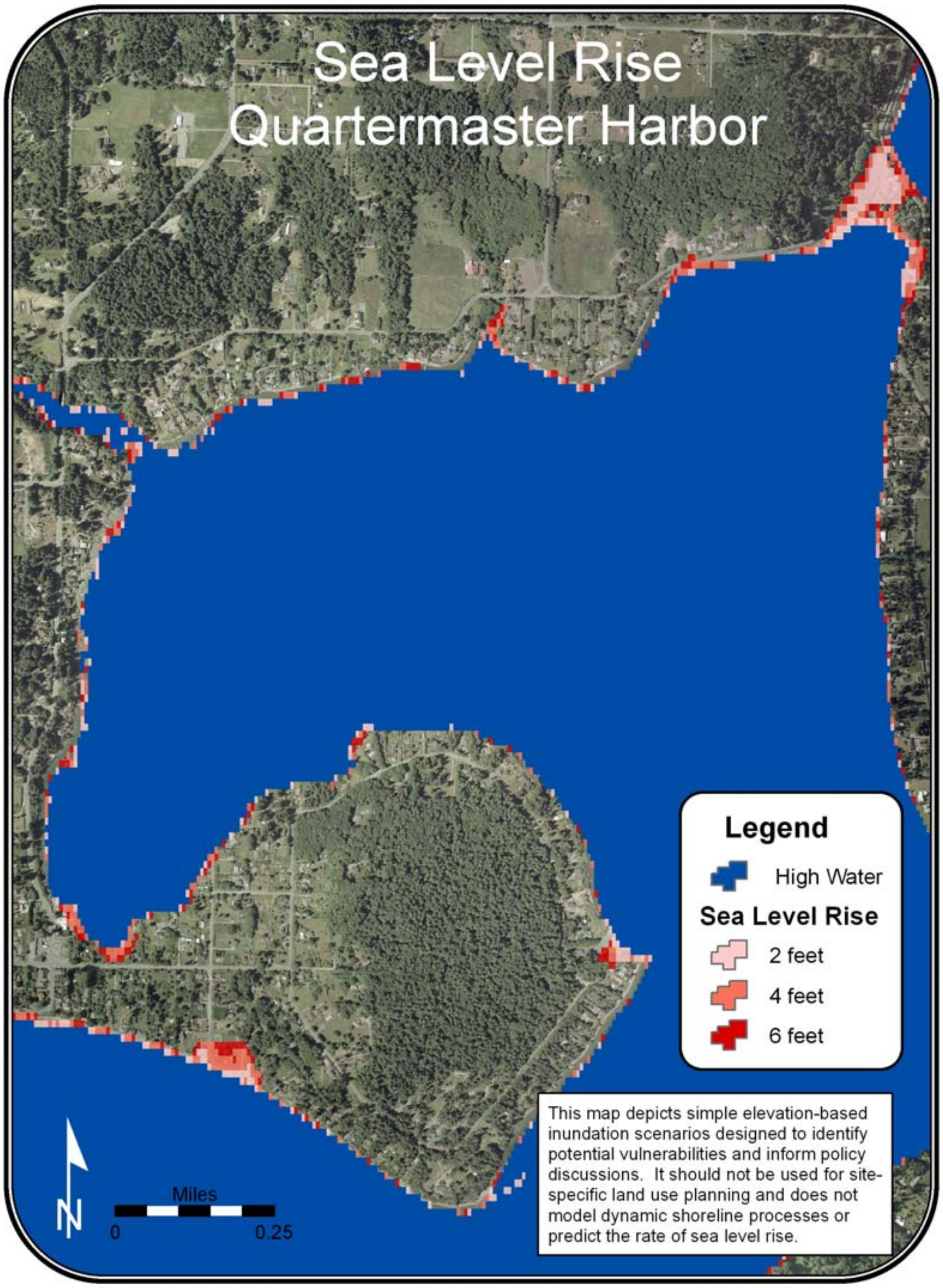


**Figure 4: Quartermaster Harbor inundation scenarios**

Sea level rise inundation scenarios (two-feet, four-feet, and six-feet) for Quartermaster Harbor between Vashon and Maury Islands

Vashon and Maury Islands represent the only unincorporated marine shoreline within King County's jurisdiction and are thus the only coastal areas within King County's jurisdiction for the SMP update process. The bluff backed beaches surrounding the harbor are typical for Puget Sound and show little inundation with increasing sea level. The majority of the impacts will be felt by homeowners and transportation infrastructure at the bottom of the bluffs. Increasing erosion and landsliding may affect bluff top areas as well, but these processes are not depicted with this mapping process. There is a low-lying portage between the islands that, aside from the elevated roadway, it is susceptible to inundation with only two feet of sea level rise. The road, however, will likely be subject to storm surge, wave action, and over-wash long before becoming submerged.

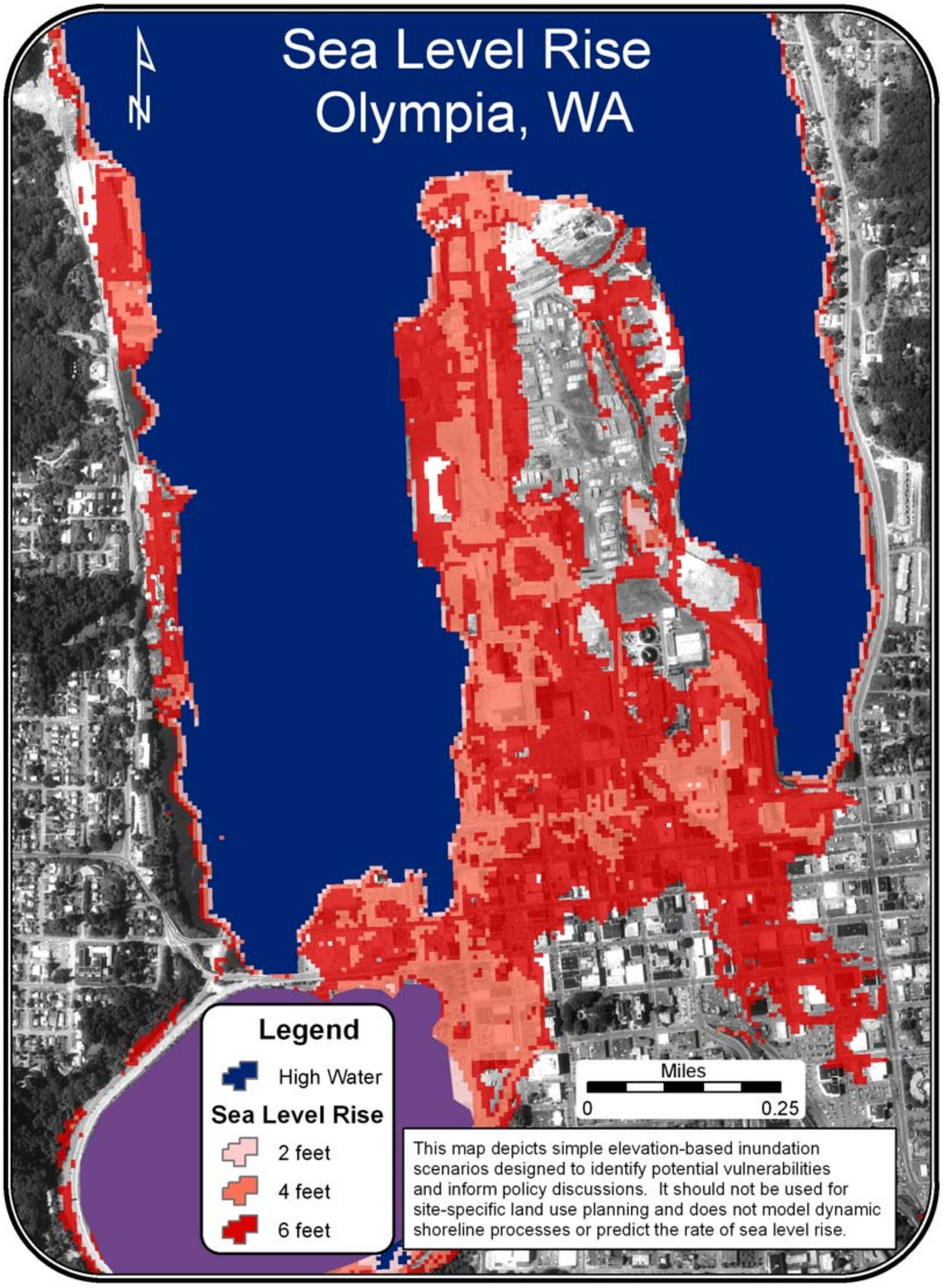


**Figure 5: Olympia inundation scenarios**

Sea level rise inundation scenarios (two-feet, four-feet, and six-feet) for downtown Olympia

Like the Seattle waterfront, much of downtown Olympia is also built on fill. The Port and the central business districts are vulnerable under the inundation scenarios selected. Even without sea level rise, downtown flooding has occurred more than once. Historic photographs show substantial flooding in June 1951 and December 1975 (Craig 1993). Capitol Lake (shown in purple) may be opened to tidal flushing in the near future (Garono et al. 2006) and will thus become more susceptible to sea level rise than the maps indicate. Two key infrastructure elements: the Cascade Pole hazardous waste site (northeast corner of the port peninsula) and the LOTT (Lacey, Olympia, Tumwater, Thurston) Partnership sewage treatment plant (clarifying tanks visible as black circles in the middle of the peninsula) both remain above the six-foot sea level rise scenario. Though above the inundation levels mapped, these facilities may be at risk from large storms as sea levels rise.

### 7.6 Floodplain Mapping

Sea level rise will not be experienced as the simple changes in inundation elevation depicted in the previous section. It will be experienced through increased flooding as formerly extreme events become relatively less extreme and more frequent. In an attempt to describe those changes, this study creates floodplain maps for Harbor Island, Seattle. For this area, the current regulatory flood zone is coincident with the shoreline and FEMA has not specified a coastal base flood elevation. This study uses the highest observed tide (12.14 ft. NAVD88, 1.89 feet. above Ordinary High Water[8], 1/27/1983)

[8] The process used for determining Ordinary High Water (OHW) is described in Appendix A.

measured at the Seattle tide gauge (Station ID: 9447130) as a proxy for the base flood elevation. Seattle has had an operational tide gauge since 1898. Thus, the highest observed tide during this era provides a reasonable estimate of the 100-year floodplain, especially given the one-foot vertical resolution of the DEM.

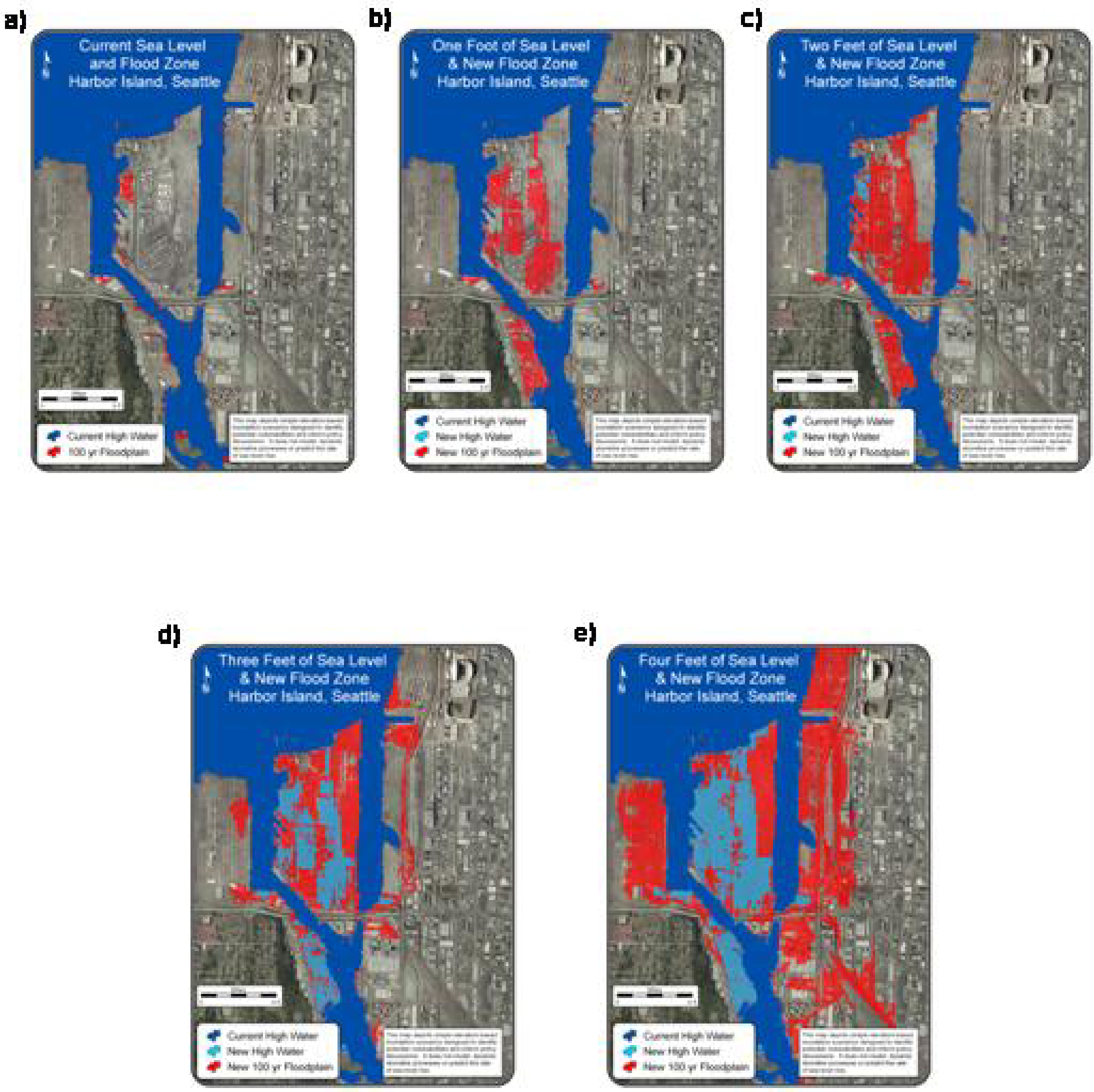


**Figure 6: Harbor Island floodplain changes**

a) Current sea level and associated floodplain, b) one-foot of sea level rise and new floodplain, c) two-feet of sea level rise and floodplain, d) three-feet of sea level rise and floodplain, and d) four-feet of sea level rise and floodplain

The current OHW is shown in dark blue and the associated 100-year coastal floodplain elevation, the base flood elevation, is shown in red on all five maps. The light blue depicts the new shoreline under each sea level rise scenario. Initially the heavily armored shoreline limits the extent of the floodplain (a). A one-foot increase in sea level creates a commensurate one-foot increase in the base flood elevation (b). As the sea levels increase, the floodplain expands, as does the area potentially vulnerable to large storms and major flood events (c & d). With a four-foot rise in sea level (e), the new flood zone is equivalent to the six-foot inundation scenario.

In each case, infrastructure within the new flood zone is at risk to impacts from large storm events. Changes in the climate system may change the frequency of those major storm events. A recent study by Salathé (2006) used statistical downscaling to predict changes in precipitation and storm tracks in the Pacific Northwest. His study predicts an increase in precipitation and more westerly storm orientations, instead of the currently more common southwest trajectory. This could increase the exposure frequency for some Puget Sound beaches. Thus, it is not simply the frequency but also the orientation of storm events that will likely change in the future.

# 8.0 Legal and Institutional Structure

## 8.1 Existing Framework

The legal landscape surrounding the issue of sea level rise is complex. There are many relevant laws and institutions at the federal, state, and local levels. Key agencies at the federal level include: the Environmental Protection Agency (EPA) responsible for administering the Clean Water Act; the Army Corps of Engineers (ACOE) responsible for issuing dredge and fill permits; the National Oceanic and Atmospheric Administration (NOAA) responsible for implementing the Coastal Zone Management Act (CZMA); and the Federal Emergency Management Agency (FEMA) responsible for administering the National Flood Insurance Program. At the Washington State level, the Department of Ecology (DOE) oversees implementation of the CZMA and floodplain management; the Department of Natural Resources (DNR) leases submerged lands; and the Department of Fish and Wildlife (WDFW) issues Hydraulic Project Approval permits. Local cities and counties implement a variety of coastal zone programs through development of a Shoreline Master Program (SMP), use of flood maps, designation of Critical Areas Ordinances, and creation of building codes.

### *8.1.1 Key Legal & Regulatory Components*

Figure 7, below, highlights the connections between the three different levels of government (federal, state, and local) and the geographic overlap of regulatory jurisdictions surrounding land use planning in Washington State's coastal zone.

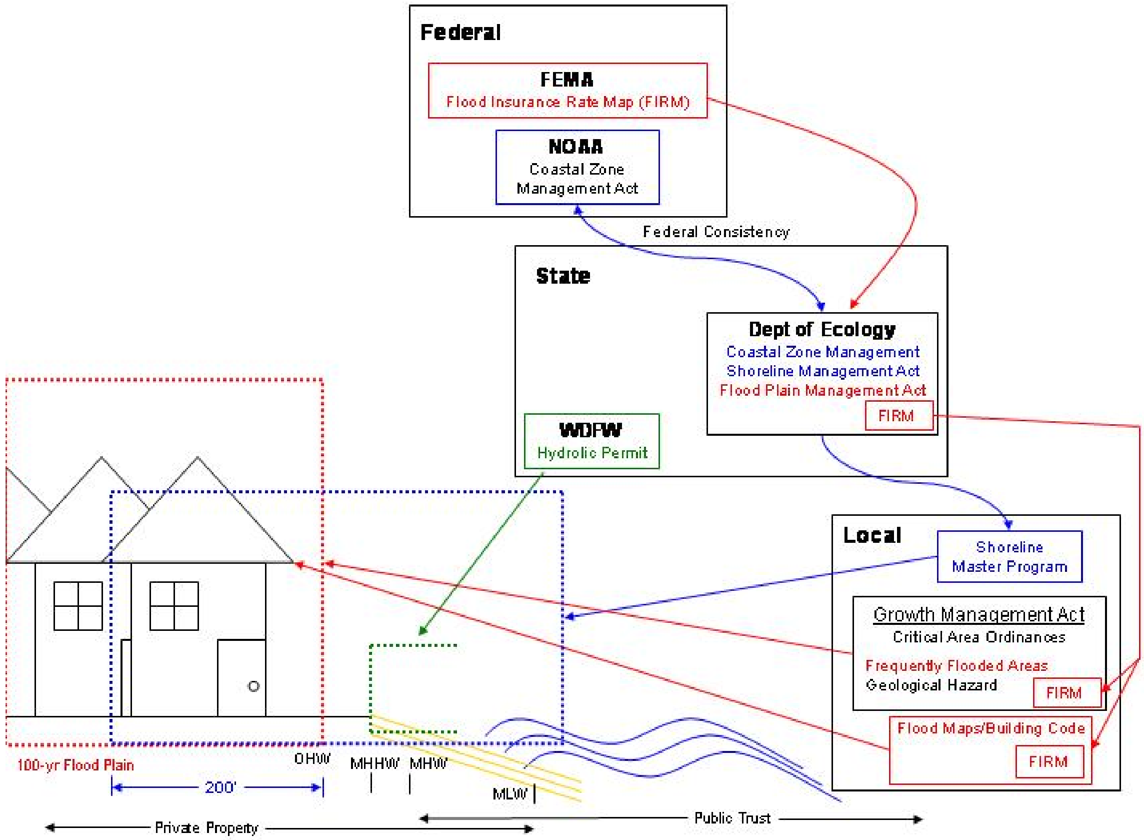


**Figure 7: Washington State coastal laws and regulations**

A conceptual diagram of key laws and regulations affecting the coastal zone in Washington State.

This diagram represents a simplified view of the regulatory jurisdictions and legal connections. For example, the SMA is primarily focused on the 200-foot shoreline zone (as shown) but is not limited to that boundary and can be expanded to include relevant floodplains and wetlands. The Growth Management Act (GMA) jurisdiction applies to the entire county and includes many components not shown. The included subset of the Critical Area Ordinance represents the sections most relevant to coastal zone planning.

Also, the dynamic reality of the coastal zone means that the boundaries between jurisdictions are not as clearly delineated in practice as they are in the diagram.

### *8.1.2 Previous Work*

A summary of the national, state and local laws and policies that affect sea level rise response in Washington State has already been completed (Klarin et al. 1990a, Klarin et al. 1990b). Although there have been some changes to these laws and regulations (*i.e.* addition of the Growth Management Act), this study does not attempt to repeat that analysis. Instead, this study identifies a number of current potential sea level rise response opportunities at the local government level and the impediments to implementation associated with those opportunities.

One key finding from the Klarin et al. (1990b) evaluation is that:

> Typically, policies addressing sea level rise are linked to existing coastal regulatory program objectives such as erosion control, coastal ecosystems preservation, and flood hazard protection. […] Policies or activities that are based on pre-existing authority have generally been found to be politically acceptable and easier to implement than attempts to establish new authorities. (pg vi)

This observation is still accurate today. Though it would be possible to design an entirely new regulatory structure to address sea level rise, many appropriate responses can also be based on existing laws and regulations. This approach may require a change in focus or new application not necessarily practiced in the past. Sea level rise will magnify the effects of existing coastal hazards such as erosion. Designing response strategies that make use of the current legal and regulatory structure can be more efficient and potentially more successful than starting from scratch. With this approach, sea level rise response can be incrementally integrated into the existing legal structure.

### 8.2 Summary of Key Opportunities

Opportunities for responding to sea level rise exist in a variety of arenas ranging from floodplain management to the recently required shoreline master program updates. Each of the four avenues discussed in the subsequent sections shows promise, but each also has associated impediments that must be overcome in order to make the response successful.

Broken down topically, each of the following sections outlines the legal framework for the issue. Where appropriate, the section will include discussion of important technical issues, the surrounding institutional framework, cross-scale dynamics, regulatory issues, and response options.

Defining the scale of the system under consideration is critical to any effort to assess or increase resilience. Cross-scale interactions are important in determining the resilience and effectiveness of response strategies. Where appropriate, the sections will include discussion of relevant cross-scale issues. However, this study will remain focused on the response options available to local governments as part of the larger legal landscape.

## 8.3 Flooding

Increasing flood frequency and landward migration of coastal floodplains are expected impacts of rising sea levels. Yet, the magnitude of these events is uncertain. Since both coastal and riverine flooding are current issues, there are a variety of laws at many governmental levels designed to reduce flood-related vulnerability. At the local level, the Seattle Municipal Code (SMC) has regulations that identify “flood prone areas” (SMC 25.09.020) and set building design requirements based on location relative to the floodplain (SMC 25.06). The State requires designation of frequently flooded areas by local governments as part of Critical Areas Ordinance (CAO) (RCW 36.70A.170) section of the Growth Management Act (GMA) (RCW 36.70A). Both the local government and state flood area designation are coincident with the Flood Insurance Rate Maps (FIRMs) developed by the Federal Emergency Management Agency (FEMA) as part of the National Flood Insurance Program (NFIP) (42 USC § 4001). This vertical connection between the different levels of government provides consistency, but ends up creating over-reliance on the FIRMs.

### *8.3.1 Technical Issues*

FEMA flood insurance studies are based on analysis of past flood events. The 100-year standard (1% annual probability) attempts to balance uncertainty and risk with the costs and benefits of implementation. The use of the 100-year flood event based on the historical record is established in laws and regulations and is not easily changed. The historical record will probably not accurately reflect future likelihood with global climate change and sea level rise. Without accurate maps, NFIP premiums and associated building requirements will be inadequate and over time more and more development will face increased flood risks (Hudgens 1999). It is particularly difficult to predict future changes in the timing and form of precipitation that will affect local floodplain designations, especially in riverine environments.

The effectiveness of the current floodplain designation to address issues of sea level rise is limited. In Seattle, for example, FEMA and subsequently the City have paid very little attention to coastal flooding. The detailed Flood Insurance Study for King County (FEMA 2005) devotes substantial effort to describing riverine flood environments but little or no effort on designating coastal floodplains. In fact, the currently designated coastal flood zone is coincident with the Seattle shoreline (FIRM 1995). The approach taken in Olympia contrasts that taken in Seattle as the base flood elevation has been mapped for Budd Inlet and Olympia’s coastal margin (FEMA 1981).

The Shoreline Management Act (SMA) promotes the use of current scientific information where feasible (RCW 90.58.100). One of the provisions of the Growth Management Act is the use of “best available science” in designating and protecting critical areas (RCW 36.70A.172), including frequently flooded areas (WAC-365-190-080). For critical areas within SMA jurisdiction, the SMP regulations must maintain the same level of protection as that granted by the GMA critical areas ordinances (WAC 173-26-221 2ii). The current state of climate change science is such that consideration of sea level rise could now be included as part of the "best available science" literature. The ultimate success of this approach for defining flood zones is dependent on a variety of factors including the size and capabilities of the jurisdiction creating the regulations (Francis et al. 2005).

### *8.3.2 Institutional Framework*

A thorough, uniform, and generally accepted procedure has been established to develop the FIRMs. Detailed studies of river flow environments and hydrological modeling are used to create the flood maps. These maps provide a centralized source of information that then creates a consistent floodplain definition that is referenced and used in other local laws and regulations. The use of a single consolidated set of flood maps provides consistency between local, state and national level regulations. The use of this single set of maps by multiple institutions such as the City of Seattle, Washington Department of Ecology, and FEMA provides one aspect of vertical integration that potentially improves policy outcomes (Underdal 1980). Unfortunately, it is possible to have too much of a good thing. An over-reliance on the FIRMs (discussed in sections 8.3.4 and 8.3.5) is just one aspect of some larger issues associated with federal flood insurance.

### *8.3.3 Larger Scale Issues*

In many cases, federal flood insurance and the promise of disaster declarations act as subsidies for coastal homeowners. This subsidy lowers the cost of insurance and provides an incentive for building (or re-building) in hazardous areas (Platt 1999). Federal insurance was designed as an incentive to increase building requirements and decrease the vulnerability (increase the resilience) of communities. It is considered vital in the event of a major disaster, but has the unintended consequence of increasing construction in hazardous areas. The program "…thus undermines its own efforts to promote mitigation…" (Platt 1999, pg 291). Developing solutions is not easy because land use planning is constrained by the property rights movement and the *takings*[9] issue (Platt 1999). It is beyond the scope of this study to provide recommendations or solutions to this complicated issue; however, it is important to realize that these existing federal regulations play a role in defining the response landscape and affect the viability of sea level rise response options.

#### *8.3.4 Regulatory Structure*

The final issue related to floodplain management comes from update requirements. Every seven years both local comprehensive plans and development regulations as part of the GMA (RCW 36.70A.130) and local SMPs (RCW 90.58.080) shall be reviewed and revised if necessary. Given the long-term nature of sea level rise, a seven-year update frequency is sufficient to allow flexible responses to changes in the local environment and to increase adaptive capacity. The National Flood Insurance Program contains similar provisions, stating that designated flood zones shall be reviewed by the FEMA director every five years (42 USC § 4101). The director will determine the need to revise or update the floodplain designations based on this review. Although the five-year review frequency appears more than adequate to facilitate sea level rise adaptation, in

---

[9] See Section 8.4.3 for a more detailed discussion of the *takings* issue.

practice, floodplain maps are updated much less frequently. The current 20+ year update frequency in Washington[10] is not adequate for adaptation to sea level rise. For example, assume a 2-foot rise in sea levels over the next 100 years and 25-year update frequency. This equates to a 0.5-foot rise during the period a FIRM is in use. In Olympia, this 0.5-foot rise is the difference between a 10-yr flood event and a 100-yr flood event (FEMA 1981). Clearly, that discrepancy represents a substantial change in the extent and frequency of flood events, and the FIRM would be out of date long before it was updated.

*8.3.5 Potential Response Options*

The first potential sea level rise response strategy is to increase the focus on coastal flooding. Adding explicit consideration of coastal zone flooding will raise awareness of coastal flooding, enhance building requirements, and decrease the impacts of coastal flooding events.

A second response option is to focus on increasing resilience by designing laws and regulations that are reviewed and updated as environmental conditions change. This idea has been proposed previously in the form of rolling easements (Titus 1998) or policies triggered by geomorphic changes (Klarin et al. 1990b) and the potential for implementation already exists. Implementation may be hindered by the perceived need for regulatory stability. Therefore, success requires shifts in perspectives and expectations from those creating, enforcing, and interpreting the regulations as well as

[10] The update frequency is based on the most recent dates for flood insurance rate maps in the region. The most recent flood insurance study for Olympia, Washington was completed in 1981.

those following them.   Increasing the frequency of flood map updates would be a step in this direction.

A third option would be for the local government to change its building codes and increase the height requirements above the base flood elevation.  Currently, the Seattle Municipal Code (SMC) requires two feet of free board above the base flood elevation for all new residential, non-residential, and live-work unit construction as well as three feet of free board for critical facilities, such as hospitals, located within the flood zone (SMC 25.06.110).  These standards exceed the minimum federal floodplain management requirement of elevating structures to the base flood elevation (44 CFR 60.3).  Much like the change in base elevation for the new City Hall in Olympia, raising these requirements an extra foot, or expanding the Seattle requirement to other jurisdictions, would provide: a safety margin; allow for changes in flood elevation; and increase the resilience of the system.  This could be a sub-component of a more general building strategy of “maximizing robustness and adaptability in the built environment” in response to climate change and uncertainty (Lowe 2004, pg 76).

### 8.4 Shoreline Armoring, Cumulative Impacts, and “No Net Loss”

The issue of shoreline armoring plays a key role in the legal landscape of the coastal zone and is a particularly relevant and important issue within Puget Sound.   Shoreline armoring is connected to sea level rise, cumulative impact assessments and the SMA’s "*no net loss*" requirement. This requirement provides an opportunity to explore the shoreline armoring issue and respond to sea level rise.

Washington State's Shoreline Management Act (RCW 90.58) and its implementing regulations are the core of the State's Coastal Zone Management Program and provide more than one avenue for addressing sea level rise. The first of these is the legal requirement that "local master programs shall include policies and regulations designed to achieve *no net loss* of those [shoreline] ecological functions" (WAC 173-26-186 8b, emphasis added). Consideration of *no net loss* is a new addition to the SMP Guidelines, adopted in 2002, and the process for making this determination is still being developed. The SMA Guidelines state that determination should be made with consideration of the "…cumulative impacts of *reasonably foreseeable future* development…" (WAC 173-26-186 8d emphasis added) and "…circumstances affecting the shorelines and *relevant natural processes*" (WAC 173-26-186 8di emphasis added).

### *8.4.1 Technical Issues*

Here again the dynamic and changing nature of the climate system is relevant. Currently, cumulative impacts are assessed based on the assumption of a static shoreline. However, that assumption is no longer appropriate for the *reasonably foreseeable future*. Given the state of knowledge, climate change, sea level rise, and the concomitant impacts should be considered part of the *relevant natural processes* and *reasonably foreseeable future* when designing policies and regulations for the coastal zone.

Cumulative impact assessment need not be tied to a specific date. It can be used to analyze the affects of the maximum development allowed under the proposed regulations regardless of when that development takes place. The addition of sea level rise to this analysis is complicated due to the large uncertainties in sea level rise and resultant changes in ecology and shoreline structure. Combining these uncertainties with a variety of development scenarios would make proving no net loss of ecological function even more difficult.

### *8.4.2 Institutional Structure*

The Washington State Department of Ecology plays a central role in the shoreline armoring (Section 8.4.4) and no net loss issues through the SMA. They are, however, not the only agency responsible for making shoreline armoring decisions. The Washington Department of Fish and Wildlife also has some control over shoreline armoring under the Hydraulic Project Approval (HPA) permit process (RCW 77.55). The permit requirement is designed to protect fish life and habitat from construction that occurs below the mean higher high water mark. Marine shoreline owners are given special consideration for property protection. Single-family homeowners are not exempt from the permit process and must meet a set of requirements on bulkhead placement (RCW 77.55.141). However, "protection of fish life is the only ground upon which approval of a permit may be denied or conditioned" (RCW 77.55.021 3a). The overlapping jurisdictions and different focus of the SMA and HPA permit processes highlight the complex nature of the institutional and regulatory structure in Washington's coastal zone.

In addition to these agencies, the U.S. Army Corps of Engineers (through the Rivers and Harbors act of 1899 and section 404 of the Clean Water Act) also has permit authority for some coastal zone actions. The vertical and horizontal integration and coordination between these institutions will be a factor in determining the full efficacy of any approach to address sea level rise. Potentially overriding this issue of integration is the tension between public and private interests in the use of coastal property.

#### 8.4.3 Larger Scale Issues

Protecting the shorelines for the benefit of the public is one of the State's responsibilities under the *Public Trust Doctrine* (Johnson et al. 1992). At the same time, great value is placed on private property and excessive regulation could be seen as a *taking* under the $5^{th}$ Amendment of the U.S. Constitution by removing reasonable use of the land and requiring just compensation to the private property owner (Constitution, *Lucas* 1992, Beydoun & Pearlman 2001). Thus, state and local governments must balance enhancing the public's enjoyment of the shoreline with protecting the rights of private property owners. The tension created by these two potentially conflicting goals can be seen in the shoreline protection issue.

The U.S. Supreme Court has determined that each *takings* case must be reviewed individually and that a "set formula" cannot be applied in every situation (*Penn Central* 1978). In general, the boundary between private uplands and public tidelands has been the mean high tide line and this boundary line extends or restricts with gradual imperceptible changes due to accretion, reliction, or erosion (Johnson et al. 1992).

*8.4.4 Regulatory Structure*

One aspect central to discussion of both the regulatory and institutional structure at the State level is the special status afforded to single-family residencies. Single-family homes are given priority in the SMA (RCW 90.58.020) along with ecological function, water-dependent, water-related, and water-enjoyment uses (WAC 173-26-211). Many types of development and construction in the shoreline area require "substantial development permits" (WAC 173-27). These permits allow for a review of proposed construction. However, there are three key exceptions to this requirement: 1) normal maintenance or repair of existing shoreline structures (WAC 173-27-40 2b); 2) construction of normal protective bulkheads for single-family residences (WAC 173-27-40 2c); and 3) construction of a "single-family residence" landward of the ordinary high water mark (WAC 173-27-40 2g). This does not mean that such structures are unregulated.

> An exemption from the substantial development permit process is not an exemption from compliance with the act or the local master program, nor from any other regulatory requirements. (WAC 173-27-40 1b)

However, it does remove one layer of oversight. The cumulative affect of these developments may have been considered as part of the SMA's cumulative impact assessment, but an aggregate analysis may not contain the same level of specificity and detail as an individual property specific analysis.

### *8.4.5 Potential Response Options*

Titus (1998) proposed the use of a rolling easement as a potential solution to the *takings* issue. As sea levels rise and the inundation area increases, the new high water mark becomes the new property line. Because change happens gradually, this approach does not eliminate economic use of the property and thus should not be considered a regulatory *taking*.

Though the underlying boundary delineation used in this approach is straightforward, it is the subsequent regulations that may be met with resistance. Implementing new setback requirements based on sea level rise predictions or limits on the type and/or placement of shoreline armoring run contrary to the current regulatory framework that provides preferential treatment for protection of single-family residences. A rolling easement approach has yet to be implemented and thus has not been exposed to legal challenge.

Options such as rolling easements are designed to increase the flexibility and adaptive capacity of the system. Instead of basing development decisions on the assumption of a static shoreline, this approach has the potential to increase the resilience of the system by increasing adaptive capacity. It also has the benefit of making use of the long-term nature of sea level rise and does not exclude economic use of property while it is still viable.

Another potential response option is based on the no net loss requirement and cumulative impact assessments. These assessments are particularly difficult when considering not just development but also dynamic shoreline changes. Despite this difficulty, the addition of a single sea level rise scenario, selected by the local jurisdiction, could lay the foundation for more comprehensive sea level rise consideration in the future.

## 8.5 Shoreline Management Act: Shoreline Designations

A second opportunity available through the SMA is the use of shoreline designations. As part of the SMA, implementation of this option will face many of the regulatory, institutional, and larger scale issues described in the previous section. As such, that discussion will not be repeated and this section will discuss only the relevant regulatory structure and potential response options.

### *8.5.1 Regulatory Structure*

The SMA requires local jurisdictions to create shoreline designations for different geographic areas (primarily based on current and projected shoreline uses). There are six general categories (high intensity, shoreline residential, urban conservancy, rural conservancy, natural, aquatic) but the creation of alternative designations is also allowed (WAC 173-26-211). Sea level rise could be built into the designation of these categories, allowing for tailored responses specific to the coastal regime. Two specific avenues could be explored.

*8.5.2 Potential Response Options*

The first response opportunity is the creation of a "threatened by sea level rise" shoreline designation. Based on potential sea level rise inundation maps, like those in this study, the designation could exist initially as a means of distributing information and informing landowners of potential risks. It could later be developed to include specific building and design requirements, setbacks, easements, or retreat policies.

The second strategy is to build sea level rise consideration and response into each of the specific shoreline designations. This would allow a local planning agency to develop location specific requirements based on current and future uses as well as the geological characteristics of the area. Areas designated as "high intensity" or "urban conservancy" are generally highly developed and may contain critical infrastructure. Due to the high economic value of these areas, protection, through land raising or shoreline armoring, is the likely community response to sea level rise. On the other hand, areas that are currently less modified, such as "natural" designations, could have a different set of regulations designed to facilitate natural ecosystem responses to rising sea levels. In these areas, limits on shoreline armoring could be set to allow for wetland migration. Consideration of the geological characteristics for each area would also be important as low-lying areas, or areas prone to erosion, require different regulations than other less vulnerable areas.

## 8.6 Coastal Zone Management Act

A fourth opportunity to address sea level rise exists through the connection between Washington's Coastal Zone Management Program (CZMP) and the Federal Coastal Zone Management Act (CZMA) (16 USC § 1451-1465). In the findings section, supporting the 1990 updates to the CZMA, Congress states that:

> Sea level rise will result in the loss of natural resources such as beaches, dunes, estuaries, and wetlands, and will contribute to the salinization of drinking water supplies. Sea level rise will also result in damage to properties, infrastructures, and public works. There is a growing need to plan for sea level rise.
> (Pub. L. 101-508 section 6202 a7)

This specific mention of sea level rise creates a response opportunity.

### *8.6.1 Institutional Framework*

The intricate relationship between federal and state governments and agencies created through the Federal Consistency requirement of the CZMA (15 CFR 930) is not unique to the issue of sea level rise. The Consistency provision of the CZMA requires any federal action that "affects the coastal zone" be consistent to the "maximum extent practicable" with the "enforceable policies" of a state's approved CZMP (15 CFR 930). This rule applies to all federal agency actions and those actions permitted or funded by federal agencies. For example, the Army Corps of Engineers (ACOE) performing dredge and fill operations or granting permits for those actions falls under this Federal Consistency requirement.

### *8.6.2 Regulatory Structure*

In 1976, Washington became the first state to have a federally approved CZMP. The program is considered a "networked program" because it consists of a set of coordinated laws and enforceable policies that existed prior to the CZMA (Swanson 2001). The core of this network is the SMA. The 1990 amendments to the CZMA contain numerous references to sea level rise. One example is quoted below:

> Because global warming may result in a substantial sea level rise with serious adverse effects in the coastal zone, coastal states must anticipate and plan for such an occurrence. (16 USC § 1451 l)

Since Washington's CZMP was already approved and in place when these amendments were made, the State is not required to make changes to its CZMP. However, the language of the CZMA does provide support for responding to sea level rise if the State decides to do so. Consideration of sea level rise is thus not currently part of the SMA, but future updates to the SMA, by the Washington State Legislature, could require local governments to consider sea level rise and use the CZMA as justification for that approach.

### *8.6.3 Cross-scale Issues*

When updating their SMPs, or implementing other state laws, local jurisdictions frequently have difficulty using their limited resources to meet State requirements. Thus, it is unlikely that they will choose to go out of their way to add a complicated task, such as the consideration of sea level rise, unless it is a requirement. This is particularly true for smaller jurisdictions with fewer resources and is less of a constraint for King County and the City of Seattle.

#### *8.6.4 Potential Response Options*

First, the State could update the SMA to require consideration of sea level rise. Through the Federal Consistency provision, this decision would then affect federal actions in the coastal zone. Once again, the ACOE provides a relevant example. If the ACOE granted a dredge and fill permit, under CWA Section 404, that did not conform with the new requirements, the State could deny the permit as not being consistent with its approved CZMP. The ACOE could appeal this determination to the Secretary of Commerce (who oversees NOAA). The Secretary would then consider the goals and intent of the CZMA in making a determination if the ACOE action is consistent with the objectives of the CZMA (15 C.F.R. § 930.121). The outcome would of course depend on the specific facts of the case. However, since sea level rise is included in the CZMA, this approach has the potential to increase the State's power to control activities within its coastal zone and allow the State additional leverage to address sea level rise.

A second avenue for developing sea level rise response through the CZMA is federal funding. If the DOE decides that consideration of sea level rise response is important, it can apply for federal funds to achieve that goal. The CZMA provides "coastal zone enhancement grants" (16 USC 33 § 1456b) to help states comply with the "enhancement objectives" of the CZMA. Specifically, enhancement objective 2 includes "...anticipating and managing the effects of potential sea level rise…" (16 USC 33 § 1456b a2). The State could use this objective to justify requesting additional funds that it could then use, or pass on to local jurisdictions, for implementing sea level rise responses. These funds would be available to support the opportunities already discussed, updating flood maps, performing cumulative impact assessments with a changing natural environment, developing specific sea level rise scenarios, or conducting vulnerability assessments.

# 9.0 Conclusion

Global climate change is a complex and multi-faceted issue. Response to this issue requires actions on a variety of fronts and at many levels of government. Only in combination will these semi-independent steps be enough to change the trajectory of climate change, allow societies to adapt to the unavoidable changes, and decrease climate change impacts.

This study of sea level rise adaptation and response options for local governments is geographically restricted to the Puget Sound region and constrained to the context of public institutions. These constraints are appropriate for two reasons. First, realistic and useful sea level rise scenarios are specific to the topography of a local region. Geographic restriction allows for the creation of non-catastrophic sea level rise scenarios valuable for qualitatively determining vulnerability. The process described can, of course, be generalized and applied in other regions.

Second, local governments and public institutions are a good fit with regional scale adaptation. They have long-term planning horizons appropriate for designing response strategies to sea level rise. These institutions are also customarily responsible for coastal land use management. Current decisions in this arena will play a major role in determining the ultimate consequences of sea level rise.

The research questions in this study focus on analyzing the regulatory and institutional structure surrounding coastal zone management and the sea level rise issue. However, a detailed analysis of this framework and the viability of potential sea level rise response opportunities must be based on an understanding of sea level rise science.

Section 4 describes the current scientific basis for sea level rise. It is apparent that the issue of sea level rise is complicated by the difficulties in understanding and modeling ice-sheet dynamics. It is not currently possible to make exact sea level rise predictions due to both the scientific uncertainty and the long-term sea level rise dependence on human responses to climate change. This embedded uncertainty means that decision-makers are unable to wait for perfect information before taking action. Thus, it is important to develop a theoretical framework and tools that will allow decision-makers to take action in this uncertain environment.

Though not an initial goal, this study has found that concepts of resilience (Section 5) provide a valuable framework for addressing sea level rise (Section 6). Resilience acknowledges the complex and potentially non-linear nature of the combined social-ecological system as well as the possibility of threshold responses and multiple equilibria. This view represents a paradigm shift from that used in more traditional management practices. Though it may be difficult to implement, this new perspective is necessary to develop successful response options when addressing climate change and sea level rise.

Approaching the issue of sea level rise from a resilience perspective does not attempt to eliminate the inherent uncertainty, but attempts to find better ways to prepare for change and co-exist with that uncertainty. It looks not to maintain the status quo, but increase the ability of the system to adapt and respond to inevitable changes. It is no longer sufficient to make decisions and construct management plans based on the expectation of a static shoreline. The ideas of resilience support a decision-making framework that considers a dynamic shoreline, future environmental change, and the long-term affects of decisions on the combined social-ecological system.

Sea levels will continue to rise for many centuries and forward thinking decision-makers will have the ability to design proactive response strategies that will allow for adaptation to those changes. The concepts of resilience provide a framework for analyzing not only potential sea level rise impacts but also policy response options.

The effort to determine effective policy response options is aided by the use of current mapping technology. High-resolution data sources provide a powerful and useful tool with which to respond to sea level rise. Computing resources allow for the efficient generation of a variety of relative sea level rise scenarios based on the local realities of vertical land movement and topography (Section 7). The choice of scenarios can build community understanding and highlight areas of vulnerability. The availability of high-resolution data allows for the creation of non-catastrophic scenarios that can be used to inform local decisions and initiate consideration of legal and regulatory opportunities for response.

It is now possible to answer the initial research questions:

> *1) What are the key regulatory and institutional barriers to incorporating sea level rise science and its associated uncertainty into decision making?*
>
> *2) How can these impediments be overcome in order to develop a policy framework that can effectively incorporate consideration of the uncertainty associated with sea level rise?*

*1)* The laws, regulations, and institutions affecting the coastal zone create a complicated landscape that can be hard to navigate. Overlapping legal and regulatory jurisdictions can create conflicts between institutions, over-dependence on out dated flood maps, and difficulty finding viable solutions or sea level rise response options.

*2)* This study does not identify an individual response option as a perfect solution to the issue of sea level rise. However, it does highlight four potential opportunities, their associated barriers, and potential policy responses (Section 8). The following table provides a detailed summary of the key opportunities, impediments, and response options.

**Table 1: Legal impediments and opportunities**

Identification of four potential sea level rise response opportunities in Washington State, their associated legal structure, and impediments.

| Opportunities | Laws and Regulations | Impediments | Response Options |
|---|---|---|---|
| **Designated Floodplains & Building Codes** | ▪ FEMA Flood Insurance Rate Maps<br>▪ CAO Frequently Flooded Areas<br>▪ Shoreline Management Act<br>▪ City of Seattle Flood Regulations<br>▪ City of Seattle Building Codes | ▪ Coastal flooding not fully considered<br>▪ FEMA 20+ year FIRM update frequency<br>▪ Current floodplain maps based on past event that may not accurately reflect future probabilities | ▪ Expand flood map studies to include coastal environments<br>▪ Design laws and regulations to update as environmental conditions change<br>▪ Increase frequency of floodplain updates to SMA & GMA 7 year requirements |
| **Management of Shoreline Armoring** | ▪ SMA Cumulative Impacts<br>▪ SMA No Net Loss of Ecological Functions | ▪ Expectations of private property rights<br>▪ Multiple choices for appropriate sea level rise planning scenarios<br>▪ Determination of horizon for cumulative impacts difficult | ▪ Use rolling easement for property boundary determination as sea levels rise.<br>▪ Use dynamic shoreline when making no net loss or cumulative impact determinations |
| **Shoreline Designations** | ▪ SMA Shoreline Designations | ▪ Inclusion of sea level rise not required as part of the SMP update process.<br>▪ Limited capacity of small jurisdictions to satisfy more than the minimum requirements | ▪ Create "threatened by sea level rise" category for vulnerable areas<br>▪ Tailor sea level rise response to specific shoreline designations |
| **Connection to Federal Coastal Zone Management Priorities** | ▪ Coastal Zone Management Act<br>▪ Washington State CZMP<br>▪ Shoreline Management Act | ▪ State's approved CZMP not required to be updated to reflect federal amendments | ▪ Update SMA to include consideration of sea level rise<br>▪ Leverage the Federal Consistency provision to require sea level rise consideration in federal actions<br>▪ Request additional funding through CZMA "enhancement grants" |

The first two response options, summarized in Table 1 above, arise directly from a consideration of social-ecological resilience. The recommendation for regular floodplain map updates, in order to account for changing environmental conditions and sea level rise, depends on an acknowledgement of the dynamic and ever changing nature of the coastal zone. The explicit consideration of a dynamic shoreline in cumulative impact assessments and the idea of rolling easements also depend on this realization. Each of the response options is focused on increasing the resilience of the system to sea level rise and climate change. The concepts of resilience provide decision-makers a framework with which to make choices and take actions in an uncertainty environment.

The long-term nature of sea level rise affords a response opportunity not available in other areas. By planning now and using the tools currently available, local governments and communities can increase their ability to adapt to future changes. Explicitly considering sea level rise as one component of the local land use planning process will decrease the cost of future responses and increase the resilience of the surrounding social-ecological system.

# List of References


Adger, W.N., 2000. Social and ecological resilience: are they related?. *Progress in Human Geography*. **23**(3): 347-364.

Alley, R., Clark, P., Huybrechts, P., Joughin, I., 2005. Ice-sheet and Sea-level Change. *Science*. **310**: 456-460.

An Inconvenient Truth, 2006. Dir. Davis Guggenheim. Lawrence Bender Productions. Paramount Classics. USA.

Anderies, J., Walker, B., Kinzig, A., 2006. Fifteen Weddings and a Funeral: Case Studies and Resilience-based Management. *Ecology and Society*. **11**(1): 21-33.

Berkes, F., Colding, J., Folke, C., (Eds.). 2003. *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change.* Cambridge University Press. New York, NY, USA.

Berkhout, F., Hertin, J., Jordan, A., 2001. Socio-economic futures in climate change impact assessment: using scenarios as 'learning machines'. Tyndall Centre for Climate Change Research. Working Paper 3. UK.

Beydoun, M. & Pearlman, K., 2001. Takings and Land Use Regulations: A Review of Recent Law Journal Literature. *Journal of Planning Literature* **16**(1): 19-61.

Brooks, N., Adger, W.N., Kelly, M., 2005. The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change.* **15**: 151-163.

Burkett, V., Wilcox, D., Stottlemyer, R., Barrow, W., Fagre, D., Baron, J., Price, J., Nielsen, J., Allen, C., Petersen, D., Ruggerone, G., Doyle, T., 2005. Nonlinear Dynamics in Ecosystem Response to Climatic Change: Case Studies and Policy Implications. *Ecological Complexity*. **2**: 357-394.

Carpenter, S., Walker, B., Anderies, M., Abel, N., 2001. From Metaphor to Measurement: Resilience of What to What?. *Ecosystems*. **4**: 765-781.

Chapin, S., Lovecraft, A., Zavaleta, E., Nelson, J., Robards, M., Kofinas, G., Trainor, S., Peterson, G., Huntington, H., Naylor, R., 2006a. Policy Strategies to Address Sustainability of Alaskan Boreal Forests in Response to a Directionally Changing Climate. *PNAS*. **103**(45): 16637-16643.

Chapin S., Robards, M., Huntington, H., Johnstone, J., Trainor, S., Kofinas, G., Ruess, R., Fresco, N., Natcher, D., Naylor, R., 2006b. Directional changes in ecological communities and social-ecological systems: a framework for prediction based on Alaskan examples. *The American Naturalist.* **168**(6): S36-49.

Chen, J., Wilson, C., Tapley, B., 2006. Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet. *Science*. **313**: 1958-1960.

Church, J., White, N., Coleman, R., Lambeck, K., Mitrovica, J., 2004. Estimates of the Regional Distribution of Sea Level Rise over the 1950-2000 Period. *American Meteorological Society*. **17**: 2609-2625.

Code of Federal Regulations (CFR). 2007. Title 15. Section 930. Federal Consistency with Approved Coastal Management Programs.

Code of Federal Regulations (CFR). 2007. Title 44 Section 60.3. Criteria for Land Management and Use. Requirements for flood plain management regulations.

Cohen, S., 2005. Climate Change Will Impact the Seattle Department of Transportation. Submitted to Seattle Mayor and City Council Members. Conducted by the Office of the City Auditor.

Constitution of the United States. Amendment V.

Craig, D. 1993. Preliminary assessment of sea level rise in Olympia, Washington: Technical and policy implications. Policy and Program Development Division, Olympia Public Works Department, Olympia.

Federal Emergency Management Agency (FEMA). 1981. *Flood Insurance Study. City of Olympia, Washington, Thurston County.* Community Number 530191.

Federal Emergency Management Agency (FEMA). 2005. *Flood Insurance Study. King County, Washington and Incorporated Areas* Volumes 1-3. Flood Insurance Study Numbers: 53033CV001A, 53033CV002A, 53033CV002A.

Finlayson, D., 2005. Combined bathymetry and topography of the Puget Lowland, Washington State. University of Washington. http://www.ocean.washington.edu/data/pugetsound/ (Downloaded Fall 2006)

Fiorino, D. 1995. *Making Environmental Policy*. University of California Press. Berkeley and Los Angeles, CA.

Flood Insurance Rate Map (FIRM). 1995. King County Washington and Incorporated Areas. Map Number 53033C0630 F. Federal Emergency Management Agency.

Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C.S., Walker, B., Bengtsson, J., Berkes, F., Colding, J., Danell, K., Falkenmark, M., Gordon, L., Kaspersson, R., Kautsky, N., Kinzig, A., Levin, S., Mäler, K., Moberg, F., Ohlsson, L., Olsson, P., Ostrom, E., Reid, W., Rockström, J., Savenije, S., Svedin, U., 2002. Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations. Report for the Swedish Environmental Advisory Council.

Folke, C., 2006. Resilience: The Emergence of a Perspective for Social-ecological Systems Analyses. *Global Environmental Change*. **16** 253-267.

Francis, T., Whittaker, K., Shandas, V., Mills, A., Graybill, J., 2005. Incorporating Science into the Environmental Policy Process: a Case Study from Washington State. *Ecology and Society*. **10**(1): 35-51.

Füssel, H. & Klein, R., 2006. Climate Change Vulnerability Assessments: an Evolution of Conceptual Thinking. *Climatic Change*. **75**: 301-329.

Garono, R., Thompson, E., Koehler, M., 2006. Deschutes River Estuary Restoration Study Biological Conditions Report. Wetland & Watershed Assessment Group Earth Design Consultants, Inc. submitted to Thurston Regional Planning Council.

Holdahl, S., Faucher, F., Dragert, H., 1989. Contemporary vertical crustal motion in the Pacific Northwest. Slow Deformation and Transmission of Stress in the Earth. *Geophysics Monograph Series*. **49**: 17-29.

Holling, C.S., 1973. Resilience and stability of ecological systems. *Annual Review of Ecological Systems*. **4**: 1-23.

Howat, I., Joughin, I., Scambos, T., 2007. Rapid Changes in Ice Discharge from Greenland Outlet Glaciers. *Science*. **315**: 1559-1561.

Hudgens, D., 1999. Adapting the National Flood Insurance Program to Relative Sea Level Rise. *Coastal Management.* **27**: 367-375.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Emissions Scenarios Summary for Policy Makers.* A Special Report of Working Group III.

Intergovernmental Panel on Climate Change (IPCC). 2001. Climate Change 2001: *The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. [Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.)]. Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA. 881 pp.

Intergovernmental Panel on Climate Change (IPCC). 2007a. *Climate Change 2007: The Physical Science Basis. Summary for Policy Makers.* 10th Session of the Working Group I of the IPCC. Paris, France.

Intergovernmental Panel on Climate Change (IPCC). 2007b. *Climate Change 2007: Climate Change Impacts, Adaptation and Vulnerability*. Working Group II Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report.

Johnson, R., Goeppele, C., Jansen, D., Paschal, R., 1992. The Public Trust Doctrine and Coastal Zone Management in Washington State. *Washington Law Review*. **67**: 521-598.

King County. 2006. *King County Shorelines Technical Appendix*. Draft Volume 1. Shoreline Inventory and Characterization: Methodology and Results. King County, Washington. Available on-line: http://www.metrokc.gov/shorelines/technical-appendix-contents.aspx (Accessed April 23, 2007).

Klarin, P., Branch, K., Hershman, M., Grant, T., 1990a. *Sea level rise policy alternatives study: Volume 1, Alternative policy responses for accelerated sea level rise and their implications.* Battelle Human Affairs Research Centers for Shorelands and Coastal Zone Management Program. Washington Department of Ecology. Olympia.

Klarin, P., Branch, K., Hershman, M., Grant, T., 1990b. *Sea level rise policy alternatives study: Volume 2, An analytical review of state and federal coastal management systems and policy responses to sea level rise.* Battelle Human Affairs Research Centers for Shorelands and Coastal Zone Management Program. Washington Department of Ecology. Olympia.

Klein, R., Nicholls, R., Thomalla, F., 2003. Resilience to natural hazards: How useful is this concept?. *Environmental Hazards*. **5**: 35-45.

Klinke, A. & Renn, O., 2002. A New Approach to Risk Evaluation and Management: Risk-based, Precaution-based, and Discourse-based Strategies. *Risk Analysis*. **22**(6): 1071-1094.

Kluger, J., 2007. What Now For Our Feverish Planet?. *Time*. April 9. **169**(15): 50-60.

Lowe, R., 2004. Lessons from climate change: a response to the commentaries. *Building Research & Information.* **32**(1): 75-78.

Lucas v. South Carolina Coastal Council (*Lucas*). 1992. Supreme Court of the United States. 505 U.S. 1003.

McCarthy, J. Canziani, O., Leary, N., (Eds.). 2001. Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge, UK.

Meehl, G., Washington, W., Collins, W., Arblaster, J., Hu, A., Buja, L., Strand, W., Teng, H., 2005. How Much More Global Warming and Sea Level Rise?. *Science*. **307**: 1769-1772.

Milbank, D., 2007. Kerry and Gingrich Hugging Trees—and (Almost) Each Other. *Washington Post.* April 11, 2007.

Miller, L. & Douglas, B., 2006. On the rate and causes of twentieth century sea-level rise. *Phil. Trans. R. Soc. A.* **364**: 805-820.

Mitchell, C., Vincent, P., Weldon, R., Richards, M., 1994. Present-day vertical deformations of the Cascadia margin, Pacific Northwest, United States. *Journal of Geophysical Research*. **99**(B6): 12257-12277.

Mucha, M. & Hoey, R., 2007. Climate Change and Sea Level Rise. Council Study Session. City of Olympia. Public Works Department. Olympia, Washington. March 27. Agenda Item 6A.

Nerem, R., Leuliette, E., Cazenave, A., 2006. Present-day Sea-level change: A review. *C. R. Geoscience*. **338**: 1077-1083.

Nicholls, R. & Hoozemans, F., 2002. Global Vulnerability Analysis. In *Encyclopedia of Coastal Science.* Edited by Schwartz, M. Springer.

NOAA. Tides and Currents. Tidal Datums and Benchmarks. http://tidesandcurrents.noaa.gov/ (Accessed: January 2007)

NOAA. VDatum. Updated 2004.Vertical Datum Transformation Software Version 1.06. http://nauticalcharts.noaa.gov/csdl/vdatum_projectsWA.htm (Downloaded Jan. 2007)

Nyström, M., Folke, C., Moberg, F., 2000. Coral reef disturbance and resilience in a human-dominated environment. *Trends in Ecology & Evolution*. **15**(10): 413-417.

Overpeck, J., Otto-Bliesner, B., Miller, G., Muhs, D., Alley, R., Kiehl, J., 2006. Paleoclimatic Evidence for Future Ice-Sheet Instability and Rapid Sea-Level Rise. *Science*. **311**: 1747-1750.

Penn Central Transportation Company v. New York City (*Penn Central)*. 1978. Supreme Court of the United States. 438 U.S. 104.

Peterson, G., Cumming, G., Carpenter, S., 2003. Scenario Planning: a Tool for Conservation in an Uncertain World. *Conservation Biology*. **17**(2): 358-366.

Platt, R., 1999. Disasters and Democracy, The Politics of Extreme Natural Events. Island Press. Washington, D.C.

Public Law 101-508. 1990. Omnibus Budget Reconciliation Act of 1990. Sections 6201-6217. Coastal Zone Act Reauthorization Amendments of 1990.

Rahmstorf, S., 2007. A Semi-empirical Approach to Projecting Future Sea-level Rise. *Science* **315:** 368-370.

Resilience Alliance. 2007. Thresholds and Alternate States in Ecological and Social-Ecological Systems Database. http://www.resalliance.org/185.php. (Accessed: May 2007).

Revised Code of Washington (RCW). 36.70A. Growth Management Act.

Revised Code of Washington (RCW). 77.55. Construction Projects in State Waters.

Revised Code of Washington (RCW). 86.16. Flood Plain Management.

Revised Code of Washington (RCW). 90.58. Shoreline Management Act of 1971.

Rial, J., Pielke, R., Beniston, M., Claussen, M., Canadell, J., Cox, P., Held, H., Noblet-Ducoudré, N., Prinn, R., Reynolds, J., Salas, J., 2004. Nonlinearities, Feedbacks and Critical Thresholds within the Earth's Climate System. *Climatic Change*. **65**: 11-38.

Rignot, E. & Kanagaratnam, P., 2006. Changes in the Velocity Structure of the Greenland Ice Sheet. *Science*. **311**: 986-990.

Robards, R. & Greenberg, J., 2007. Global constraints on rural fishing communities: whose resilience is it anyway?. *Fish and Fisheries*. **8**(1): 14-30.

Salathé, E., 2006. Influences of a shift in North Pacific storm tracks on western North American precipitation under global warming. *Geophysical Research Letters*. **33**. L19820. 4 pages.

Sarewitz, D., Pielke, R. Jr., Keykhah, M., 2003. Vulnerability and Risk: Some Thoughts from a Political and Policy Perspective. *Risk Analysis.* **23**(4): 805-810.

Schneider, S., 2002. Can we Estimate the Likelihood of Climatic Changes at 2100? An Editorial Comment. *Climatic Change.* **52:** 441-451.

Seattle Municipal Code (SMC). Chapter 25.06 Floodplain Development.

Seattle Municipal Code (SMC). Chapter 25.09. Regulations for Environmentally Critical Areas.

Shipman, H., 1989. Vertical Land Movements in Coastal Washington. *Washington Geologic Newsletter.* **18**(1): 26-32.

Subbotina, M., Thomson, R., Rabinovich, A., 2001. Spectral characteristics of sea level variability along the west coast of North America during the 1982-83 and 1997-98 El Niño events. *Progress in Oceanography*. **49**: 353-372.

Swanson, T. (Ed). 2001. Managing Washington's Coast. Washington's Coastal Zone Management Program. Washington State Department of Ecology. Publication 00-06-029.

Titus, J., 1998. Rising Seas, Coastal Erosion, and the Takings Clause: How to Save Wetlands and Beaches without Hurting Property Owners. *Maryland law Review*. **57**(4): 1279-1399.

Tol, R., 2005. Adaptation and mitigation: trade-offs in substance and methods. *Environmental Science & Policy*. **8**: 572-578.

Tompkins, E. & Adger, W.N., 2004. Does Adaptive management of Natural Resources Enhance Resilience to Climate Change?. *Ecology and Society*. **9**(2): 10.

Underdal, A., 1980. Integrated Marine Policy. What? Why? How?. *Marine Policy.* **4**:159-169.

United States Code (USC). Title 16. Chapter 33. Coastal Zone Management.

United States Code (USC). Title 33. Chapter 9. Rivers and Harbors Act of 1899.

United States Code (USC). Title 33. Chapter 26. Water Pollution Prevention and Control. Clean Water Act.

United States Code (USC). Title 42. Chapter 50. National Flood Insurance.

Verdonck, D., 2006. Contemporary vertical crustal deformations in Cascadia. *Techonophysics*. **417**: 221-230.

Walker, B., Holling, C.S., Carpenter, S., Kinzig, A., 2004. Resilience, Adaptability and Transformability in Social-ecological Systems. *Ecology and Society*. **9**(2): 5-13.

Walker, B., Gunderson, L., Kinzig, A., Folke, C., Carpenter, S., Schultz, L., 2006. A Handful of Heurisitics and Some Propositions for Understanding Resilience in Social-Ecological Systems. *Ecology and Society*. **11**(1): 13-27.

Washington Administrative Code (WAC). Title 173. Chapter 173-26. State master program approval/amendment procedures and master program guidelines.

Washington Administrative Code (WAC). Title 173. Chapter 173-27. Shoreline management permit and enforcement procedures.

Washington Administrative Code (WAC). Title 365. Chapter 365-190. Minimum guidelines to classify agriculture, forest, mineral lands and critical areas.

Washington State Geospatial Data Archive (WAGDA). 2002. Central Puget Sound color Orthophotography. UTM Zone 10 North provided by USGS. http://wagda.lib.washington.edu/data/type/photography/puget_sound/

Wigley, T., 2005. The Climate Change Commitment. *Science*. **307**: 1766-1769.

# Appendix A: Mapping Methodology

The maps were created using ArcGIS 9.1 products (ArcMap, Arc Catalog) in the following steps.

1) The Puget Sound Combined DEM (Finlayson 2005) was downloaded, converted to raster format and the projection was defined to match that specified by the metadata. Horizontal coordinate system: Washington State Plane North, Lambert Conformal Conic, North American Datum of 1983. Vertical coordinate system: North American Vertical Datum of 1988.

2) The "Clip" tool was used to select subsets of the data around each of the three areas considered.

3) In areas with prevalent low lying inland sinks, (i.e. Harbor Island, Seattle and Quartermaster Harbor, Vashon and Maury Islands) the "Fill" tool raised the elevation within the sinks to the lowest bounding point. Though these areas are susceptible to flooding, the higher elevation land would likely protect them from direct inundation. The resulting maps better depict the inundation areas with a direct connection to the associated sea level. This step was not taken for Olympia due to complications with Capitol Lake and the limited number of inland sinks.

4) NOAA's tidal benchmarks (NOAA Tides and Currents 2007) and the VDatum conversion tool (NOAA VDatum 2004) were used to identify the Mean Higher High Water (MHHW) elevation for each of the selected areas. This required a conversion from NAVD88 to MHHW and the two sources agreed within 0.05 feet. In the case of Quartermaster Harbor, a nearby tidal benchmark was not available so only the VDatum conversion tool was used.

5) Within Puget Sound, the Ordinary High Water (OHW) Mark is between 1.0 and 1.5 feet above the MHHW mark (Doug Canning, field observations). Thus, 1.25 feet was added to the MHHW elevation to determine the OHW elevation for each area. Due to the integer format of the raster data set, a choice of 1.0 foot or 1.5 feet would not have changed the map of the OHW level, except for Olympia where a choice of 1.5 feet would have designated slightly more land as below the OHW elevation.

6) This OHW elevation was then chosen to represent the current (2005) shoreline. The ArcMap tool "Raster Calculator" was used to identify portions of the DEM that are less than or equal to ( $\leq$ ) the OHW elevation. This data layer was then converted to a shapefile using the conversion tool "From Raster to Polygon."

7) The different sea level rise scenarios were calculated using two different methods. The first method used the “Raster Calculator” to identify each of the three different sea level rise scenarios: 2 feet, 4 feet, and 6 feet above the OHW. In the second method, a conditional function was used in the “Raster Calculator.” This function (SLR = CON(DEM >OHW & DEM ≤ Max SLR, DEM) selected only the areas of the DEM between the OHW and the maximum sea level rise (SLR). This selection could then be classified in different elevation groups corresponding to individual scenario. Each scenario corresponds to increasing levels of inundation.

8) In order to better understand and communicate the potential impacts of the three sea level rise scenarios, Orthophotographic images were added to each GIS map. For Seattle as well as Vashon and Maury Islands, the USGS June 2002 photos were accessed through the Washington State Geospatial Data Archive (WAGDA 2002). In Olympia, the photo was again accessed through the University of Washington and is a 7.5’ Department of Natural Resources (DNR) Quad #1617 photo taken in 1990. All aerial photography was referenced to UTM Zone 10 North. This is not the same projection as that used with the Puget Sound DEM. The Puget Sound DEM has a central meridian of -120.833 and the Orthophotos are projected with a central meridian of -123. Distortions can increase with distance from the meridian; however, in this case, visual inspection reveals little or no distortion. The photo overlays are consistent enough for the qualitative evaluation of vulnerability.

9) The floodplain maps use the same base DEM to identify the 100-year floodplain. The highest observed tide (12.14ft NAVD88, 1.89ft above OHW, 1/27/1983) measured at the Seattle tide gauge (ID # 9447130) is used as a proxy for the base flood elevation. Seattle has had an operational tide gauge since 1898. Thus, the highest observed tide during this era provides a reasonable estimate of the 100-year floodplain, especially given the one-foot vertical resolution of the DEM. A one-foot increase in sea level is linearly translated into a one-foot increase in flood elevation. Maps were made in one-foot increments up to four feet of sea level rise.