UNIVERSITY OF CALIFORNIA
Santa Barbara

Impacts of Rising Sea Level on Coastal Communities: A Santa Barbara Case Study

A Group Project submitted in partial satisfaction of the requirements for the degree of Master's in Environmental Science and Management for the Bren School of Environmental Science & Management.

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The Group Project is required of all students in the Master's of Environmental Science and Management (MESM) Program. It is a four-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue.

This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

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DATE: ____________________

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Abstract

Over the past 100 years, sea level has been rising at an accelerated rate. Rates are projected to increase over the next century due to dynamic glacial and ice sheet melt, ocean thermal expansion, and land subsidence. Past research on the physical and economic impacts of sea level rise has been focused on regions with low coastal relief. Using Santa Barbara as a case study, this project seeks to estimate the physical and economic impacts of sea level rise on a coastal community with complex topography.

To assess future sea level rise impacts, predictions of .5, 1.4, and 2 meter increases were modeled in a geographic information system. Extreme high water events were integrated into the model to assess increased risk of coastal flooding due to storm events under each sea level rise scenario. Results were used to estimate property, infrastructure, and transportation at risk for inundation and temporary flood events. Based on our model, permanent inundation is relatively minimal from a mean sea level rise of 2 m or less. However, a larger risk is associated with temporary flooding during large coastal storm events. To protect coastal regions from damages due to inundation and storm surge, adaptation and protection solutions will have to be implemented along regions of the Santa Barbara coastline and policy makers will have to account for sea level rise in future coastal planning.

Executive Summary

While sea level has varied dramatically over the lifetime of the human species, it has remained relatively constant during the history of human civilization. Recent anthropogenic activities have caused significant increases of carbon dioxide in the atmosphere, accelerating glacial melt and the pace of recent sea level rise.

The California coast will be directly impacted by sea level rise over the next century in terms of land loss, transportation impacts, infrastructure inundation, water quality issues, beach tourism, and population safety. To prepare for the impacts of sea level rise, California Governor Arnold Schwarzenegger issued Executive Order-13-08 on November 14, 2008, which requires the California Resource Agency to collaborate with several other agencies to create a sea level rise assessment report for the entire state of California by December 1, 2010.

As a coastal community, the city of Santa Barbara will have to evaluate and implement new management strategies in order to mitigate the impacts of sea level rise. Santa Barbara is a city with a population of nearly 90,000 located on the Central Coast of California. Santa Barbara's altitude varies from sea level to 620 feet, and its coastline includes erodible cliffs, low-lying drainage areas, and sandy beaches.

In order to properly plan for sea level rise, it is essential for city managers to understand the likelihood of different sea level rise scenarios and the risks associated with under-preparing for these scenarios.

Scientific evidence suggests that thermal expansion (the change in water volume with increasing ocean temperatures) and glacial melt will be the two main causes of sea level rise over the next century. Thermal expansion is relatively predictable; the main uncertainty in sea level rise estimates comes from glacial melt. However, over the last 5 years, research has led to significant improvements in models of future sea level rise based on glacial melt scenarios.

In the fourth assessment report of the IPCC, released in early 2007, sea level was projected to rise between 0.18 and 0.59 m by the end of the century. However, these estimates largely ignored ice melt due to the lack of scientific consensus at the time of the report's publication. More recent ice melt research suggests sea level rise in the range of .5 to 1.4 m is more likely (Rahmstorf, 2007). An analysis of the physically possible glacial melt conditions for Greenland found that 2 m was the maximum total sea level rise expected by 2100 (Pfeffer et al, 2008).

California coastal communities like Santa Barbara should also prepare for storms occurring during future high tide El Niño events, when a significant storm surge far exceeding the normal sea level could temporarily inundate the city. Over the past 25 years large storm events, specifically in 1983 and 1995, have seriously affected city infrastructure, especially transportation. Not only will storm surges be worse due to higher sea levels, but also the storm events themselves are likely to be more frequent and more powerful as a result of global warming.

Methodology

The region of study for this analysis was constrained to Santa Barbara's city limits. To assess future sea level, areas at contour lines at or below 0.5m, 1.4m and 2m were delineated to measure land area covered by permanent inundation. Modeling of storm surge scenarios was conducted to estimate the effects of sea level rise on future coastal flood events. These heights were added to each scenario to serve as an estimate of the extent of flooding exacerbated by sea level rise. In addition, 75 transects were used to model shoreline change over the next 100 years, with 5% and 10% increases to account for erosion exacerbated by sea level rise.

GIS data of city boundaries, tax assessment parcels and streets were obtained from the online Santa Barbara County Spatial Data Catalog (County of Santa Barbara Information Technology Department). Data on hazardous materials sites, utilities, essential facilities and transportation were obtained from the database for HAZUS-MH (Hazards U.S. Multi Hazard) which is a multi-hazard loss estimation model for the U.S. developed by Federal Emergency Management Agency (FEMA) and the National Institute of Building Sciences (NIBS). For each of the four sea level rise scenarios, economic impacts were calculated by assessing which economic input layers were located within the inundation zones of each scenario.

Results and Discussion

The impact of future sea level rise on the city of Santa Barbara will largely be due to damages from temporary flooding during major storm events rather than permanent inundation losses. According to our modeling, permanent inundation of land areas is expected to be minimal under sea level rise scenarios of 2 m or less. However, a substantial amount of land area is at risk for temporary flooding during large storm events, which, as climate change progresses, are likely to increase in occurrence. Episodic cliff collapse will continue to occur along the Santa Barbara coastline especially during storm events.

Transportation impacts of sea level rise inundation and flooding from more intense storms were analyzed for roads and railways. Transportation losses will be minimal due to sea level rise compared with impacts during storms. The combination of more intense storms and further levels of flooding and inundation due to future sea level rise means that there will be significant flooding issues to major transportation corridors in Santa Barbara. The railways will have no permanent losses, but will be subject to storm flooding under future sea levels.

In order to manage sea level rise along the coast, city managers must update the local coastal plan to incorporate necessary land use and zoning adjustments. While Santa Barbara's current local coastal plan, written in May 1981 and last amended in November 2004, takes into consideration 100-year flood zones, erosion and dredging, coastal aesthetics, conservation planning, and environmental habitats, the regulations regarding these issues must be updated to account for possible sea level rise scenarios

To protect coastal regions from damages due to inundation and storm surge, adaptation and protection solutions will likely have to be implemented along regions of the Santa Barbara coastline. In our analysis, we looked at four main areas of Santa Barbara's coastline that will be impacted by climate change and sea level rise: the airport, downtown Santa Barbara, the harbor, and Arroyo Burro. These regions need to be evaluated for cost effective solutions that diminish future sea level rise impacts and damages. In using protection strategies to block ocean water from flooding and inundating any drainage area of Santa Barbara, city managers must also be careful to engineer structures that allow the water to drain out from the city and into the ocean.

We hypothesize that a cost benefit analysis will reveal the construction of a sea wall structure will be cost effective in protecting the airport area, but not the Arroyo Burro and downtown areas. We suggest city planners investigate mitigation strategies, such as structure elevation and increased breakwater height to minimize sea level rise and storm impacts on the Santa Barbara Harbor.

We recommend that city planners continue to monitor climate change literature for new estimates of sea level rise over the next century. Even in the course of this project, new literature with varying estimates was published. We also recommend that planners strive to integrate the value of public land and structures, which were not available in the HAZUS database, into our model. Furthermore, it would be beneficial to include economic valuations of the services provided by public parks and beach areas which may be threatened by sea level rise.

Finally, during a storm event, the city is flooded both from the storm surge and from the rain that falls on the mountains and quickly flows down through the city. Major drainage issues will arise as the increased precipitation and runoff from the mountains combines with raised sea level heights that will reduce the hydraulic head of the flood drainage zones. Therefore, we suggest future research of the impacts of sea level rise on the city of Santa Barbara take drainage issues into account.

Introduction

Rising sea level is an inevitable consequence of anthropogenic global warming. The consensus modeling of the Intergovernmental Panel on Climate Change (IPCC, 2007) predicts 0.18 to 0.59 m of sea level rise by the end of this century. Significantly, these projections ignore the possibility of dynamic fluctuations of ice flow from continental ice sheets in Greenland and Antarctica, a possibility made increasingly probable by recent observations (Rignot et al, 2008). While unlikely in the near future, the complete melting of the Greenland ice sheet alone would lead to a global sea level rise of 7 m—a planetary crisis. Integrating the IPCC results with current literature on potential changes in ice flow of Greenland and Antarctica will provide a more accurate projection of sea level rise in the next century.

This increase in sea level will impact coastal communities in various ways, both physical and economic. Sea level rise is a global problem with impacts generally evaluated globally (e.g., "N million square kilometers of coastal land inundated", etc.). However, methodologies are lacking for local agencies, governments, and populations to translate global predictions into local impacts. To our knowledge, no study or framework currently exists that systematically links sea level rise to impacts on the physical and economic infrastructures of medium-sized coastal communities like Santa Barbara. By identifying and ranking the major economic and physical impacts of sea level rise on the city, we believe that this project will be useful for local policy makers and city planners in their efforts to prepare for sea level rise over the next century.

Objectives

Objective for this project are as follows:

- Review literature to determine the likely range of sea level rise by 2100.
- Identify physical impacts of sea level rise.
- Model physical impacts of sea level rise in Santa Barbara city limits under multiple scenarios.
- Analyze the costs of sea level rise on the city's physical and economic infrastructure.
- Identify appropriate adaptation and mitigation measures for use by Santa Barbara city officials and planners.

Background

Climate Change and Sea Level Rise

Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC) is a scientific body established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) (About IPCC, 2008). Comprised of experts from around the world, the IPCC's objective is to provide decision-makers with policy-neutral information on the causes and impacts of climate change. The IPCC does not perform research; instead its reports synthesize the current scientific literature in all disciplines related to climate change. IPCC reports reflect the current understanding of climate change and the current viewpoints of the scientific community. By accepting and approving the IPCC's Assessment Reports, governments acknowledge the scientific credibility of the IPCC. The IPCC's most recent Assessment Report was published in 2007.

Climate Change

Modern climate change refers to projected long-term changes in global and regional average weather events due to gradual global temperature increases induced by anthropogenic factors (IPCC, 2007). Weather events such as temperature variation, precipitation events, and wind patterns are variable on a short-term basis. When averaged over the long term, these weather events are the predictable characterizations of a region's climate.

The link between greenhouse gases and increasing temperatures is well established (IPCC, 2007). Greenhouse gases absorb longwave (infrared) radiation emitted from the Earth's surface. Higher greenhouse gas concentrations in the atmosphere mean less longwave radiation will escape through the atmosphere causing Earth's global average temperature to rise. Fossil fuel combustion and land use changes, such as deforestation and urbanization, are factors contributing to increases in atmospheric greenhouse gases.

Global greenhouse gas levels have increased drastically since 1750 as a consequence of anthropogenic activities (Figure 1) (IPCC, 2007). Average carbon dioxide levels in the atmosphere are now around 387 parts per million – up nearly 40% since the beginning of the industrial revolution (Tans, 2008). Ice core analyses show that current atmospheric carbon dioxide and methane concentrations exceed the natural maxima observed in the past 800,000 years (Wolff, 2006).

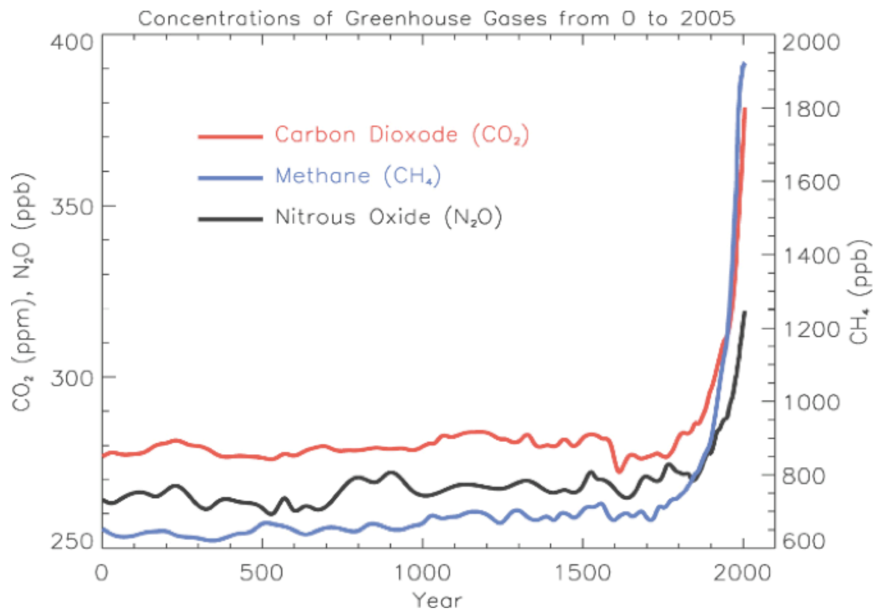

Figure 1: *Global concentrations of carbon dioxide, methane, and nitrous oxide since the year 0.*
Source: IPCC, 2007.

11 of the past 12 years (1995-2007) have been the hottest since reliable recording began in 1850, and global average temperatures are predicted to rise 1.8-4.0˚C by 2100 as seen in Figure 2 (IPCC, 2007). To summarize the scenarios used in Figure 2: A1B represents a future world where nations are fairly integrated and energy emphasis is derived from all types of sources; A2 represents a future world that is more divided with a continuously increasing population; and B1 represents a more ecologically friendly and integrated world.

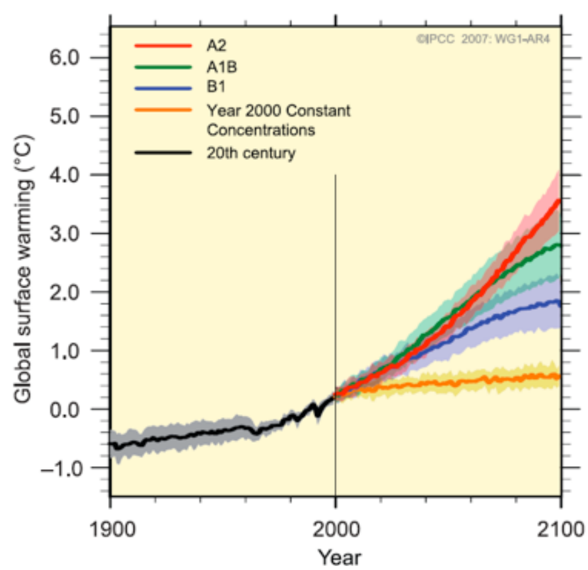

Figure 2: *Predicted increases in global surface temperatures by 2100.*
Source: IPCC, 2007.

Global temperature rise due is expected to change global climate patterns in the following ways:

- Increased global precipitation.
- Intensification of storm events.
- More frequent rain and flooding events in some regions and more drought events and desertification elsewhere.
- Significant alterations in regional biodiversity due to changes in species migration patterns, breeding activities, and extinction rates.
- Shrinking of sea ice cover and accelerated glacial melting.
- Rise in average sea level height due to glacial melting and thermal expansion of ocean water.

Sea Level Rise

According to paleoclimatic data, when global temperatures were 2-3° C above current levels 3.5 million years ago, the world's ice sheets responded directly to the change and sea levels rose by 25±10 m (Dowsett et al, 1994). More recently, when the remaining Laurentide Ice Sheet collapsed between 8,740 and 8,160 years ago, global sea levels rose up to 1.4 m (Clarke et al, 2004). Hansen (2004) argues ice sheets collapse may be due to multiple positive feedbacks such as:

- Changes in albedo (i.e. ice sheets lose their reflective snow cover, absorb more of the sun's energy, and melt faster)
- Warmer oceanic temperatures contributing to the collapse of outlet glaciers leading to increased glacial acceleration (i.e. land glaciers are unplugged and flow to the ocean more quickly)
- Increased surface melt that percolates to glacial bases and lubricates basal flow (i.e. glaciers slide toward oceans more quickly).
- Polar amplification of mean global temperature (e.g. a 2.5° C increase globally may result in a 5° C warming at the poles)

Accelerated glacial melting, increasing ocean temperatures, and the thermal expansion of ocean water have contributed to the 195mm increase in average sea level height observed over the past century (Church & White, 2006). Currently, scientists estimate that thermal expansion contributed to ~50% of the sea level rise observed since the 1950s, but as glacial melt rates increase, the proportion of thermal expansion's contribution to sea level rise is likely to decrease (Lombard et al, 2005; Wigley & Raper, 1987).

Based on model projections, the IPCC estimates global sea level will rise 0.18 m to 0.59m by 2100 (IPCC, 2007). Because scientific consensus was lacking on the subject at the time of publication, the IPCC's sea level rise projections do not include potential changes in Greenland and Antarctica ice melt rates. 70% of Earth's fresh water is locked into Greenland and Antarctic ice sheets. The IPCC Assessment

Report states that if ice flow rates were to increase linearly in these regions, the upper range of their sea level rise projections should be increased by 0.1 to 0.2 m. It is estimated that complete melting of Greenland's ice sheet alone would result in a 7 m sea level rise (IPCC, 2007).

There is considerable uncertainty as to whether Greenland's ice sheet dynamics have reached a "tipping point" that will result in rapid ice sheet mass loss. Recent observations of Greenland and Antarctica do show accelerated ice sheet loss (Luthcke et al, 2006; Velicogna & Wahr, 2006). The Greenland ice sheet shrank by 154 billion tons in 2007 (Witze, 2008).

A recent study concluded "if current climate models from the IPCC included data from ice dynamics in Greenland, the sea level rise estimated during this century could be twice as high as what they are currently projecting" (University of Buffalo, 2008). Therefore, the recent observations of rapid changes in Greenland and Antarctic ice sheets suggests that future dynamic changes in ice flow needs to be incorporated in sea level rise predictions and planning strategies (Rignot et al, 2008).

In Antarctica, ice mass loss is expected to increase from 80 Gt/year in the mid-1990's to 130 Gt/year in the mid- 2000's. East Antarctica has a near zero ice mass loss, but West Antarctica and the Antarctic Peninsula are losing ice mass at a rate of 132 and 60 Gt/year, respectively (Rignot et al, 2008). Unlike Greenland, there is little surface melting in Antarctica. Most of the increased ice discharges are a result of increased glacial velocities in the Peninsula and West Antarctica, where the melt of ice sheets is of particular concern since they rest on bedrock below sea level (Steffen et al, 2008). Currently, most of the Antarctic glaciers are contained by the ice sheets blocking their discharge into the ocean, but these ice sheets are thinning or breaking at an increased pace. At this time, models cannot predict with great certainty any impact of Antarctic melt on sea level rise over the next century; but scientists caution abrupt increases in sea level could occur if sensitive and thinning ice sheets unexpectedly break apart.

Recent research by Stefan Rahmstorf of the Potsdam Institute for Climate Impact Research, estimated a new sea level rise range of .5 to 1.4 m above 1990 levels by 2100 as seen in Figure 3 (Rahmstorf, 2007). Rahmstorf ran his climate model using the IPCC's 6 warming scenarios with an improved linear approximation of ice melt, but emphasized that the ice melt approximation still may not be satisfactorily robust. Time-lagged feedbacks like bed lubrication and ocean warming at the base of ice streams could induce even higher rises in sea level.

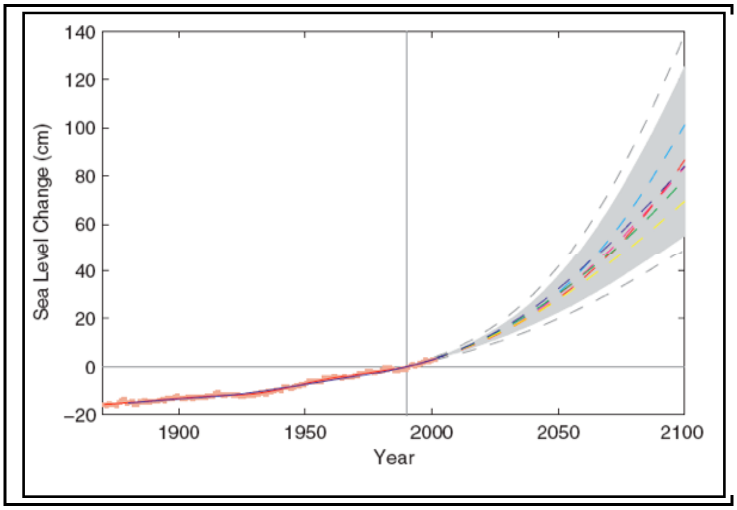

***Figure 3**: The range of sea level rise for the IPCC climate scenarios as modeled by Rahmstorf (2007). Source: Rahmstorf, 2007.*

Because of increases in snowfall at higher elevations, Greenland is thickening in some areas but this increase in ice mass is offset by accelerating outlet glaciers near the coasts and increased summer melting as rising temperatures (Steffen et al, 2008). The mass balance loss of Greenland's ice sheet has doubled over the past decade from 100 Gt/year in the mid-1990's to more than 200 Gt/year in 2006.

It is extremely unlikely that the Greenland ice sheet will melt completely by 2100. Using a climate model that integrates multiple ice melt variables of Greenland's ice sheet, Pfeffer et al. (2008) found 2m was the maximum physically possible estimate of sea level rise by 2100 – far less than the 7m expected should Greenland melt entirely. Ice melt variables included glacial ice velocity, ice stream widths, and gateway cross-sectional areas. In order to observe a sea level rise greater than 2m, the researchers estimated Greenland's outlet glaciers would have to discharge at an average rate greater than 26.8 km/year – a rate far exceeding any current discharge rates and considered the upper limit of physically possible glacial melt.

Physical Impacts of Sea Level Rise

A major physical impact of sea level rise is shoreline retreat, which is variable and depends on the slope and geology of the coastal area. Increased coastal erosion rates are likely with rises in sea level (Rosser et al, 2006). While relatively minimal displacement would be seen for shorelines with steep slopes, a more dramatic shoreline retreat would be seen in areas with flatter slopes. Coastlines with cliff edges may shift less quickly than flat shores, but increased erosion at the base of cliffs could result in increased incidents of cliff collapse (Rosser et al, 2006). Figure 5 demonstrates the progression of cliff erosion over time, a process that may accelerate with sea level rise.

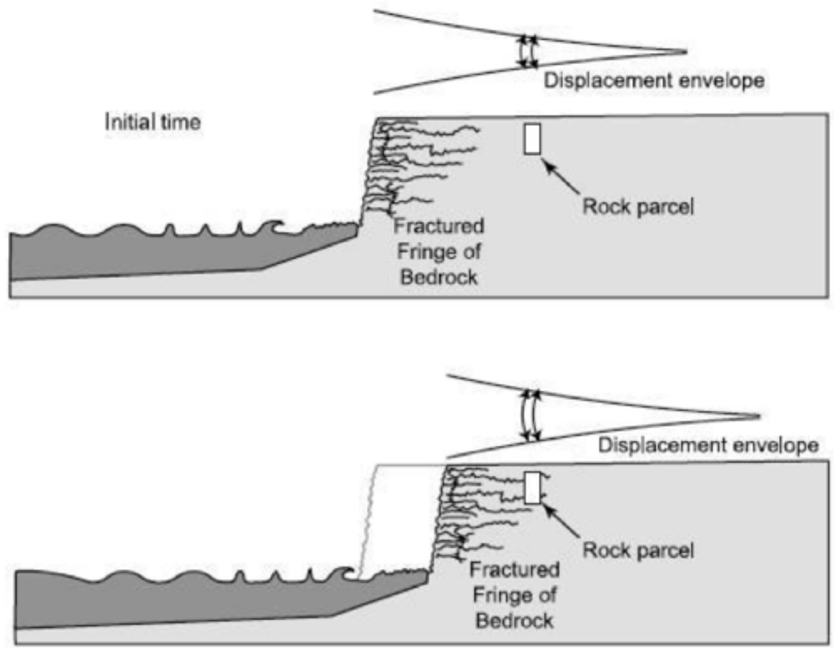

Figure 4: *The progression of cliff collapse due to wave action at the cliff base.*
Source: Adams et al, 2005.

As sea level rises and storms intensifies, coastal areas which had previously dealt with mild to moderate damages resulting from storm flooding would likely face increased losses from larger storm surges (Douglas, 1991). Additionally, increases in sea level rise will decrease 'hydraulic head' and cause water drainage rates to decrease during storm events (Titus et al, 1987).

Salinization of ground water stores would also be an expected consequence of sea level rise. Salt-water contamination of coastal aquifers is already a well-documented problem, with the infiltration of salt water often resulting from over-pumping of the aquifer. Sea level rise would exacerbate this problem and decrease the quantity of water that could be pumped without putting the aquifer at risk of contamination (Kana, 2008).

Storm Changes Due To Climate Change

Climate change will not only raise the general level of the sea, it will potentially create more frequent intense storm and weather events (Hallegatte et al 2008). Climate change models estimate that future tropical cyclones (typhoons and hurricanes) and storm events will become more powerful, with greater wind speeds and more rain, correlated with continual increases of sea-surface temperatures (IPCC 2007). Already, the actual changes in storm intensity since 1970 are much larger in some areas than the models would have predicted (IPCC 2007).

The current pattern of extra-tropical storm tracks moving pole-ward over the last half century is expected to continue, causing more frequent storms in some regions (Hallegatte et al 2008). Additionally, there will very likely be increases in precipitation for high-latitude regions; while there have been scenarios (A1B) where subtropical land regions experience a 20% decline in rain (IPCC 2007).

Studies have found that by 2080 a 100-yr event in the North Sea could increase sea level in height by 10 to 20 cm; a more intense 200-yr event could be 60 to 70 cm higher than it is today (Woth et al 2006). By the end of the century, 50-yr storm events will become 40 to 60 cm higher around the coast of Denmark when taking into account medium-high emissions scenario, atmospheric pressure, sea level rise and land movements (Lowe et al 2005).

Due to damages from intense storm events such as Hurricane Katrina, the effect of storms upon coastal regions has become a focal point for both policymakers and society. The 20 to 30 years leading up to the 1990s had a low range of storm frequency, leading to an increase in aggressive coastal land development; when Hurricane Andrew hit in 1992, the damages were around $25 Billion (NOAA, 2005). Projected from past storms, future damages from storm events could conservatively average $5 Billion per year (Pielke and Landsea, 1998).

Estimating the impacts of future storm events requires projections from long time series of historic data, which may not reveal unambiguous relationships (IPCC 2007). For example, there is currently no clear relationship between sea-surface temperatures and the frequency of tropical storms. It is possible that the amount of extra-tropical cyclones will become less frequent but equally possible there will be an increase in the amount of intense storms (IPCC 2007).

The City of Santa Barbara

Santa Barbara is a city located on the Central Coast of California (Figure 6). It is positioned along a southward facing stretch of coastline between the Santa Ynez Mountains and the Pacific Ocean. The city has a population of 81,305 people (US Census Bureau, 2006) and its boundaries encompass 43.09 square miles, 21.09 mi^2 of which are land (The City of Santa Barbara, 2008). U.S Highway 101 is the most important transportation artery for Santa Barbara. It links the city with the rest of the Central Coast region, with Los Angeles (96 miles to the south) and San Francisco (340 miles to the north). Santa Barbara has a domestic airport that offers scheduled and general aviation services to the local community.

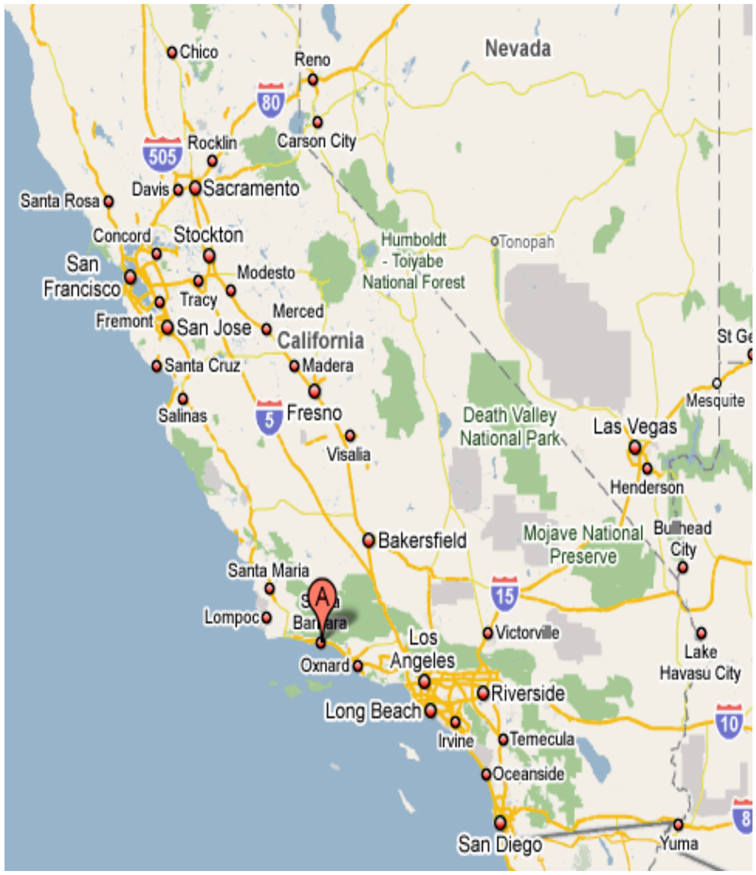

Figure 5: *The geographic location of Santa Barbara on the California coast as marked with letter A. Source: Google Maps, 2009.*

With a thriving tourism and resort industry, Santa Barbara's economy is primarily centered in the service sector. Additionally, the local economy consists of education, technology, health care, finance, agriculture, and manufacturing sectors. The University of California Santa Barbara is located in the adjacent city of Goleta and is a major employer in the region.

Cretaceous through late Cenozoic sedimentary strata dominates the geology of the Santa Barbara coastal plain. Santa Barbara has a year-round average temperature of 64 degrees, with an average maximum of 74 and an average minimum of 56 degrees. Santa Barbara's altitude varies from sea level to 620 feet. The average amount of rainfall in downtown Santa Barbara is 18.8 inches per year, but large storm events especially during El Niño years, can bring higher amounts of precipitation to Santa Barbara as seen in Figure 7 (County of Santa Barbara, 2006). Furthermore, the mountain ranges in the county have increased precipitation with elevation which, combined with the short and steep watersheds of the area, can result in flash flooding during storm events. Seasonal fires in the mountains can aggravate this effect.

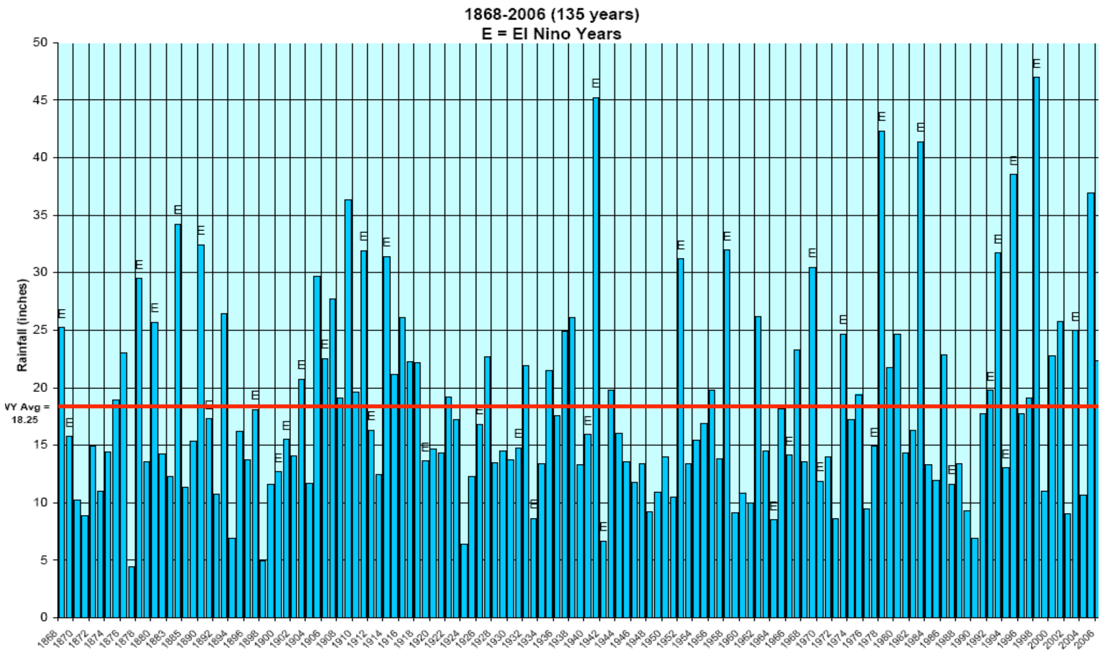

Figure 6: *Rainfall totals for downtown Santa Barbara.*
Source: County of Santa Barbara, Public Works, 2007.

Santa Barbara Coastline

In Santa Barbara, coastal erosion occurs each winter during storm events. Sandy beaches gradually recover during late spring to summer/fall due to a gentle wave climate (Grggs et al, 2005). Generally, waves break at angles to shore. Sediment transport is driven by wave energy, often referred to as the alongshore river or littoral transport. Littoral transport occurs almost exclusively from west to east on the Santa Barbara Coast; other swell directions are usually blocked by the Channel Islands. Southeastern swells generally reach Santa Barbara's coast less than 10 days per year. El Niño-Southern Oscillation (ENSO) patterns play a vital role in erosion in California. La Niña years bring cooler weather, El Niño years are warmer with more storm activity. 75% of storms that caused either high erosion or major damage occurred during El Niño years.

Beaches are the primary buffer for wave action; they protect cliffs from erosion and property from destruction. Waves generally break at angles along the shore and transport sediment along the littoral cell, the zone bounded by breaking waves and shore. Historically, the majority of beach sand has been supplied from the Santa Maria and Santa Ynez Rivers (2 million cubic yards per year). Construction of dams on these reaches have blocked significant sediment supply to the coast. Transport from further north is generally blocked by Point Conception. Sediment supply from cliff erosion is not enough to maintain stable beach widths. Most cliffs are comprised of fine grain shale, which contributes little to the sediment budget. It is estimated that cliff erosion accounts for only 1% of beach sediment supply (Griggs et al, 2005).

The US Army Corps of Engineers conducted a study on sediment supply and transport times in the region. Two years of good rain yields a high sediment supply, with 3.5 years lag to see beach accretion because of alongshore transport times. Wave action in Santa Barbara is generally too weak to move sand shoreward if water depths are more than 15 feet deep (Griggs et al, 2005).

Cliff erosion is a highly episodic process. Cliffs in the Santa Barbara county area are generally 50-200 feet tall. These uplifted marine terraces are eroded by waves and tend to fail during rainstorms due to their mechanically weak nature, as seen in Figure 8. Most cliffs in the area are highly erodible sedimentary rocks of the Monterey Shale formation. Waves, earthquakes, landslides, runoff, salt weathering, and groundwater seepage can all influence cliff retreat. Waves may undermine cliffs, but in Santa Barbara, non-marine processes are by far the most important cause of cliff retreat. Rainstorms are often the major cause of landslides on coastal bluffs. Average retreat in Santa Barbara is 3-12 inches per year (Griggs et al, 2005).

Figure 7: *Historic erosion of cliff supporting for Ilsa Vista homes.*
Top left: 1987, Top right: 1997, Bottom left: 2005, Bottom right: 2007. Source: Art Sylvester.

Harbor

The Santa Barbara Harbor and breakwater were built in the 1920s. More than 1,100 vessels, both pleasure and commercial, dock in the harbor slips (Harbor Patrol, 2008). The annual catch of seafood brought in to the harbor from the Santa Barbara fishing region is between 6.6 and 7 million pounds or $26-28 million worth of product (John Bridley, personal communication, 2008). The Santa Barbara Waterfront Department has an annual expense budget of $13.6 million and revenue base of $11.2-$11.6 million.

The L-Shaped breakwater blocks alongshore sediment transport, hindering supply to the east as far as Rincon Point and resulting in constant siltation of the harbor entrance. Approximately 300,000 cubic yards of sediment, costing $1.5 million to dredge annually, are deposited along the harbor breakwater and in its channel (John Bridley, personal communication, 2008). Dredging has been conducted every year since 1933.

The 1983 storms, classified as 100-year storm events, caused $3-4.5 million worth of damage to the Santa Barbara Harbor and Waterfront (John Bridely, personal communication, 2008). Two storms in 1995 caused $448,269 and $26,786 worth of damage to the harbor, while the 1998 El Niño event had an estimate damage cost of $1.2 million. During storm events and even high tides, wave run up can reach beyond the Yacht Club parking lot and inundate the central Harbor area (Figure8).

Figure 8*: The Santa Barbara Yacht Club as seen normally and during a 1983 El Niño storm event. Source: Anderson, 2007.*

Airport

The Santa Barbara airport (FAA code: SBA) is owned and run by the city of Santa Barbara, and it provides scheduled and general aviation services to the local community. SBA is located 7 miles west of downtown Santa Barbara. While adjacent to UCSB and the city of Goleta, the airport's land belongs to the city of Santa Barbara. The airport area of our study also includes 120 businesses, which together with the airport authority employ 2,000 people with annual wages of $80 million (Santa Barbara Airport, 2001). The airport is also responsible for significant tax revenues: Its tenants and owners pay about $500,000 in property taxes, and generate $4.1 million annually in sales tax. 13% of these tax receipts go directly to the city of Santa Barbara. The total indirect tax revenues generated by the airport due to tourism and other related economic activity are estimated at $35 million. Over 200,000 visitors pass through the airport annually, and over 14,000 jobs and $336 million is attributed to this tourism traffic.

Most of the airport is between 10 and 15 feet above sea level and is bordered by wetland. The runway elevations are 8 and 9 feet respectively. At present, the airport's administration has no contingency plans for protecting the airport from sea level rise. However, according to Jeff McKee (personal communication, 2008), the airport's environmental compliance officer, likely mitigation strategies would include installing a seawall, or lifting the whole site through "filling." One meter of sea level rise would inundate the parallel runways. It costs $20-33 million to lay a new runway at the airport (Santa Barbara Airport, 2007). Moving the airport is not a viable option, as finding a suitable location close to Santa Barbara is considered impossible.

Tectonic Activity in Santa Barbara

The Santa Barbara area is tectonically and seismically active with faulted formed hills and raised ancient beaches. In 1925 a magnitude 6.8 earthquake devastated downtown Santa Barbara (Keller & Gurrola, 2000). Furthermore, offshore faults in the Santa Barbara Channel could produce a magnitude 7.0 earthquake, which could result in a localized tsunami (ibid. 65). The tectonic activity in the area is the cause of the Santa Barbara Fold Belt (SBFB) (ibid. 4).

One consequence of tectonic activity is subsidence or uplifting of coastal land relative to sea level. A significant rate of subsidence or uplift can thus exacerbate or mitigate the consequences of sea level rise. The Santa Barbara coastal area, comprised of reverse faulting anticlines, is experiencing uplift at a rate of 1-2 m per 1000 years (ibid. 6). This rate of uplift converts to 1-2 millimeters per year – an insignificant amount to consider on a timescale of 50-100 years. The rate of subsidence due to geologic folding processes occurring in the present-day marshes/sloughs and the downtown area is similarly miniscule (Keller, personal correspondence, 2009). Therefore, tectonic activity will not be included in our model and analysis.

Groundwater Salinization

One goal of this project was to determine the extent, if any, of accelerated seawater intrusion on the groundwater basins of Santa Barbara due to sea level rise.

In groundwater basins of coastal regions, salt water and freshwater form a lens-like interface at the fresh water's discharge boundary into seawater (Alley et al, 2002) (Figure 9). The interface is shallow to non-existent at the water's edge and becomes deeper as one moves inland. In regions with basins made of homogeneous porous material, a transition zone usually separates freshwater from the salty, seawater beneath. In basins composed of heterogeneous porous material, more complicated mixing zones can occur.

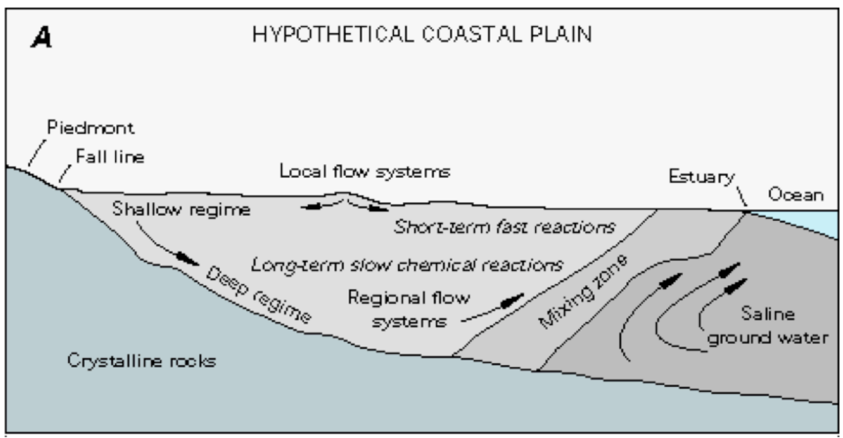

Figure 9: *The freshwater and saline water interface seen in coastal groundwater basins. Source: Winter et al, 1998.*

Large withdrawals from coastal groundwater basins can cause salt water to move inland, decrease fresh water volume, and contaminate specific over-pumped wells (Alley et al, 2002). Over-pumping coastal wells can disrupt the discharge equilibrium – where the freshwater outflow is equal to the opposite pressure of intruding saltwater – by removing the fresh water that normally would flow to the transition zone (Winter et al, 1998). This, in turn, pulls saline water into the fresh water basin. As sea level rises, the freshwater-saltwater lens interface will also likely rise accordingly. Without careful monitoring of near coast wells, pumping could induce seawater infiltration into critical groundwater basins.

Currently, the city of Santa Barbara has a water demand of 15,121 acre feet per year, but has approximately 18,300 acre feet available for use each year (Baca et al, 1992 as cited in SBC Public Works, 2005). Most potable water used in Santa Barbara is drawn from Lake Cachuma, the Gibraltar Reservoir (14,453 acre feet combined), and the State Water Project (3,000 acre feet). Groundwater accounts 10% of Santa Barbara's water supply (SBC Public Works, 2006). Groundwater basins in the area are important, however, because they are treated as underground storage reservoirs for use during emergencies.

Two groundwater basins serve the city of Santa Barbara: the Santa Barbara basin and the Goleta basin (Figure 10). The Santa Barbara basin is comprised of two hydraulic units: Storage Unit #1, located in the downtown area, and Storage Unit #3, located west of downtown in the Mesa area. Together with the North-Central sub-basin and the West Sub-basin, the Foothill basin, formerly called Storage Unit #2, form the Goleta Basin. Most of the water pumped from the Goleta Basin is used in areas outside Santa Barbara's city limits.

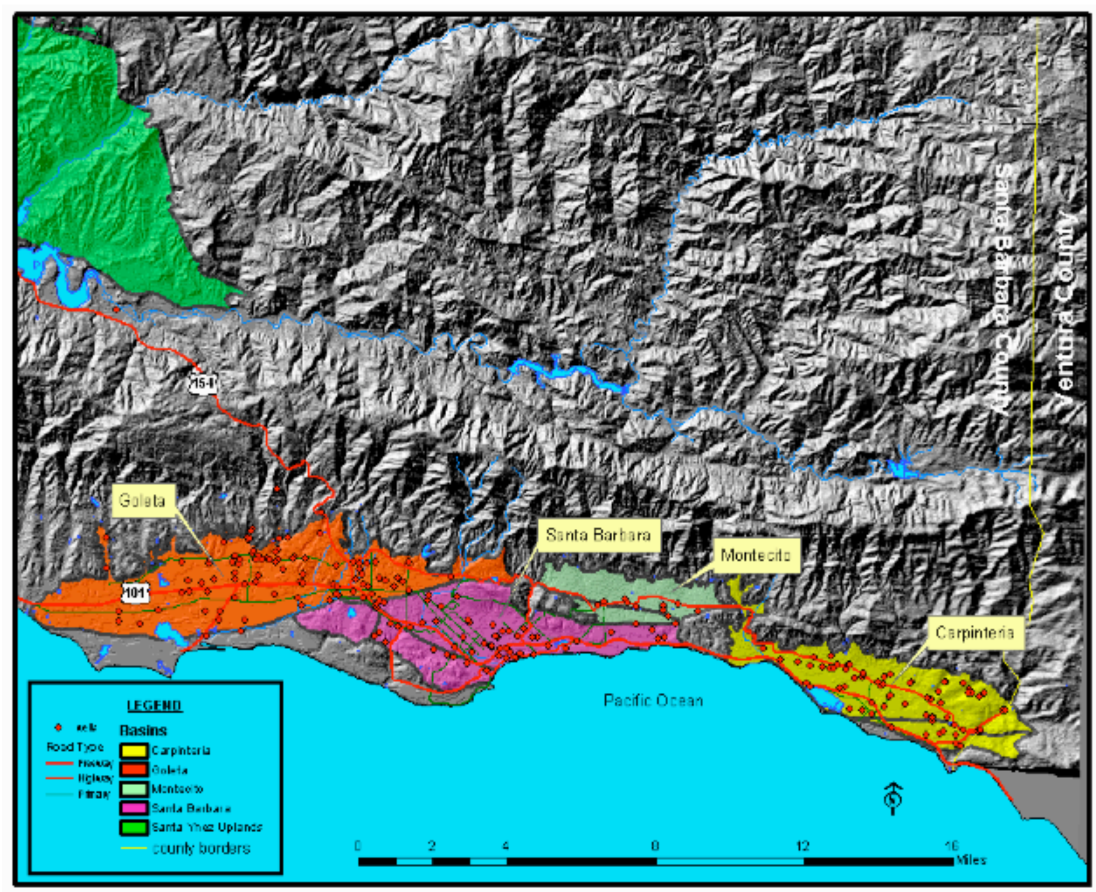

Figure 10: *South Coast Groundwater Basins.*
Source: SBC Public Works, 2006.

Estimated available storage in the Santa Barbara Basin is 10,000 acre feet (SBC Public Works, 2006). During the 1970's saltwater intrusion occurred in the Santa Barbara Basin when groundwater levels dropped 100 feet due to heavy pumping of municipal wells (Martin, 1984; SBC Public Works, 2006). Since 1991, however, pumping in the Santa Barbara Basin has dropped significantly and, currently, only 847 acre feet of water per year is pumped from the basin (SBC Public Works, 2006).

Together with groundwater injection, this decreased pumping has restored groundwater level and quality in the Santa Barbara basin. Because the city is now managing the basin as an underground storage reservoir and is the dominant pumper of water from the Santa Barbara basin, water level and quality are closely monitored. Therefore, because of good pumping practices, the risk of salt water intrusion now or with sea level rise is unlikely. Also, because most municipal wells in the area have depths of 60 to 245 m, an increase in sea level rise between .5 and 4.2 m is not expected to shift the underground salt-water lens significantly (Martin, 1984). Of course, officials should pay close attention to pumping in areas close to the ocean, where well depths are much shallower and more prone to salt water migration.

Available storage of the Foothill Basin is nearly 5,000 acre-feet per year (SBC Public Works, 2006). Sustainable pumping rates by the city of Santa Barbara, La Cumbre Mutual Water Company, and private landowners in the Foothill basin is estimated to be 953 acre-feet per year. Seawater intrusion is not now, or expected to be, an issue in the Foothill Basin as it is located north of the Modoc and Mission Ridge faults and therefore isolated from salt-water migration.

Goleta basin's North-Central Sub-basin and West Sub-basin have a combined storage capacity of 7,500 acre-feet per year (SBC Public Works, 2006). While in the past the two sub-basins were overdrafted, there was no evidence of seawater intrusion. Like the Foothill basin, the two sub-basins are protected from seawater migration by impervious rock formations and the More Ranch Fault.

We conclude that seawater intrusion is not a significant problem for Santa Barbara's groundwater resources and is not likely to become an issue under our projected sea level rise scenarios. Seawater intrusion will likely only be an issue should pumping rates in the coastal area increase beyond current sustainable, safe-yield allowances.

Coastal Hazards Policy

The California Coastal Act of 1976 established a planning and regulation framework for development in hazardous coastal areas (PRCS, 1976). The Coastal Act is governed by California Coastal Commission (CCC) and local governments, which are responsible for land use plans and ordinances. The Coastal Act regulates proposed shoreline protection structures and establishes new development guidelines. The guidelines' objective is to minimize risks to life and property. The guidelines are: assure stability and structural integrity and not produce any further erosion; do not rely on seawalls for new developments (must be safe without artificial means); prevent proliferation of beach armoring; and protect existing developments. Impacts of new structures must be fully mitigated (e.g. scenic viewshed, sand supply, and public access). Coastal armoring structures are usually approved if an existing development is threatened by erosion.

Local Coastal Programs (LCPs) are part of the Coastal Act, which requires local governments to design management plans for coastal hazards. The CCC must approve the plan, and policies must reflect Coastal Act guidelines: setbacks must be adequate; developers must prove site stability; standards must be met for new shore structures; and impact avoidance/mitigation strategies must be prepared.

The Coastal Commission regulates development until a LCP is approved, at which point jurisdiction will be awarded to the local government and their policies become legally binding. In its last General Plan, Santa Barbara chose to submit its LCP in portions, designing an entirely separate LCP for the airport. The Santa Barbara General Plan and LCPs are currently being revised with a new version expected in 2009 (Plan Santa Barbara, 2007).

The Coastal Commission faces several problems when enforcing its guidelines. The accuracies of geologic surveys of cliff retreat and sediment transport are often in question. The economic life of structures, and what constitutes redevelopment, can be unclear. Existing development is sometimes difficult to define. For example, some owners have applied for coastal armoring permits only months after construction has finished.

Aside from the California Coastal Commission, there are several other agencies that may play a role in the coastal regulatory process. FEMA is in charge of the National Flood Insurance Program, which is available for communities that have a flood management plan. The US Army Corps of Engineers does construction projects on navigable waters. NOAA regulates shoreline structures within marine sanctuaries. State agencies such as the California State Lands Commission issues environmental impacts statements and regulates coastal uses. Regional water quality control boards will have to deal with water quality issues due to sea level rise (increased groundwater chloride concentrations and stormwater from coastal flooding) and the Department of Fish and Wildlife will be involved with ecological impacts.

Executive Order S-13-08 by the Governor of California

On November 13, 2008, co-authors Fredrich Kahrl and David Roland-Holst from the University of California at Berkeley released a paper which outlined potential damages to the State of California over the next century due to climate change. The paper studied the effects of climate change upon many sectors including water, energy, real estate, insurance, tourism, recreation, transportation, forestry, agriculture, fishing, and public health (Kahrl and Roland-Holst, 2008).

After the study was published, the California governor's office issued Executive Order S-13-08, mandating the California Resource Agency (CRA) to take the lead in creating a comprehensive sea level rise assessment for the state's coastal regions (Office of the Governor, 2008).

The CRA, in coordination with the Department of Water Resources (DWR), the California Ocean Protection Council (OPC), the California Energy Commission (CEC), and the California coastal management agencies are directed to request that the National Academy of Sciences create an independent panel of experts to forge a final sea level rise assessment for the state of California to be completed no later than December 1, 2010 (Office of the Governor, 2008).

The executive order requires four key components to be included in the final assessment report: (1) specific sea level rise projections for the state of California, taking into consideration the impact of coastal erosion rates, tidal impacts, El Niño and La Niña events, storm surge, and land subsidence rates; (2) the amount of scientific uncertainty within the different sea level rise projections; (3) a summary of the impact projected sea level rise will have upon state infrastructure, natural areas, and coastal and marine ecosystems; and (4) an analysis of future needs, mitigation, and adaptation strategies in relation to sea level rise for the state of California. The document shall be reviewed by a joint task force consisting of the OPC, DWR, CEC, California coastal management agencies, and the State Water Resources Control Board every two years or as necessary (Office of the Governor, 2008).

In addition, the order mandates that all state agencies planning construction projects in areas subject to sea level rise must incorporate inundation risk management into their planning criteria. In their preparation, state agencies are instructed to consider a variety of sea level rise projections for the years 2050 and 2100. On top of this, local agencies are required to account for local uplift and subsidence, coastal erosion rates, storm surge, and storm wave data (Office of the Governor, 2008).

Methods

Study Region

The region of study for this analysis was defined by Santa Barbara's city limits, shown in Figure 11. Although physically surrounded by the city of Goleta, Santa Barbara Airport was included because it is a part of the incorporated City of Santa Barbara.

Figure 11: *Santa Barbara's city limits.*

Area Profile of Elevation Zones

The digital elevation model (DEM) used for this analysis was obtained from the United States Geological Survey's National Elevation Dataset (NED USGS Seamless Server) with a resolution of 1/3 arc second (approximately 10m). An analysis was done to determine the connected area between 1-meter equal intervals, to a maximum of seven meters. This delineates all connected area, initially adjacent to the sea (at a one-meter interval) and then neighboring subsequent contour intervals. This excludes areas, which could be below a certain elevation, but not connected to the sea or previously flooded zone.

Modeling Mean Sea Level Rise

Using the same DEM, areas at contour lines of or below 0m, 0.5m, 1.4m or 2m were delineated to assess area of land covered by permanent inundation.

Modeling Storm Events

In addition to assessing a mean sea level rise, storm surge events were modeled to evaluate the effects of sea level rise on future coastal flood events. Base flood elevations (BFE) are a common way to express extreme high water events. The occurrence probability of these BFE events are classified as a 1% or greater chance of occurring each year. These heights were added to each scenario. This will serve as an estimate to the extent of flooding exacerbated by sea level rise.

Modeling Erosion

Seventy-five transects were used to model shoreline change over the next 100 years. Erosion rates, provided by Dr. David Revell (Revell, 2008) were derived from stereo aerial photography and referenced from an offshore data point. A linear regression was used to assess shoreline change, taking into account multiple data points, to derive annual erosion rates for the back-beach. The widths of beaches were measured for years with existing aerial photography, using changes in back beach and mean sea level as a reference.

Economic Impact Data

GIS shapefiles of city boundaries, tax assessment parcels and streets were obtained from the online Santa Barbara County Spatial Data Catalog (County of Santa Barbara Information Technology Department). Data on hazardous materials sites, utilities, essential facilities (i.e. police, fire stations, hospitals, schools etc.) and transportation were obtained from the database for HAZUS which is a multi-hazard loss estimation model developed by FEMA and the National Institute of Building Sciences (NIBS). For each of the four sea level rise scenarios, economic impacts were calculated by assessing which economic input layers were located within the inundation or flood zones of each scenario. Tables presenting economic and physical impact values were generated and exported.

Results

A vast area of Santa Barbara is below 1m elevation and consists mostly soft beaches or wetland areas of the Goleta Slough. A major "tipping point" was found after 2-meter contours (**Table 1**).

***Table 1**: Total area (km^2) in study region in the given elevation ranges.*

Contour	0-1m	1-2m	2-3m	3-4m	4-5m	5-6m	6-7m
Area (km2)	0.21	0.24	2.01	1.43	0.74	0.55	1.06

GIS models of 0 m, .5 m, 1.4 m, and 2 m sea level rise were rendered as a set of images which display the effects of permanent inundation on downtown, the Arroyo Burro, and the harbor area (Figures 12-14). Separate images show the effects of a 100-year flood for each sea level rise scenario in the three regions (Figures 15-17).

The images show that the effects of flooding increase greatly during large storm events at higher sea level scenarios, compared with the effects of general inundation. However, the effects of inundation are permanent, whereas flooding only happens during storm events, so the images must be evaluated with an understanding of the differences between permanent losses and temporary impacts.

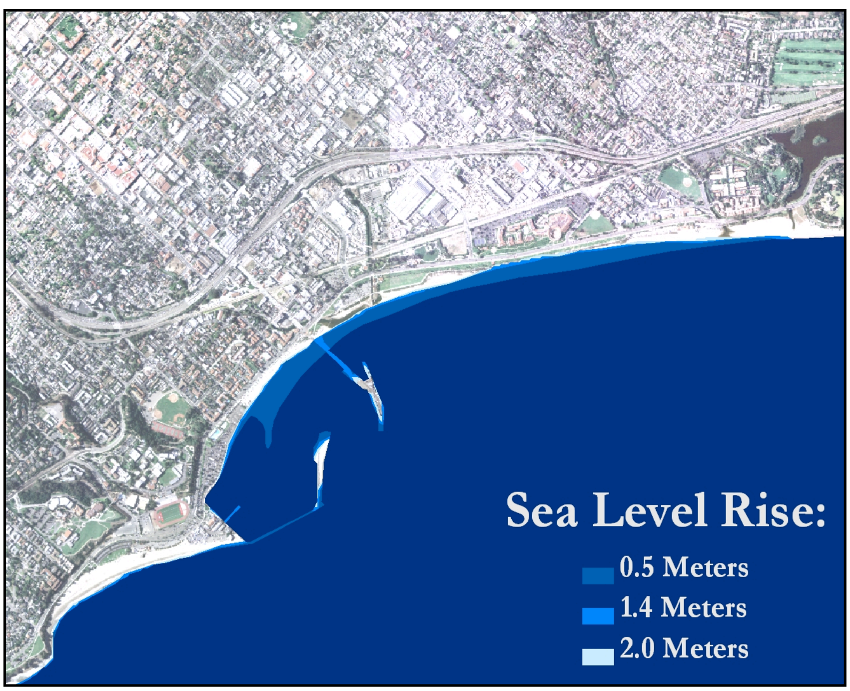

***Figure 12:** Downtown Santa Barbara and Harbor at 0 m, 0.5 m, 1.4 m, and 2 m of sea level rise.*

Figure 13: *Arroyo burro at 0 m, 0.5 m, 1.4 m, and 2 m of sea level rise.*

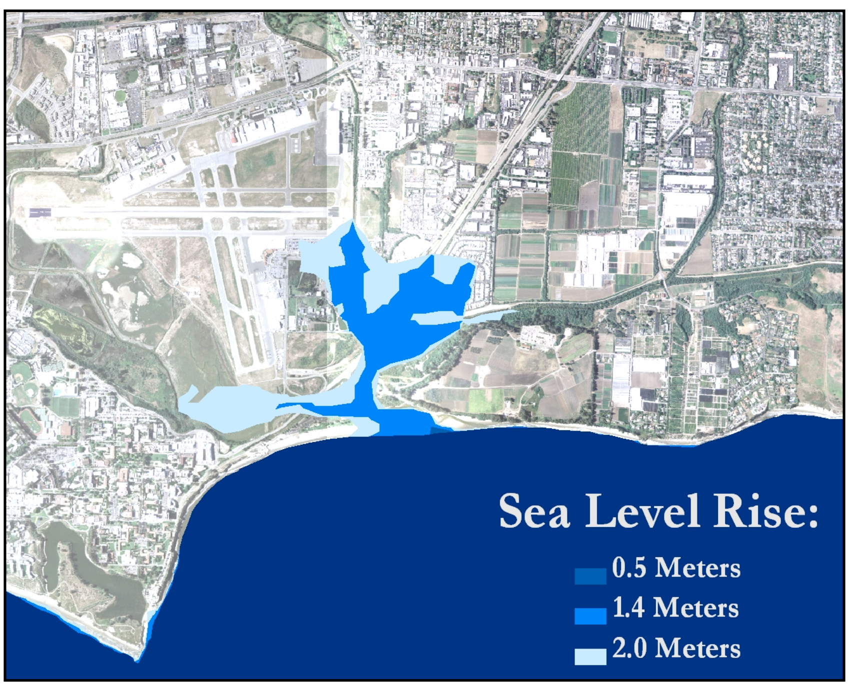

Figure 14: *The Santa Barbara Airport at 0 m, 0.5 m, 1.4 m, and 2 m of sea level rise.*

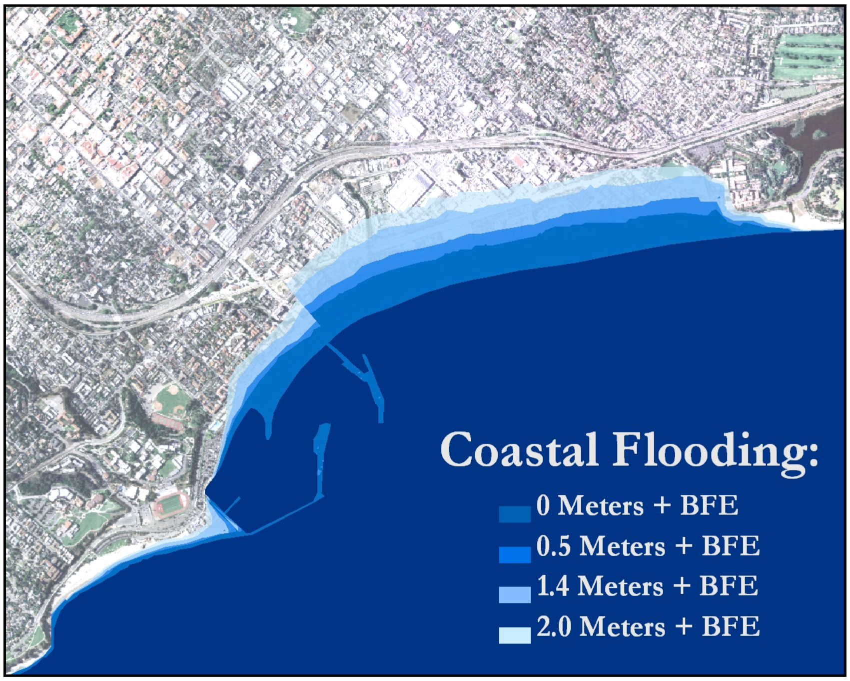

Figure 15: *Downtown Santa Barbara and Harbor during a 100-year flood at 0 m, 0.5 m, 1.4 m, and 2 m of sea level rise.*

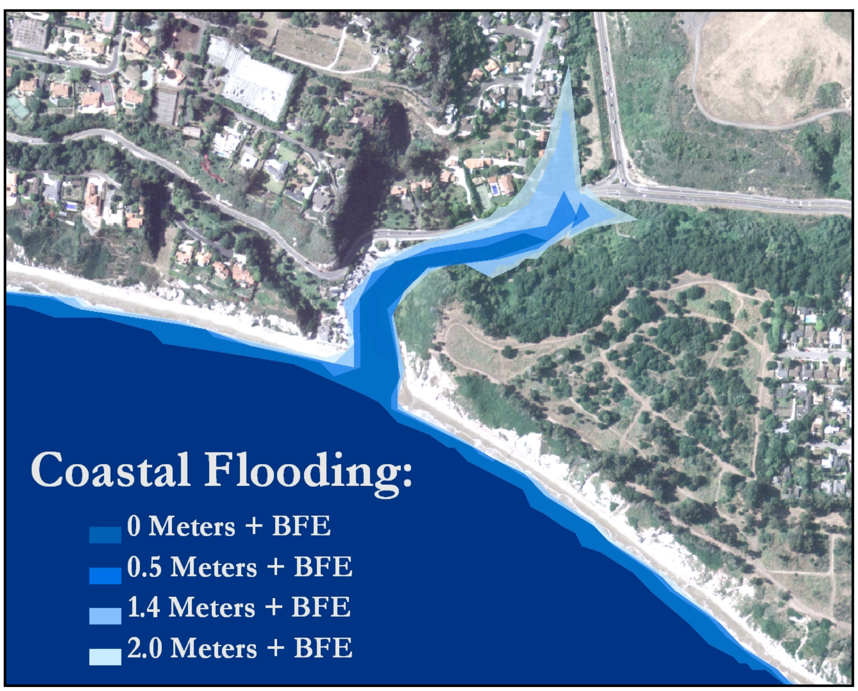

Figure 16: *Arroyo Burro during a 100-year flood at 0 m, 0.5 m, 1.4 m, and 2 m of sea level rise.*

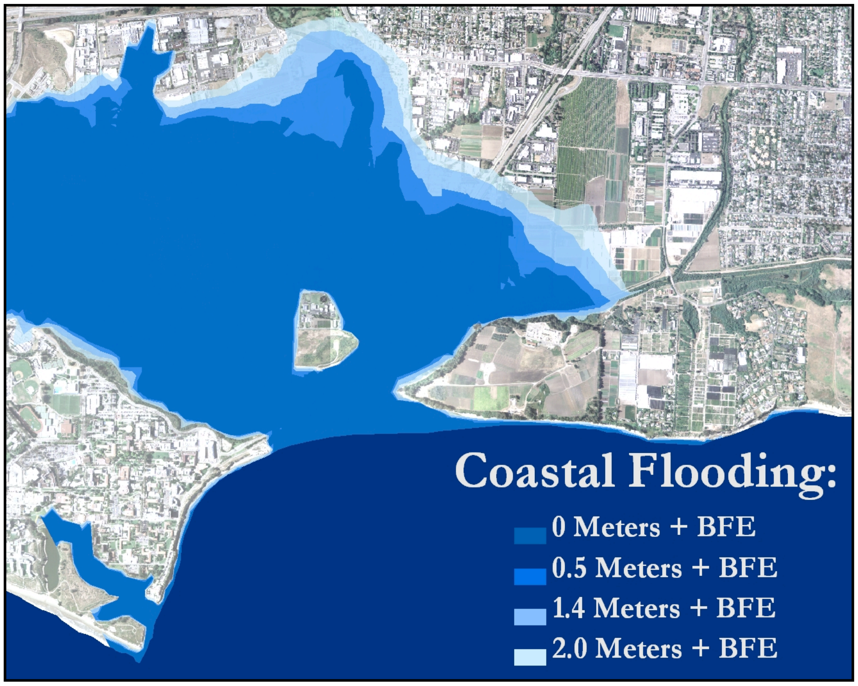

Figure 17: *The Santa Barbara Airport during a 100-year flood at 0 m, 0.5 m, 1.4 m, and 2 m of sea level rise.*

Figure 18 shows the disparity between area of land permanently inundated under the 3 sea level rise scenarios and the area of land at risk for flooding under sea level rise and a 100 year storm.

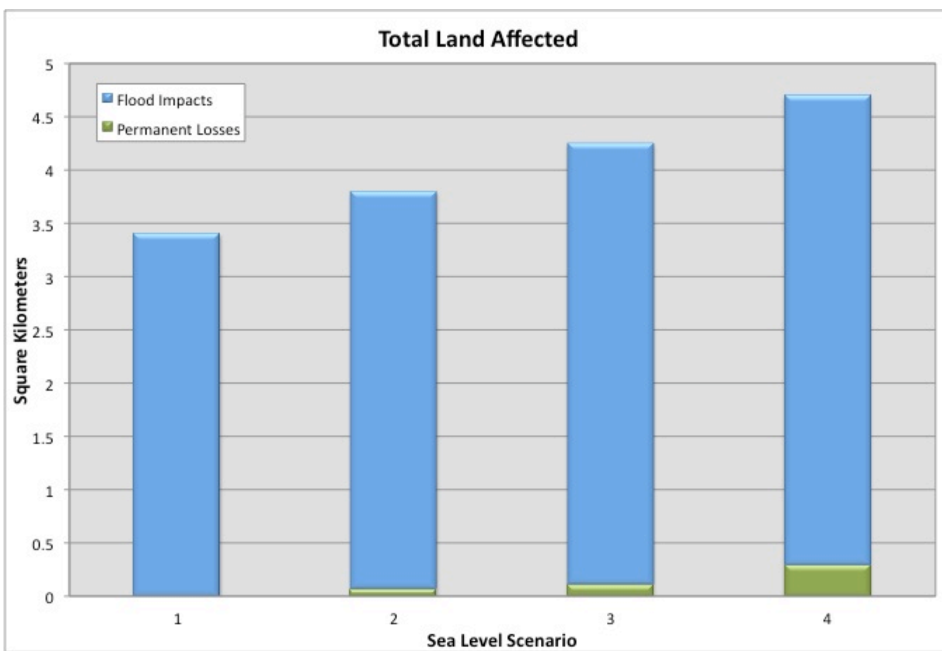

Figure 18: *Total land in Santa Barbara permanently inundated and at risk of storm flooding at 0 m, .5 m, 1.4 m, and 2 m of sea level rise.*

Property Damages

Under future sea level rise scenarios, permanent inundation of properties in Santa Barbara will be coupled with flooding during major storms, which are likely to increase in frequency as a result of climate change.

Table 2 below shows a breakdown of costs to the downtown, the airport, and Arroyo Burro. Losses begin to accumulate as sea level rises 0.5 m in the downtown, while the airport is initially affected at 1.4 m and the Arroyo Burro region is only affected once flooding occurs with 1.4 m in sea level rise.

Table 2: *Total Area and value of land/structures at risk for inundation by sea level rise and 100-year floods for the city of Santa Barbara, broken into three separate regions (downtown, airport, and Arroyo Burro).*

Location	Area Permanently Inundated (km^2)	Area at Risk for Storm Surge (km^2)	Value Permanently Inundated	Value at Risk for Storm Surge
Harbor/Downtown				
0 Meters		0.291		$228,650,475
0.5 Meters	0.069	0.411	$145,256,984	$296,627,372
1.4 Meters	0.101	0.670	$145,949,144	$412,872,466
2 Meters	0.124	0.839	$145,949,144	$527,091,018
Arroyo Burro				
0 Meters		0.013		
0.5 Meters		0.018		
1.4 Meters		0.028		$4,861,133
2 Meters		0.035		$8,170,566
Airport				
0 Meters		3.100		$335,393,903
0.5 Meters		3.298		$335,690,644
1.4 Meters	0.010	3.439	$282,631,496	$340,812,198
2 Meters	0.168	3.533	$282,631,496	$340,812,198

A 2 m increase in sea level will inundate $428 million worth of property in Santa Barbara (**Figure 19**). Storm flooding under this scenario would impact another $876 million worth of property, although these will not be permanent losses. Properties that are flooded during major storms will still maintain some level of value depending upon the frequency and intensity of the flooding.

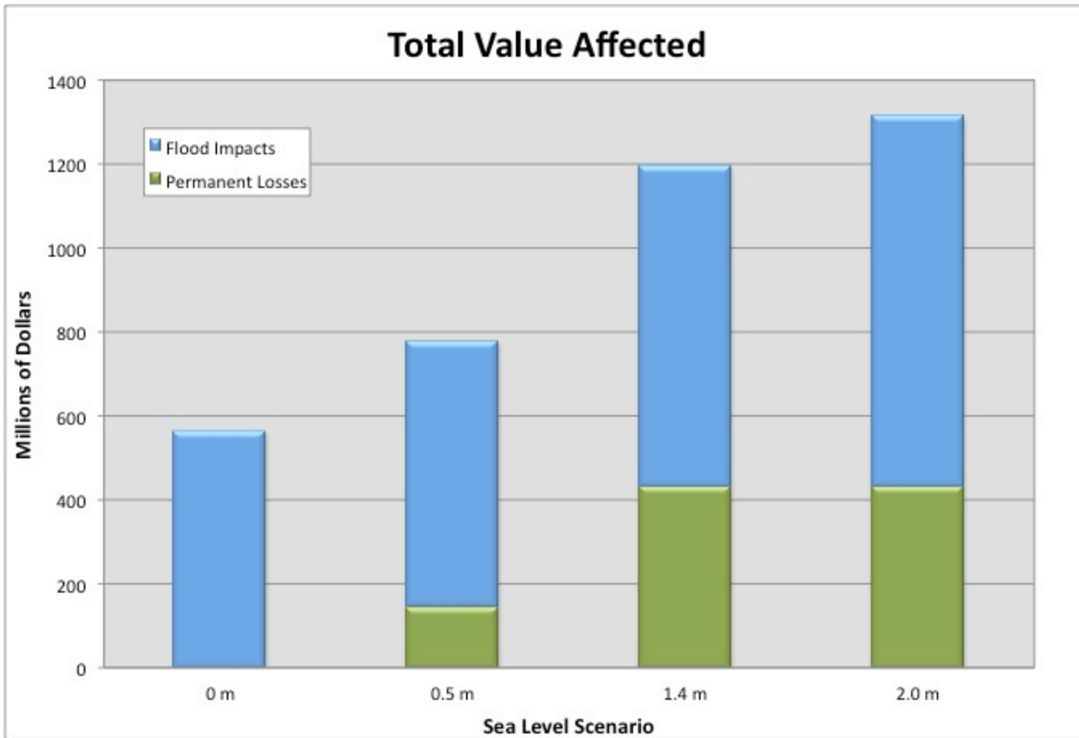

Figure 19: *Affected Property for the city of Santa Barbara due to sea level rise and storm impacts.*

Transportation

Transportation impacts of inundation and flooding due to sea level rise were analyzed for roads and railways (Figures 20 & 21). Transportation losses will be minimal due to inundation compared with impacts during storms. The combination of more intense storms and further levels of flooding due to future sea level rise means that there will be significant flooding issues for certain transportation corridors in Santa Barbara.

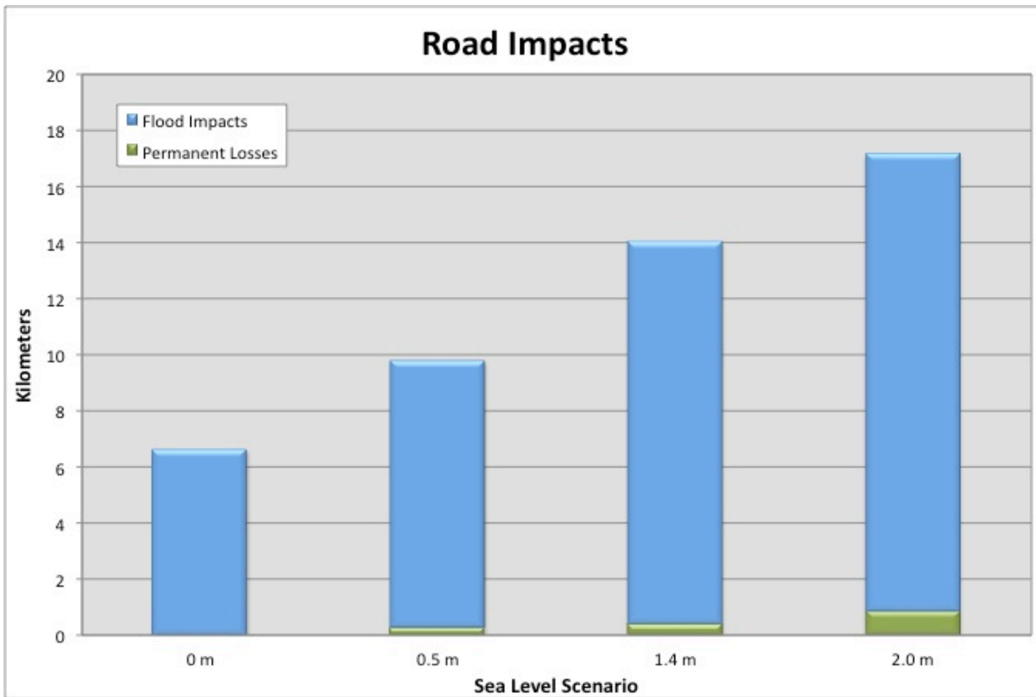

Figure 20: *The total length of roads that will be permanently inundated and the roads at risk for flooding during a 100-year storm event.*

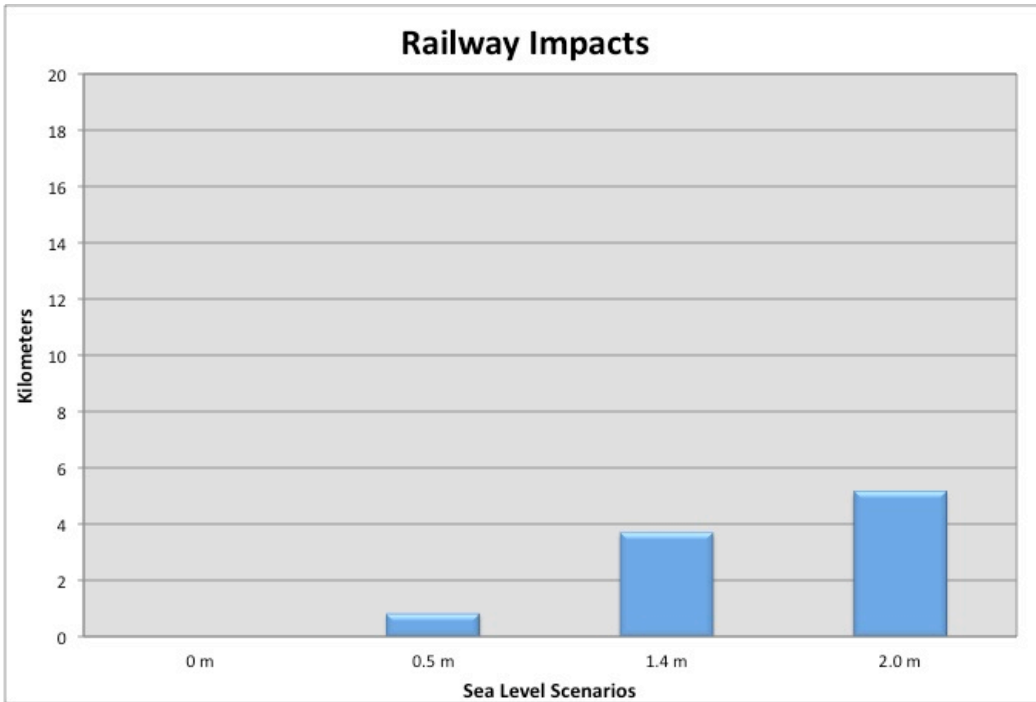

Figure 21: *The length of railroad at risk for flooding during a storm event.*

In the downtown and harbor area, stretches of Stearns Wharf road will be permanently inundated at 1.4 m and 2 m of sea level rise. During major floods, Cabrillo Blvd. and Milpas St. will be seriously affected, even at today's sea levels, while Corona Del Mar, State St. and Chapala St. will be affected during floods under higher sea levels. There will be no permanent inundation of railways and no effects until flooding occurs with 0.5 m of sea level rise, in which case 800 m of railway will be impacted. This figure jumps to 5 km for flooding combined with 2 m of sea level rise.

At the airport, Fowler St. will be affected at 1.4 m of sea level rise, as will stretches of Placentia St. Once 2 m of sea level rise occurs, parts of Fairview will be permanently inundated as well. During floods at today's sea level, main impacts will be to parts of Hollister and Fairview, with Highway 217 becoming increasingly vulnerable as sea level rises, beginning with a rise of 0.5 m. Additionally, 75 m of railway will be flooded during storms with 2 m of sea level rise.

Finally, the roads at Arroyo Burro will be unaffected by sea level rise and are not impacted at current flood levels; however, beginning with 0.5 m of sea level rise, Cliff Dr. will be flooded. Should sea levels increase beyond 0.5 m, this effect will be more pronounced, and Alan Drive will also be impacted during floods with 1.4 m of sea level rise. No railways will be affected in Arroyo Burro.

If storm events in 100 years become more severe than our predictions due to increased storm intensity resulting from climate change, the predicted flood impacts on roads would further increase. The modeled flooding discussed above is from storm surge only and does not include flooding due to insufficient drainage.

Erosion

Overall, the average erosion rate for the entire coastline for the city of Santa Barbara is 15.6 m over a 100 year period; however, the erosion rates for Santa Barbara will vary greatly along different parts of the Santa Barbara coastline depending upon the topography (Figure 22 & 23).

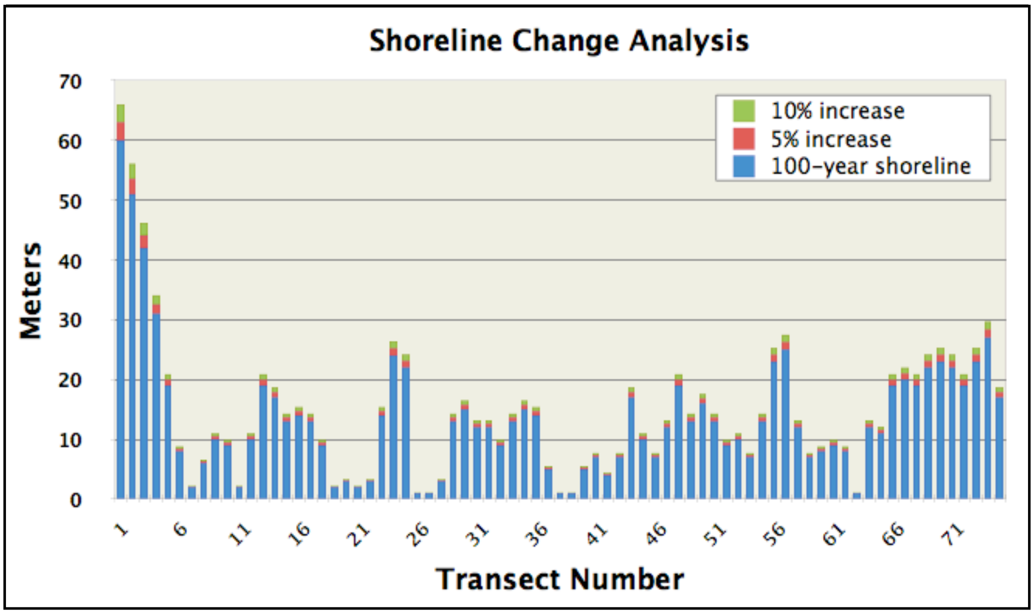

Figure 22: *Erosion rates for the city of Santa Barbara coastline over the next 100 years, including 5% and 10% increases to account for expected acceleration of erosion over the next 100 year period. Transects are ordered from east to west. Transects 1 to 4 = Coastal area south of Sea Ledge Lane. Transects 23 to 26 = Arroyo Burro. Transects 28 to 75 = Mesa. Transect 60 to7 5= Shoreline Park*

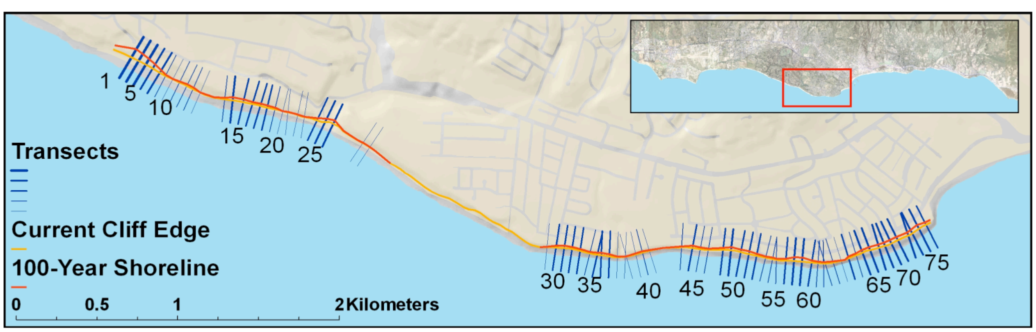

Figure 23*:Transects 1-75 and their location along Santa Barbara's coastline. Transects 24 to 27 = Arroyo Burro Beach and Park. Transect 60 to75 = Shoreline Park*

The areas of highest erosion correspond to transects 1 through 4 which is the coastal area south of Sea Ledge Lane. This area features oceanfront homes built atop steep bluffs (**Figure 24**). It is interesting to note that the homes along transects 1 – 4 have shorter bluffs and a higher erosion rate than the homes between transects 4 and 7, which have taller bluffs and a reduced erosion rates. However, although it is difficult to discern from the figure, there is more riprap along the taller bluff-face. Transects 8-12 have larger bluffs with development set further back from the bluff face and, thus, reduced erosion rates. The other regions that are projected to erode more than 20 m are the Arroyo Burro area (transects 24 and 25 and the mouth of Arroyo Burro Creek) and large portions of Shoreline Park.

Figure 24: *Aerial bird's eye view of transects 1 – 8, a coastal region with steep bluffs. Note: Transect locations are approximated. Source: Microsoft Corporation Live Maps © 2009.*

Discussion

The impact of future sea level rise on the city of Santa Barbara will largely be due to damages from increased flooding during major storm events, rather than permanent inundation losses.

In order to manage sea level rise along the coast, city managers must update the local coastal plan to incorporate necessary land use and zoning adjustments. While the previous Santa Barbara LCP, written in May 1981 and last amended in November 2004, takes into consideration 100-year flood zones, erosion and dredging, coastal aesthetics, conservation planning, and sensitive environmental habitats, the regulations regarding these issues should be updated in the new LCP to account for possible sea level rise scenarios up to 2 m by the year 2100. Certain regions in Santa Barbara may have to remain undeveloped, or else construction strategies that mitigate increased flooding and higher sea levels, such as raising houses in flood zones, should be adopted in affected regions.

Response Considerations

Coastal armoring

Armoring (usually riprap or sea walls) is an option Santa Barbara public officials could consider to protect city areas from inundation and storm flooding. Coastal armoring has increased in California substantially over the past 3 decades, with the amount of armored coastline in California increasing 350% over a 27 year survey (Griggs et al. 2005). While armoring structures can reduce or prevent flooding, they are expensive and have potential negative environmental impacts.

Riprap refers to the placement of large rocks to slow erosion. Riprap is a relatively quick and easy solution, but may have negative impacts. The rocks used need to be large enough to not be moved by waves and high enough so that waves do not overtop them. Structures must be built deep enough not to undermine or scour – a process by which deflected wave energy weakens a structure. They must be designed with a stable slope (no less than 2:1 ratio of horizontal: vertical); thus they take up a lot of beach area.

Seawalls and bulkheads can be made of concrete, wood or steel built parallel to the shore. They are relatively narrow, so they take up little beach area, but they are much more permanent than riprap structures.

Both riprap and sea walls can affect adjacent properties by a process called outflanking, whereby the adjacent properties are eroded more quickly as wave energy is deflected away from the property primarily being protected and towards neighbors. Overtopping and undermining are major concerns for coastal reinforcement structures. Cliff armoring, which is a type of coastal reinforcement structure that is used to specifically to reduce cliff erosion, is also affected by terrestrial processes such as landslides, rain and gullying. Engineering must ensure that runoff from impermeable surfaces is routed or carried to the cliff base by pipelines, so as to not affect coastal armoring structures.

Dredging, Beach Nourishment, and Artificial Reefs

Santa Barbara officials can also consider mitigation methods that enhance the 'natural' structure of city's soft beaches, those that are composed primarily of sand and are not closely bordered by cliff or rocks. Soft beaches reduce wave impact by buffering wave action through the friction created by the sand and sediment deposits. However, soft beaches in Southern California have been shrinking in size recently because coastal sand deliveries from terrestrial runoff have been reduced by up to 50% due to structural impediments (Griggs, 2005).

Selective renourishment can enhance soft beaches.

Dredging and beach nourishment is already used on a regular basis in Santa Barbara's water, especially in the harbor area. In 2003, the Beach Erosion Authority for Clean Oceans and Nourishment (BEACON) carried out a demonstration project where sand from the perennial dredging operations at Santa Barbara Harbor was barged to Goleta Beach (Bailard, 2008).

The dredging in Santa Barbara Harbor provides a relatively continuous supply of material for beach renourishment in the region, usually east of the harbor. However, if material for increased nourishment needs to be dredged from additional locations, there may be negative ecological impacts on sensitive marine habitats, like reefs or kelp forests, resulting in difficulty in obtaining permits. Alternatively, BEACON is working on plans to divert material from upstream debris basins to the beaches (Bailard 2008). Based on a Ventura study, they estimate the incremental hauling cost to be $5-10 per cubic yard for debris basins within a 5 mile radius and $30-35 per cubic yard for material within a 30 mile radius.

Another possible option for protecting Santa Barbara's economically important beaches and coastal areas from increased erosion rates are offshore artificial submerged reefs. The benefits of submerged artificial reefs include: retention of beach nourishment due to reduced impact of wave action, no hindrance of the natural transport of material which replenishes downdrift beaches, and better diving locations as a result of increased marine habitat (Allsop, 2003, Bailard, 2008).

Response Recommendations

In order to protect coastal regions from damages due to inundation and storm surge, adaptation and protection solutions will likely have to be implemented along regions of the Santa Barbara coastline. For the areas substantially impacted by inundation and storm flooding, we recommend planners analyze the costs and benefits of three possible response actions:

- Status quo: no change in current policies and activities
- Protection: such as installing sea walls, levees, or riprap
- Adaptation: such as infilling land, raising buildings, or renourishing beaches

In our analysis, we looked at four main areas of Santa Barbara's coastline that will be impacted by climate change and sea level rise: the airport, downtown Santa Barbara, the harbor, and Arroyo Burro. These regions need to be evaluated for cost effective solutions that diminish future sea level rise impacts and damages (**Table 3**). In using protection strategies to block ocean water from flooding and inundating any drainage area of Santa Barbara, city managers must also be careful to engineer structures allow runoff to drain out from the city and into the ocean or compensate for such drainage.

Table 3: *Costs of current and proposed mitigation strategies (all costs are conservative estimates). Sources: Bailard, 2008; Bridley, 2008; Griggs et al. 2005; Jones et al. 2006; Kato, 2008; and Santa Barbara, 2007.*

Mitigation Strategy	Cost
Emergency riprap	$1 million per mile
Permanent revetments/seawalls	$3 million per mile
Beach nourishment by trucking in sand	$1.5 - 2 million per 100,000 cubic yards
Beach nourishment from offshore dredging	$0.88 million per 100,000 cubic yards
Elevating Buildings	$17-49 per square foot
Santa Barbara Harbor dredging	$1.5 million per year per 300–350,000 cubic yards
Santa Barbara Harbor breakwater replacement	$600,000 per 100 yards
Elevating airport and repaving runway	$15 million

Airport

The Santa Barbara Airport is already facing trouble during major storms and has flooded several times in the past. A large part of the airport region will be permanently inundated by the end of the century given 2 m of sea level rise. The expense of moving the airport, or raising it by constructing higher runways, is simply too costly compared with building a sea wall or other structure to prevent intrusion (Table 3).

A 0.8 mile long sea wall or levee would be needed to protect the airport. There are continuous maintenance costs associated with removing sediment build-up behind a sea wall at Goleta Slough. Currently the Santa Barbara County Flood Control District removes sediment buildup from the airport and slough area once a year, although the cost of doing so will increase if a sea wall or levee is installed. However, this may be mitigated by incorporating floodgate or flap sluice system with pumps built into the sea wall to allow for sediment-rich runoff to exit the Slough while preventing the up-gradient advance of storm surges.

Floodgates, particularly bulkhead gates, are manually removable vertical walls designed to stop water flow entirely as part of a levee or storm surge system. Depending on engineering, a floodgate can be lifted to allow water to flow under or retracted sideways into the levee or sea wall structure. Past prices of floodgates reportedly range from $14.7 to $27 million (Dolan, 2007; Grissett, 2006). In the case of both floodgates and flap sluices (described below), pumps must be installed to remove water built up on the Slough side of the sea wall. The price of a pump is estimated at $800,000, but this does not include maintenance and energy costs (Grissett, 2006).

With hinges at the top, flap sluices act as one-way check valves and may be considerably less expensive to install than floodgates. When water pushes on one side, like outflow from the Goleta Slough, the pressure lifts open the flap and water flows through. When water places pressure on the other side, as the ocean could during a storm or hide tide with sea level rise, the gate is pushed closed. A flap sluice system, recently installed in England cost 30,000 pounds, or $42,000 (Wring & Knott, 2005).

Protection of the airport will inherently involve cooperation with the city of Goleta which has jurisdiction of the Goleta Beach area and the terrestrial impediment currently mitigating storm surge impacts on the airport. The city of Goleta has been weighing various beach erosion mitigation strategies (Goleta Beach, 2008). One option is a managed retreat of man-made structures and recreational areas to restore natural shoreline dynamics. The other major option is placing a permeable pier adjacent to Goleta Pier to temporarily trap sand from the long-shore transport and increase the sediment budget and thereby beach length. Although these options may not mitigate the impacts of long-term sea level rise scenarios, they may be an integral tool to reduce short-term inundation risks to the airport.

Harbor

Similar to the airport in economic value, the harbor, with annual estimated revenues of $11.5 million, is an essential part of the city and must be protected against sea level rise impacts. The harbor is already facing problems with sedimentation blocking the mouth of the channel where boats enter and exit; annual dredging of the harbor entrance costs approximately $1.5 million per year. Additionally, the breakwater that protects the harbor from current storm surges could also be increased in height to help lessen or prevent storm surge damages to the harbor and moored boats under higher (1.4 to 2 m) sea level rise scenarios. Current estimations for demolition and rebuilding of Santa Barbara's breakwater at current height are $600,000 per 100 yards (Kato, 2008). Increasing the height upon rebuilding will increase cost, but to what degree depends on the height desired. A 10% increase in breakwater height corresponds to a 15-20% increase in volume because of the increased width of the base (Reeve et al, 2004).

Downtown

While it is important to save the airport and harbor due to their high economic values, downtown will also have to mitigate the impacts of sea level rise. Unfortunately, sea wall and erosion mitigation strategies in the downtown region will likely not be cost effective in reducing the impacts of future sea level rise and storm inundation. A long stretch of sea wall (at least 2.3 miles) that would have to be erected at a cost at least $3 million per mile in order to save coastal properties may prove to be too costly monetarily and aesthetically in producing the desired results.

Because permanent inundation in our 3 scenarios barely crosses past the beach area, installing a sea wall structure along Cabrillo Boulevard would only protect land and buildings during major, but periodic storm events. Further, the structure would have to be anchored or engineered to prevent leakage around the edges. Even if a sea wall structure were to save the properties along the coast, the beaches would be eroded away, and much of the natural beauty of the downtown area would be compromised. However, city planners may want to protect the beaches in this region, at least on a shorter time-frame, due to their recreational and tourism value. As discussed previously, a variety of soft solutions such as beach nourishment and artificial reefs may accomplish this.

We therefore recommend not installing a sea wall structure but continuing the process of beach nourishment in the downtown area for the near future, otherwise the receding beach will begin to undermine and weaken Cabrillo Boulevard. We also suggest flood adaptation measures be integrated into zoning in flood prone areas, such as the raising of coastal properties. The cost of elevating buildings varies widely depending on building type, size, foundation, and elevation height but is estimated between $17-49 per square foot (Jones et al. 2006).

Arroyo Burro

Installing a sea wall at Arroyo Burro could be relatively cheap, and it could be anchored to nearby cliffs to prevent leakage. However, because it would not protect a large amount of economically important land from storm inundation we recommend that city planners maintain the status quo and leave Arroyo Burro as it is.

Conclusions and Future Research

According to our modeling, permanent inundation of land areas is expected to be minimal under sea level rise scenarios of 2 m or less. However, a substantial amount of land area is at risk of temporary flooding during large storm events, which, as climate change progresses, are likely to increase in frequency. The erosion rates for the cliffs in our study area are not expected to increase substantially, but episodic cliff collapse will continue to occur along the Santa Barbara coastline, especially during storm events.

It is critical that as city officials plan for sea level rise in the coming years, they continue to monitor the literature for new estimates of sea level rise over the next century. Even during the course of this project, new literature was published on accelerated melt rates of the Greenland and Antarctic ice sheets and we believe that estimates of these rates are only likely to increase in the near future.

This project was limited to land and structural values of private property. A more complete estimate of the property at risk for sea level inundation and storm flooding will require more research on the value of public buildings. Similarly, we did not incorporate valuations of services provided by coastal parks and beaches, which are huge draws for tourism and local recreation.

Finally, this project only analyzed the impacts of sea level rise and storm surges on the city of Santa Barbara. However, compounding the problem of increased storm intensities, higher sea levels, and higher storm surges is flooding due to insufficient and reduced drainage. The city is sandwiched between the Santa Ynez Mountains and the ocean, causing flash flood events in the area during large storms. Fires in the mountains above Santa Barbara, such as the Tea Fire in 2008, can only make the problem worse by reducing soil water holding capacity and increasing the amount of runoff that flows out of the city and mountains during storms. Therefore, we suggest future research of the impacts of sea level rise on the city of Santa Barbara take drainage issues into account. City planners or academic researchers could integrate programs like HEC-HMS, a drainage modeling program, into the GIS sea level models created in this project.

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