The Socio-Economic Impact of Sea Level Rise in the Galveston Bay Region

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Executive Summary

This project is part of a larger effort that seeks to illustrate, at a local level, the impact that climate change can have on communities. The science and impacts of climate change do little to motivate action if individuals cannot relate to them on a personal level. One of the more important changes taking place along the Texas coast is sea level rise and more specifically, relative sea level rise in the Galveston Bay region. Sea level rise is not a hypothetical phenomenon, it is happening. The instrumental record for Galveston's Pier 21 has recorded a 0.60 meter increase in relative sea level over the last 100 years. To assess the potential impact that sea level rise may have on the region, this report will focus on two scenarios of sea level rise and the associated socio-economic impact for the next 100 years.

The three county region that surrounds Galveston Bay, and that will be impacted by relative sea level rise, is dynamic and heterogeneous. This region is significantly large in many respects. It totals over 2,700 square miles and has over 46,000 census blocks. The region has a combined population of 4.1 million, employment level of over 2 million and total personal income of $183.2 billion. This region makes up 18% of Texas employment and population, and 20% of the households. The city of Houston, in the northwestern corner, is a large metroplex with a diversified economy that includes a major port and energy industry along with a large medical complex and numerous other diversified economic activities. Galveston, the city and county, has a mix of tourism, petrochemical industry and agriculture as the main economic drivers, and Chambers County is dominated by agriculture.

We model two scenarios of relative sea level rise for 100 years: 1) 0.69 meters and, 2) 1.5 meters. For each of these scenarios we estimate the impact on the following variables: 1) displaced population (number of households); 2) expected number of buildings impacted, 3) building related economic loss, 4) industrial, hazardous, superfund, solid waste sites, and 5) water treatment plants.

For the region, almost 99,000 households would be displaced under the 1.5m scenario. For Galveston County alone, 78% of the current number of total households would be displaced under the 0.69m scenario and 93% under the 1.5m scenario households. This would equate to about 1.3% of all the households in Texas and equivalent to the entire city of Corpus Christi (year 2000).

Over 75,000 structures are impacted to some degree in the region under the 1.5m scenario. Once again the regional impact is dominated by what happens in Galveston County, but Harris and Chambers are not exempt from the impact. The economic loss estimates for buildings are significant. Regional impact approaches $12.5 billion dollars. To put that figure in perspective, it would equal 1% of Texas gross state product (2008).

Just as important as the socio-economic impact of sea level rise, is the impact on public facilities and industrial sites as it relates to waste storage or treatment. The environmental impact of an inundated waste treatment or holding facility could be significant under our two scenarios. Under the 0.69 meter scenario a total of 23 sites would be threatened or impacted. Most prominently waste water treatment plants but also 3 superfund sites. Under the 1.5 meter scenario a total of 33 sites would be impacted or threatened with 16 of those being wastewater treatment plants and 9 being solid waste sites. In order to protect the public from the potential environmental and health impacts, government agencies at all levels will be required to expend resources on moving, mitigating, or protecting these sites. Finally, if Hurricane Ike were to come ashore with the sea level 0.69 meters higher, it would have caused an additional $1.7 billion in damages, for a total of $16.8 billion for the three counties only. That is equivalent to 1.3% of gross state product for Texas. The additional damage is also equivalent to the sum of the median income of 35.7 thousand Texas households.

I. Introduction

This project is part of a larger effort that seeks to illustrate, at a local level, the impact that climate change can have on communities. The science and impacts of climate change do little to motivate action if individuals cannot relate to them on a personal level. Working with Environmental Defense Fund, British Consulate-General Houston and the Texas Climate Initiative based at the Houston Advanced Research Center, and the Harte Research Institute for Gulf of Mexico Studies at Texas A&M University-Corpus Christi, a series of case studies are being produced utilizing the most relevant science and techniques associated with climate change in Texas. These placed based case studies will provide a context in which the public can integrate the changes taking place around them and its impact.

One of the more important changes taking place along the Texas coast is sea level rise and more specifically, relative sea level rise in Galveston Bay. Relative sea level rise takes into account not only global sea level rise but also local subsidence and for the purposes of this study we will use the terms interchangeably, noting that subsidence is a critical issues in the Galveston Bay region. Sea level rise is not a hypothetical phenomenon, it is happening. The instrumental record for Galveston's Pier 21 has recorded a 0.60 meter increase in relative sea level over the last 100 years. At a minimum, if that trend continues, there is the potential for significant socio-economic impact in the Galveston Bay region.

The region has the largest port (Houston) in the Gulf of Mexico and one of the largest in country. A significant energy complex of more than 3000 firms call the area home and over 31 million people visited the greater region in 2007. These factors and many more contribute to the significance that the region has to the State of Texas. To assess the potential impact that sea level rise may have on the region, this report will focus on two scenarios of sea level rise and the associated socio-economic impact.

II. Sea Level Rise and Climate Change

Sea Level Rise

Sea level rise is an increase in the mean sea level of the ocean. Eustatic sea-level rise is a change in the global sea level brought about by alteration in the volume of the world-ocean due to changes between liquid and solid states, or changes in density or salinity. Climate modelers focus on estimations of this change. Isostatic sea level rise processes due to the changes in the underlying topology of the sea floor. Relative sea-level change occurs where the local level of the ocean relative to land is changed, due to ocean rise and/or land subsidence or due to rapid land-level uplift. Impact researchers focus on this relative sea-level change which is measured by tide gauges with respect to the land on which they are located. A tide gauge is a device located on the coast that continuously measures the level of the sea in respect to the adjacent land. Mean sea level is defined as the average relative sea level over a period long enough to average the wave and tide transients (typically a month or year) (Thurman and Burton 2000, IPCC 2001, Baede 2007).

Sea level can change locally and globally due to changes in the shape of the ocean basins, and change in the total water mass and density (steric). Thermosteric changes are changes in density (thus volume) due to temperature change and halsosteric change is due to salinity change. Sea level equivalent is the change that would occur to the global average sea level given the amount of water or ice that was added or removed from the oceans (IPCC 2001, Baede 2007). Factors leading to sea level rise during global warming include an increase in the total mass of water due to melting of snow and ice; changes in water density due to increased water temperature; and salinity changes (Bates, Kundzewicz, Palutikof 2008).

The globally averaged sea-level change and its spatial variations due to climate change are important for future planning. Managing resources properly requires knowledge of the effects of the changes in ocean circulation, temperatures, and nutrients on the marine and coastal environment (Jacobs 2006).

Climate Change

Climate is typically defined as the statistical description of weather in terms of mean and variability of relevant quantities over several decades or the "average weather", due to natural inconsistencies or human activities. The quantities are usually surface variables including temperature, precipitation, and wind (IPCC 1995, IPCC AR-4, 2007).

Climate change is a change in climate quantities attributed directly or indirectly to natural inconsistency such as human activity including anthropogenic increases in greenhouse gases that alter the composition of the global atmosphere (IPCC AR-4, 2007). The changes in climate may be due to natural processes (solar radiation and volcanism), external forcing, changes in land use or persistent anthropogenic changes in composition of the atmosphere. Climate change attributed to human activities is the change in the state of the climate in addition to the natural climate variability, which can be identified (using statistical tests) by changes in the mean and the variability of its properties observed over extended comparable time periods compared to expected changes (IPCC 1995, IPCC AR-4, 2007, Verbruggen 2007).

The IPCC states in its 2007 assessment report that climate system warming is indisputable with evidence in global average air and ocean temperature rise of average sea level and melting of snow and ice. Worldwide the average temperature has been increasing, since the late 19th century of between 0.4 to 0.8º. Since, 1859, eleven of the last twelve years were in the top twelve warmest global surface temperatures. Average temperatures in the Artic increased nearly twice as much as the global average. Land temperature has increased more than ocean temperature even though oceans receive more than 80% of the heat added to the climate system (IPCC AR-4, 2007).

Climate Change and Sea Level Rise

Oceans have a important role in the storage and redistribution of heat absorbed from solar radiation, most solar radiation is absorbed near the equator then redistributed through the ocean by currents known as Thermohaline Circulation (ESR 2004). Global warming leads to thermal expansion, which causes sea level rise. The increases in sea level are consistent with warming. Global sea level rise is also a result of the exchange of water between oceans and reservoirs including glaciers, ice caps, ice sheets, and land water reservoirs (IPCC AR-4, 2007).

Global mean sea level was rising during the 20th century at an average rate of 1.7(± 0.5) mm/year. The IPCC has a high confidence that the rate has increased from the mid-19th to mid-20th centuries (IPCC AR-4, 2007). The sum of the estimated individual contributions to sea-level rise from 1993-2003 were thermal expansion of the oceans at about 57%, decreases in glaciers and ice caps at about 28% and losses from the polar ice sheets contributing about 15% (IPCC AR-4, 2007). The sum of the climate contributions is consistent within the uncertainties of directly observed sea level rise.

It is likely that the rate of occurrence of extreme high sea level at a wide range of sites has increased since 1975. Since sea level change is spatially non-uniform, some regions experience rates that are several times the global mean sea level rise while others have falling sea level. Thermal expansion would continue for centuries after the GHG concentrations are stabilized, according to the IPCC. If GHG and aerosol concentration levels had been stabilized at year 2000 levels, thermal expansion alone would be expected to cause 0.3-0.8 meters of sea-level rise. The Greenland ice sheet could eventually contribute several meters if warming increases average temperature 1.9-4.6*ºC.* Long-term consequences of global warming would create major implications along the coastlines. This long-term response of thermal expansion and ice sheet response to warming imply that mitigation strategies to stabilize GHG concentrations and radiative forcing at present levels will take time to stabilize sea level. Anthropogenic warming and sea level rise could continue for centuries even if GHG emissions were reduced to a level that GHG concentrations would stabilize the time scales associated with climate processes and feedbacks. Sea level rise from thermal expansion would continue due to ongoing heat uptake by oceans, until the rate eventually decrease from that reached before stabilization (IPCC Ar-4, 2007; Bindoff, Willebrand, Artale et. al. 2007).

Sea Level has been rising since the end of the glaciations about 15,000 years ago (Thurman and Burton 2000). The Intergovernmental Panel on Climate Change has high confidence that the rate of global mean sea level rise increased between the mid-19th and 20th centuries. IPCC states "The average rate was 1.7 ± 0.5 mm/ yr for the 20th century, 1.8 ± 0.5 mm/yr for 1961–2003, and 3.1 ± 0.7 mm/yr for 1993–2003" (IPCC AR-4, 2007). Sea level is expected to rise 56 cm by 2100 (Patz, 2000), these levels are expected to rise at a greater rate this century due to melting and loss of ice and thermal expansions of the ocean due to warming. The higher rate of sea level rise might be due to decadal variability or an increase in the long-term trend. The changes were spatially non-uniform, and from 1993-2003 some regions had a rise in sea level several times greater than the global rise while in other regions the sea level fell (IPCC 2007, Bates, Kundzewicz, & Palutikof, 2008).

There are two dominate processes that change sea-level over long periods of time: change in the liquid/solid ratio of water and thermal expansion. The change in liquid/solid ratio of water through the world is a measure of the mass of ice stored in polar ice caps. The melting of sea ice adds water to the present ocean volume, while the melting of ice sheets of Greenland, Iceland and the Antarctic have the potential of increasing the sea level about 80 meters. Icebergs, Arctic ice mass, and Antarctic ice shelves may also melt indicating climate change, but their mass is already displacing equivalent water volume so it will not cause sea level rise (Thurman and Burton 2000, Jacobs 2006).

An increase in temperature of 1ºC would expand the mean depth of the ocean 3.8km due to thermal expansion (Thurman and Burton, 2000). During the period from 1993 to 2003, thermal expansion and ice sheet mass loss contributed a total of 2.8 ± 0.7 mm/yr, this is consistent with the directly observed sea-level rise (given observational uncertainties). Increases in sea level are consistent with global warming. "Modeling studies demonstrate that overall it is very likely that response to anthropogenic forcing contributed to sea-level rise during the latter half of the 20th century; however, the observational uncertainties, combined with a lack of suitable studies, mean that it is difficult to quantify the anthropogenic contribution" (Bates et al. 2008).

Sea ice has several roles in the global climate system including serving as a insulator between the ocean and the atmosphere and restricting exchange of heat, mass, momentum, and chemical constituents. Sea ice also effects surface albedo, the measure of reflectivity of solar energy of the earths surface. Ice-free ocean typically has a surface albedo of 10-15%, melt pond 20%, snow covered ice 80%, and fresh snow up to 98%. The albedo of snow-covered sea ice is high relative to open water, sea ice reduces the amount of solar radiation absorbed at the Earth's surface (ESR 2004, Sandven and Johannessen, 2006).

The rate of sea-level rise is not spatially uniform so the effects on coastal land forms vary among the coastal regions. Some regions also experience uplift and subsidence that are due to processes independent of climate change including oil and gas extraction, groundwater withdrawals, and adjustment of the Earth's surface on a geological timescale due to changes in surface mass call isostasy. One example of isostasy is due to the changes in ice sheet mass after deglaciation that cause crustal movement. Inland factors also influence the net effects of sea-level rise on the coastal ecosystems. Figure 1 shows that Galveston, Texas is experiencing coastal subsidence while Sitka, Alaska is experiencing coastal uplift (Thurman and Burton 2000, Bates et al. 2008).

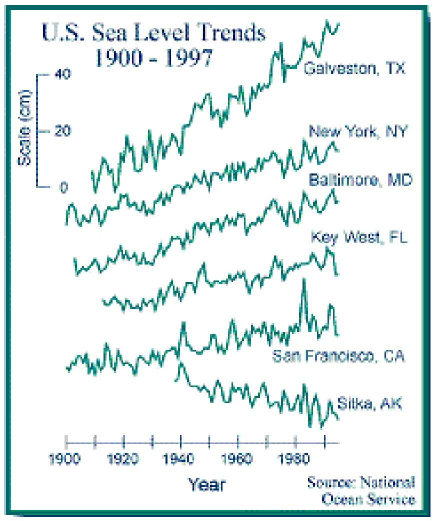


Figure 1. Sea Level Trends

Other processes such as changes in ocean circulation, atmospheric pressure, and vertical land movements also affect sea level at a regional scale. Vertical land movements from glacial isostatic adjustment, tectonics, subsidence, and sedimentation affect the global sea level by altering the shape thus volume of ocean basins (Bindoff, Willebrand, Artale et. al. 2007).

III. Impacts of Sea Level Rise

Low-lying coastal areas infrastructure and their stock is at an increasing risk to damage from sea-level rise inundation, extreme astronomical tides, storm surge flooding, hurricanes, and other storm events. This risk continues to increase due to the continuing growth of coastal cities and tourism. Damage cost estimations due to increasing sea level are often substantial (Bates et al. 2008, Fitzgerald et. al. 2008).

Rising sea level contributes to the redistribution of sediment along sandy coasts. In the long-term it can also lead to landward migration of barrier islands through offshore and onshore transport of sediment (Fitzgerald et. al., 2008). Fixed structures and changes in vegetation, block coastal habitats landward migration creating coastal squeeze and increasing impact from sea-level rise. Coastal squeeze is the squeeze of salt marshes, mangroves, and flats between rising sea level and naturally or artificially fixed shoreline. When landward migration of coastal marshes is impeded by barriers and slope and the vertical growth becomes slower than the sea-level rise, submergence occurs (Field et al. 2007). When marshes drown and are converted to open water, the tidal exchange at inlets increases and leads to sand isolation in the deltas and increases erosion of adjacent shorelines (Fitzgerald et al. 2008).

Small islands lack reliable demographic and socio-economic scenarios and projection, which results in future changes in socio-economic conditions of small islands not being presented well in existing assessments. The impacts of sea-level rise include more intense storms, and climate change without adaptation or mitigation on the small islands, will be substantial due to inundation, storm surge, erosion, and other coastal hazards. These hazards are threatening the infrastructure, local resources, settlements and facilities that are the livelihood of island communities Bates suggests that some islands and low-lying coastal areas may become unlivable by 2100 (IPCC 2007, Bates et al. 2008).

The IPCC has a very high confidence that coastal communities and habitats will be progressively stressed due to the climate change impacts combined with development and pollution. The rate of sea-level rise is expected to increase in the future along the coast. Along the Gulf and Atlantic coasts it's predicted that storm impacts will become increasingly severe. Population growth, demand for waterfront housing property, and rising value of the infrastructure along the coast increases this vulnerably (Field, Mortsch, Brklacich, Forbes et. al. 2007).

Figure 2 presents the effects of 1-m sea level rise without adaptation and mitigation measures, which would inundate low-lying areas and distress 1,117 million people in Asia, 13.5

mil. in Europe, 12 mil. in Africa, 760 thou. in Latin America, and 300 thou. in the Pacific Islands. Several Pacific Islands will likely become completely submerged. Sixteen of the

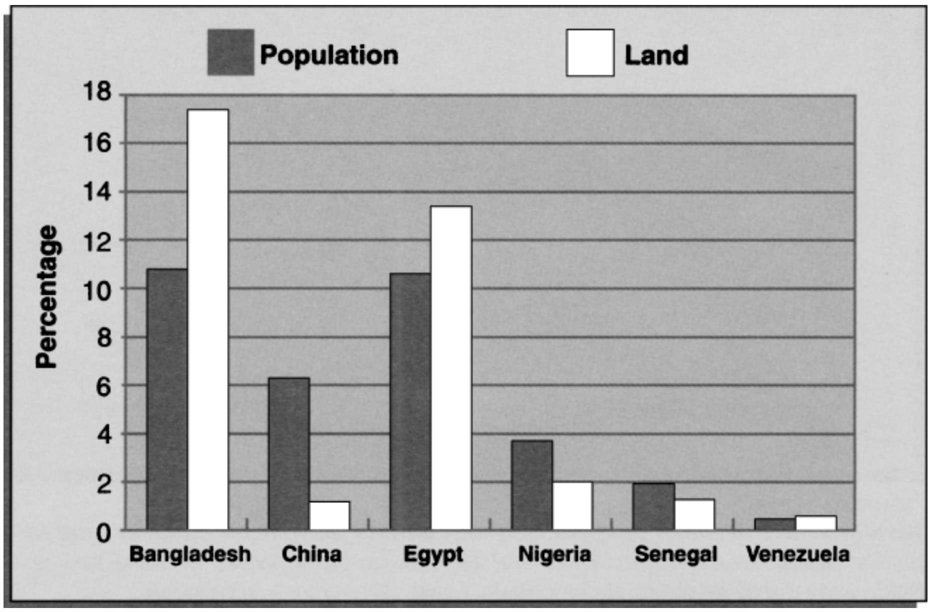


Figure 2. Populations and lands at risk from a one meter sea level rise.
(Reprinted from Patz 2000 as adapted from Strzepek KM, Smith JB, eds. 1995. As Climate Changes: International Impacts and Implications. Cambridge, UK: Cambridge University Press.)

worlds twenty mega-cities and over 10 million people are at sea-level, thus vulnerable to sea level rise; storm surges; salinization of freshwater aquifers and coastal soil; and disrupted storm water drainage and sewage disposal. Sea level rise causes recurrent and more severe flooding of coastal communities which will lead to forced migration. Sea level rise also leads to homes and communities being destroyed and people seeking safer places to live (Patz, 2000).

Sea level rise and repeated flooding of coastal communities from hydrological cycle disturbance has lead to several mass migrations already (Patz, 2000). Floods and tidal waves in North Korea from 1995-2000 lead to 300,000-400,000 people migrating to China's urban centers. Storms, land erosion, and salt intrusion into the water system lead to a massive (12-17 million) migration from various regions of Bangladesh to India and West Bengal since the 1950s, from 1970-90s 600,000 people moved from rural Bangladesh to the Chittagong Hills due to floods, storms, erosion, and government migration incentives. Four million three hundred thousand people migrated from Philippians lowland to the center uplands from 1970-90s due to flooding, land slides, and lack of usable water and soil. Salinization has caused water scarcity in Uzbekistan and Kazakstan around the Aral Sea since 1970s leading to the migration of 65,000-100,000 people annually. Inundation and flooding in the Caspian sea region of Kalmykia has lead to 2,200-8,1000 people migrating to Russia in the 1990's. In 2005 Hurricane Katrina caused a significant migration out of New Orleans and surrounding areas of Louisiana of around 1 million people (Reuveny, 2005).

IV. Galveston Bay Region

The coastal zone is influenced by the direct physical effects of sea level rise including risk of coastal flooding, shoreline erosion and storm damages (Gibbs, 1984; Bin, Dumas, and Whitehead 2007). Preparation for these effects through increasing our understanding of the effects of sea level rise and identifying a course of action (such as increasing research, construction of protective structures, and altering development patterns in coastal zones) requires balancing uncertain risks and costs. Gibbs very early (1984) analyses of the physical and economic impacts of sea level rise on Galveston lead him to estimate damages in hundreds of millions to billions of dollars and rising with the rapid economic growth in coastal zones. His study states that preparing for future sea level rise could reduce the impacts by over 60% in some cases (Gibbs 1984).

Stephen Leatherman's report on the coastal geomorphic response to sea level rise in Galveston Bay discusses three sea level rise scenarios using eight rise/year combinations selected from projected sea level rise curves (Table 1). The baseline is without any acceleration in sea level rise. Subsidence is ignored in these projections.

Table 1. Accelerated Sea Level Rise

Scenario	**1980**	**2025 cm (ft)**	**2075**
Baseline	0	13.7 (0.5)	30.0 (1.0)
Low	0	30.7 (1.0)	92.4 (3.0)
Medium	0	48.4 (1.6)	164.5 (5.4)
High	0	66.2 (2.2)	236.9 (7.8)

Infrastructure

Discussions to create a seawall and raise the elevation of Galveston island began after the hurricanes of 1886, but there was no financing available. After the Galveston Hurricane of 1900, that killed over 7,000 residents, caused millions of dollars in damages, and leveled most the city, the seawall became a necessity to the survivors. Six blocks of homes closest to the beach were destroyed and that created a wall of rubble that protected the buildings behind it (Real Galveston 2006).

Federal and Galveston County funds were jointly used for the construction of flood control structure and sand fill to increase the surface elevation of the city. The sea wall construction began in October 1902. The seawall is pile supported concrete with tied-back cut-off wall and rear embankment; the toe is protected from storm waves with sheet pilings, a pad of interlocking blocks and riprap. In 1988, the seawall was extended 11 km with a elevation of 5.4 m (17ft), it is 4.8 m wide at the base and 1-1.5 m at the top. The wall is gravity-type with a curved base and vertical top to prevent wave run-up and minimize overtopping from storm waves. The paved road serves as a splash apron and prevents erosion of the underlying fill sand. Since the construction of the seawall extension after Carla in 1961 the rates of shoreline erosion and vegetation retreat have been consistently higher at the western (down drift) end of the seawall and gradually decreasing to the southwest more than 10km from the seawall. The temporal acceleration in the average rate of erosion of West Beach is partly attributed to the relative rise in sea-level. The local increase in lateral erosion near the seawall is directly related to the coastal defense structure and decrease in sediment supply (Morton 1988).

Sand dunes are the first line of defense for most coastal properties. Along the Texas Gulf coast dunes are eroding faster than the majority of the coastal United States. This erosion is mostly due to long-term sea level rise. Galveston Island is a barrier island where land subsidence, maintenance of non-native lawn vegetation, over grazing, diversion of sediment, and the erection of coastal structures has lead to average erosions rates exceeding 2.4m annually.

The relative sea level rise at Pirates' Beach has been 0.26 inches per year according to 1909-1999 tide gauge data. Data suggests that rates this century will be around 0.4 inches per year due to sea level rise (worst case scenario from IPCC) and subsidence. This scenario will squeeze native dune communities against the barriers including non-native lawn vegetation, geotubes, seawalls, and developments. Eventually, the public beach and natural dune community will disappear and water will begin to eroded land under property or lap up to the barriers (Feagin 2005).

In 2000, a coastal engineering firm contracted by the Texas General Land Office began placing geotextile tubes (geotubes) on the ocean side of the west-end communities not protected by the seawall. Geotubes are made of woven biodegradable textiles packed with earthen material (liquid sand from the local beach) that are placed horizontally to the sea. These geotubes become a "soft" alternative to the seawall as they develop an artificial dune system (Feagin 2005).

In 2001, tropical storm Allison made landfall 30 miles from Galveston and created a short-duration surge of 3.5ft and large amounts of rainfall. The drainage pipes prevented significant erosion at Pirates' Beach. In 2002, Tropical Storm Fay, Isidore, and Hurricane Lili's longer-duration and 3-4ft surge eroded the entire frontal dune and eroded the sand in front of the geotextile tube leaving a scrap line that exposed the apron, damaged some of the geotextile tube, and removed vegetation from the damaged geotubes. Even with this damage the private property behind the dunes was still protected. In 2003, Hurricane Claudette struck 60 miles from Galveston and brought 5 ft storm surge with 8-10ft waves that broke over the top of the dunes and flooded the neighborhood behind the dunes, the vegetation, sand, and wood access ramps were washed away, the apron was uncovered and the beach in front of the geotube was scoured.

Change

Shoreline change is the position of the shoreline as it retreats landward or advances seaward as it reacts to the changes in sea level, storm occurrence, wave directions and heights, and sediment supply. The Bureau of Economic Geology compares the positions of shorelines over the years and uses liner statistical models to determine the average annual rate and direction of shoreline change. Since shoreline change is caused by variable processes a shoreline with a statistical trend of retreat over 70 years may experience periods of stability and advance seaward during other periods. The linear statistical model is less useful for predictions in areas with very dynamic shorelines (Gibeaut, Anderson, Dellapenna 2004).

The rates for Galveston have been computed using shoreline data sets from 1930-2000. The area on the southwest side of Galveston Island, less than two miles from San Luis Pass is very dynamic due to processes associated with the San Luis Pass tidal delta. During 1995-2000 this area experienced shoreline advance in tens of meters, this is indicated (by examination of past shoreline positions) as a temporary situation and equally large amounts of retreat are likely in the future. Highly variable, unpredictable areas such as this should be considered high-risk for construction (Gibeaut, Anderson, Dellapenna 2004).

Setback distances for new construction and dune protection should be based on the BEG historical shoreline change rates projected more than 20 years into the future. In areas of stable or advancing shoreline the setback line based on the current location of the dune protection line may remain in effect. Areas with highly variable change should be considered high-risk and construction should be discouraged. Ordinance and other literature needs to be created to inform the public of how and why the setback line is created (Gibeaut, Anderson, Dellapenna 2004).

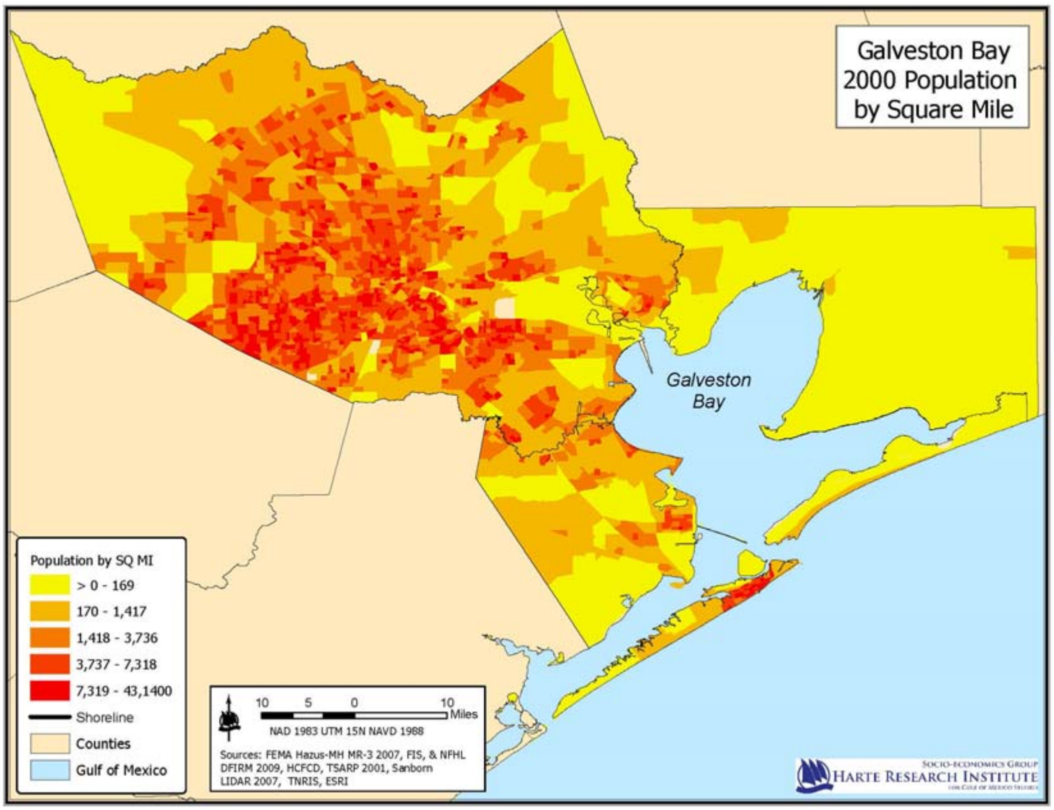
Inundation models that forecast future wetland distribution due to sea-level rise is developed from one-meter light detection and ranging (LIDAR) derived digital elevation model and detailed wetland mapping. Other components including topographic relationships of wetlands, stimulated sea-level rise (Gibeaut 2005), vertical accretion, edge erosion and land-subsidence are added to the inundation model. The Gibeaut model of Galveston Island used tide gauge records annual record of sea level, which shows the complex sea-level variation on a decadal scale. The thirty year model shows a decline in wetland coverage of twenty-two percent while the ninety year model shows recovery to a net loss of five percent. The ninety year model illustrates low-marsh wet lands being reduced by seventy-seven percent while the high-march wetlands increase by one-hundred and thirty-two percent due to upland transitioning being greater than inundation (Gibeaut 2007).

V. Region's Socio-Economic Environment

The three county region that surrounds Galveston Bay, and that will be impacted by relative sea level rise is dynamic and heterogeneous. This region is significantly large in many respects. It totals over 2,700 square miles and has over 46,000 census blocks. The city of Houston, in the northwestern corner, is a large metroplex with a diversified economy that includes a major port and petrochemical industry along with a large medical complex and numerous other diversified economic activities. Galveston, the city and county, has a mix of tourism, petrochemical industry and agriculture as the main economic drivers, and Chambers

County is dominated by agriculture. Population density per square mile identifies significant clusters of at risk populations (see Map 1).

Map 1. Population Density



It is the human footprint and the associated economic activity that is at risk with sea level rise. The region has a combined population of 4.1 million, employment level of over 2 million and total personal income of $183.2 billion (see Table 2). This makes up 18% of Texas employment and population and 20% of the households in Texas. Not all of this is at risk from sea level rise, but it will have a significant impact on the county and local governments when adjusting for changing coastal populations and economic activity.

Table 2. Socio-Economic Conditions for Galveston Bay Region

County	Population	Employment	Households	Total Personal Income
Chambers	28,779	13,733	11,685	$1,037,909,000
Galveston	283,551	137,838	110,864	$10,832,200,000
Harris	3,886,207	1,869,915	1,397,426	$171,282,800,000
TOTAL	**4,198,537**	**2,021,486**	**1,519,975**	**$183,152,909,000**

(IMPLAN, 2008 and Texas Workforce Commission, 2008)

VI. Socio-Economic Impact of Sea Level Rise

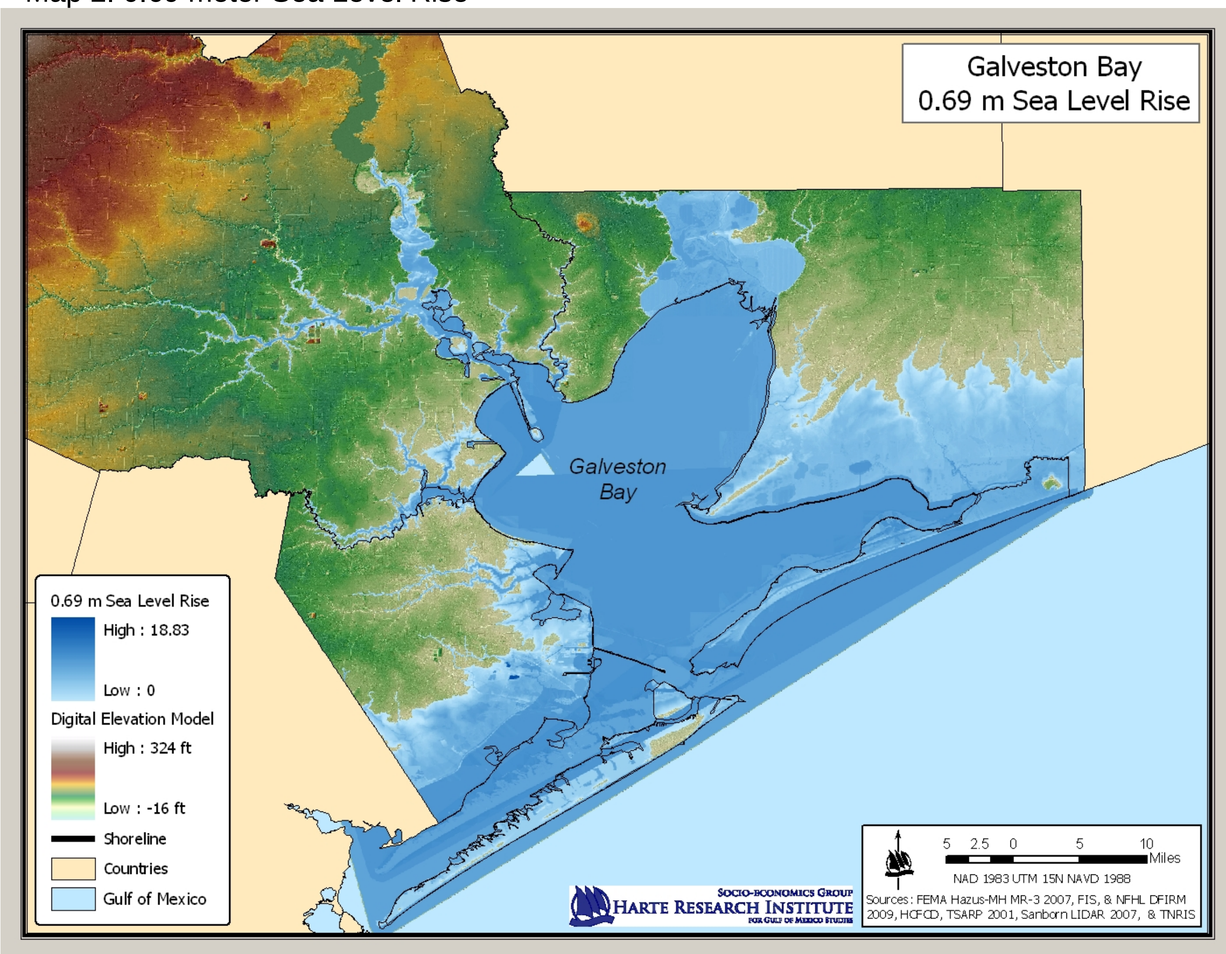
Projecting the socio-economic impact of sea level rise on the Galveston Bay region 100 years into the future is challenging. There are many confounding variables on the social and economic side of the equation as well as environmental. However, it is possible to illustrate what the impact would be if today's socio-economic characteristics were transported 100 years into the future or, impose the various sea level rise scenarios of 100 years onto today's economy. At the very least we get a sense of what we would face if nothing changed as it relates to the socio-economic characteristics of the region. Given the length of time (100 years) and uncertainty with regards to economic development, strong assumptions for the modeling process have to be made. They are:

- Mitigation, adaptation, or resiliency measures that might take place to address relative sea level rise are not considered, and;
- The socio-economic impact is based on the current conditions (2006);

We model two scenarios of relative sea level rise for 100 years: 1) 0.69 meters and, 2) 1.5 meters. The IPCC A1F1 scenario starts with constant year 2000 concentrations and projected global average surface warming to be 4ºC (range 2.4 - 6.4ºC) warmer at 2090-2099 relative to 1980-1999. The approximate CO_2 concentration corresponding to the computed radiative forcing due to anthropogenic GHGs and aerosols in 2100 is 1550ppm. The temperature change relative to 1850-1899 is an addition 0.5ºC. Sea level rise at the end of the 21st century (2090-

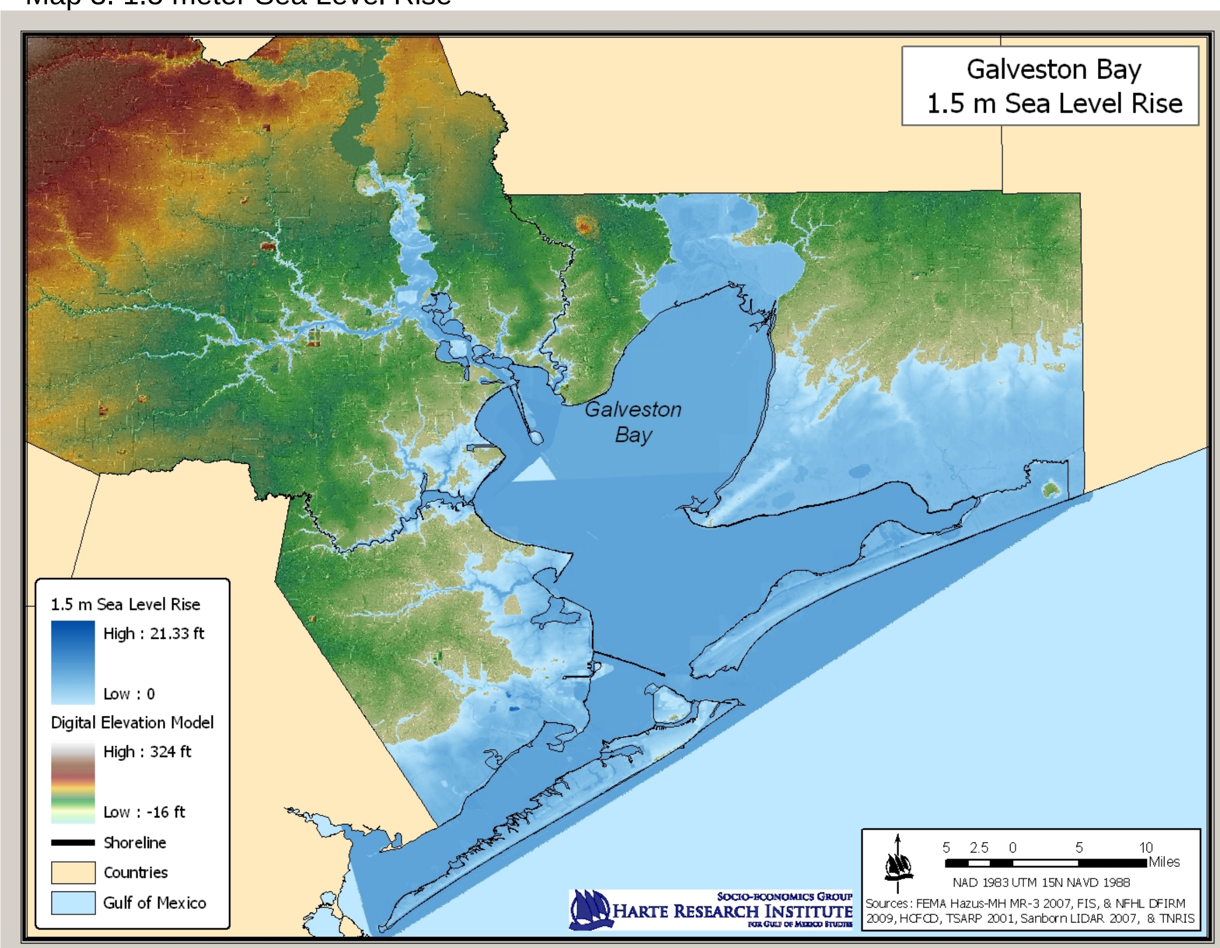
2099) model-based range is 0.26-0.59 meters (excluding future rapid dynamical changes in ice flow. This sea level projection doesn't include uncertainties in climate-carbon cycle feedbacks or the full effects of changes in ice sheet flow due to limited publish literature on the topics. The contribution due to Greenland and Antarctica ice flow is included at the rates observed for 1993-2003, but these rates could change in the future. The rate would grow linearly with global average temperature change and the upper range of sea level rise would increase 0.1-0.2 meters. This upper value of the range is not to be considered the upper bound of sea level rise (IPCC AR-4 2007). Taking into account subsidence in the Galveston Bay region, our first scenario is for 0.69 meter sea level rise over 100 years (see Map 2).

Map 2. 0.69 meter Sea Level Rise



The current global sea level rise as measured from a satellite altimeter is around 2.8 cm per decade, if this is a result of the 0.6ºC global average warming over the past century and the sea level rise response is simply linear to warming then 3ºC warming may cause around five times the current rate of sea level rise (1.4 meters) (Rahmstorf and Jaeger 2004). Rahmstorf proposes that during the pre-industrial age a semi-empirical relation does connect sea-level rise to global mean temperature and for time scales relevant to anthropogenic warming the current sea-level rise is proportional to the magnitude of warming (Rahmstorf 2006 & 2007). Taking into account subsidence in the Galveston Bay region, our second scenario is a 1.5 meter sea level rise (see Map 3).

Map 3. 1.5 meter Sea Level Rise



In order to calculate the socio-economic impact of sea level rise we utilize the Federal Emergency Management Agency's (FEMA) HAZUS- Multi-Hazard (MH) MR3 ArcGIS Extension. HAZUS-MH provides a risk-based approach to disaster management, risk mitigation, emergency preparedness, response, and recovery by identifying and displaying hazards and vulnerabilities. HAZUS is a risk assessment tool for analyzing potential losses from flood, hurricane winds, and earthquakes. It allows users to develop loss estimation studies of hazard-related damage before or after disaster occurs using community datasets that come with the software including essential facilities, lifelines, general building stock, and demographic data (FEMA 2008 and Brown and Mickey, 2008). HAZUS-MH calculates scientifically-defensible damages, economic losses, and mitigation benefits. The potential loss estimates include physical damage of residential and commercial buildings, schools, critical facilities, and infrastructure, economic loss from business interruptions and reconstruction, and the social impacts including shelter, displaced households, and population exposure to hazards.

HAZUS-MH was used to analyze the effects of sea-level rise on the Galveston Bay community. The study region, including Harris, Galveston, and Chambers counties, was created individually by county using the aggregation level of census block and flood hazard (see Appendix A for a detailed description of the process). As a caveat, it must be noted that HAZUS-MH was not specifically designed to measure the impact of sea level rise. In order to measure the socio-economic impact we utilize the flooding module in HAZUS. We have made what we feel are appropriate modifications in order to allow for measuring the impact of sea level rise given current socio-economic conditions.

As mentioned previously there are two sea level rise scenarios for 100 years; 0.69 meters and 1.5 meters. For each of these scenarios we estimate the impact on the following variables:

Socio-Economic

- Displaced population (number of households)
- Expected number of buildings impacted
- Building related economic loss

Waste Sites

- Industrial, hazardous, superfund, solid waste
- Water treatment plants

Socio-Economic

The results of the two scenarios are presented below by county and then in total. It is important to note that not only will households and families be displaced by rising sea levels but a significant amount of infrastructure, specifically buildings will be impacted as well.

The region is characterized by coastal plain and a low lying barrier island system. As the footprint map indicates, a substantial portion of human activity takes place directly adjacent to the coastal waters, thus putting it at risk from sea level rise.

Given the terrain and population density of Galveston Island it is impacted the greatest by both of the sea level rise scenarios in all of the socio-economic categories discussed here. The displaced population is based on the inundation area. HAZUS makes the assumption that individuals will be displaced from their homes when the home has suffered little or no damage either because they were evacuated or more appropriate for sea level rise, there is no physical access to the property because of flooded roadways Seventy-eight percent of the current number of total households, would be displaced under the 0.69m scenario for Galveston and 93% under the 1.5m scenario households (see Table 3). This would equate to about 1.3% of all the households in Texas and equivalent to the entire city of Corpus Christi (year 2000).

Table 3. Displaced Population-Number of Households

	0.69 Meters	1.5 Meters
Chambers	626	762
Galveston	74,452	88,905
Harris	4,354	9,237
TOTAL	**79,432**	**98,904**

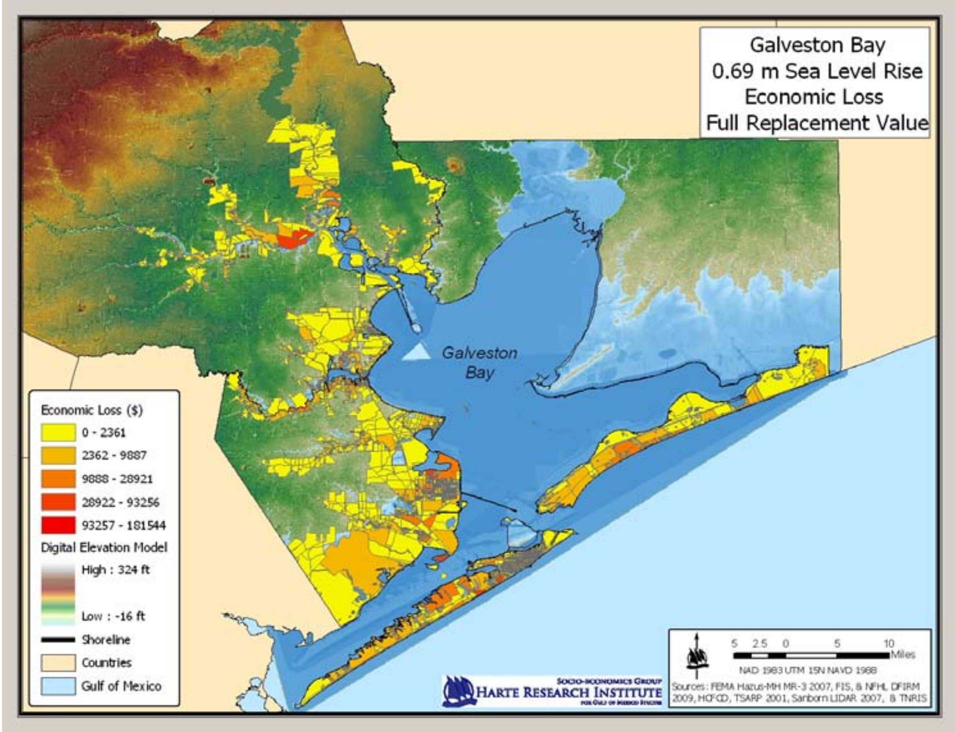
Along with household displacement comes the impact on infrastructure, in particular buildings, which includes residence, commercial, and public. HAZUS methodology for estimating direct physical damage to the general building stock is fairly simple and straightforward. For a given census block, each occupancy class (and foundation type) has an appropriate damage function assigned to it and computed water depths are used to determine the associated percent damage. The percent damage is then multiplied by full replacement value of the occupancy class in question to produce an estimate of total full dollar loss. In our

Table 4. Buildings Impacted

	0.69 Meters	1.5 Meters
Chambers	0	675
Galveston	58,251	69,478
Harris	2,238	5,020
TOTAL	**60,489**	**75,173**

study region, over 75 thousand structures are impacted to some degree (Table 4.). Once again the regional impact is dominated by what happens in Galveston County, but Harris and Chambers are not exempt from the impact. The economic loss estimates for buildings are significant. Under the 1.5m scenario, regional impact approaches $12.5 billion dollars (Table 5 and Maps 4 & 5). To put that figure in perspective, it would equal 1% of Texas Gross State Product (2007) and yet this is a very conservative number given that HAZUS assumes that there will be repairs to the partially damaged buildings after flooding waters have receded. Under the sea level rise scenarios there is no receding of the water and therefore no possibility of repairing a partially damaged building.

Map 4. Building Stock Replacement (0.69 meter)



Map 5. Building Stock Replacement Value (1.5 meter)

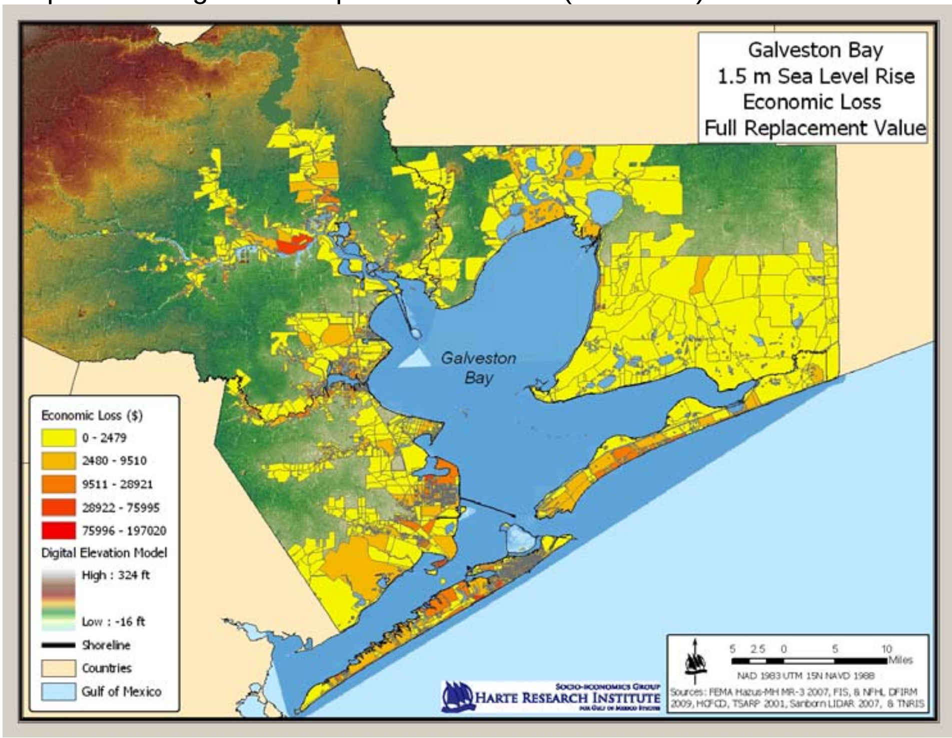


Table 5. Building Related Economic Loss (Millions $)

	0.69 Meters	**1.5 Meters**
Chambers	0	$153
Galveston	$8,743	$11,154
Harris	$584	$1,110
TOTAL	**$9,327**	**$12,417**

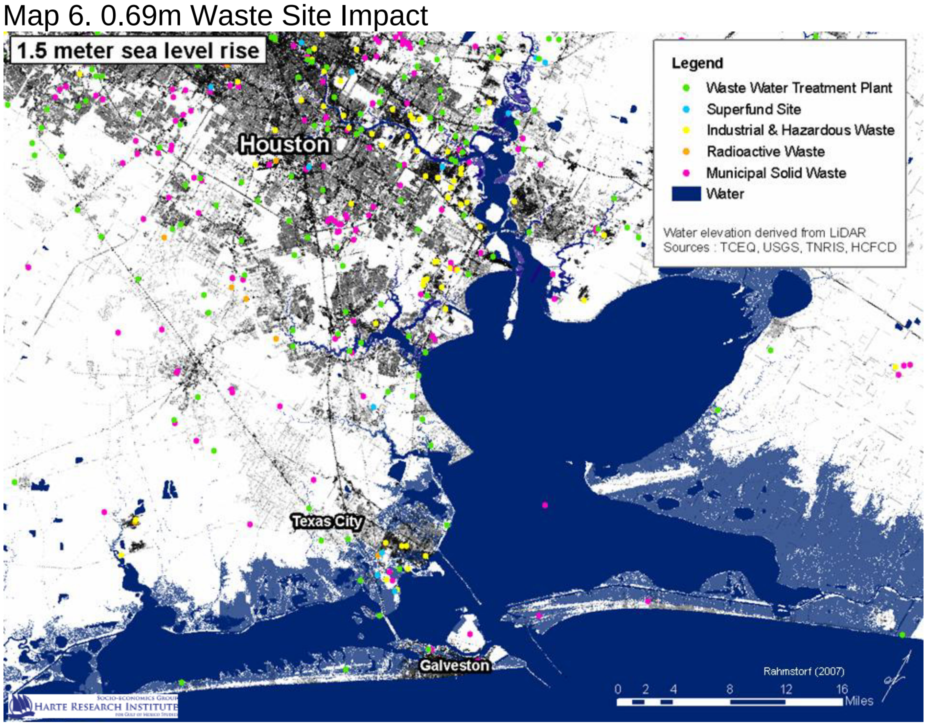
Waste Sites

Just as important as the socio-economic impact of sea level rise, is the impact on public facilities and industrial sites as it relates to waste storage or treatment. The environmental impact of an inundated waste treatment or holding facility could be significant. Table 6 and Maps 6 &7, illustrate the potential impact of sea level rise, under our two scenarios, on waste sites and treatment plants.

Table 6. Impacted or Threatened Waste Sites

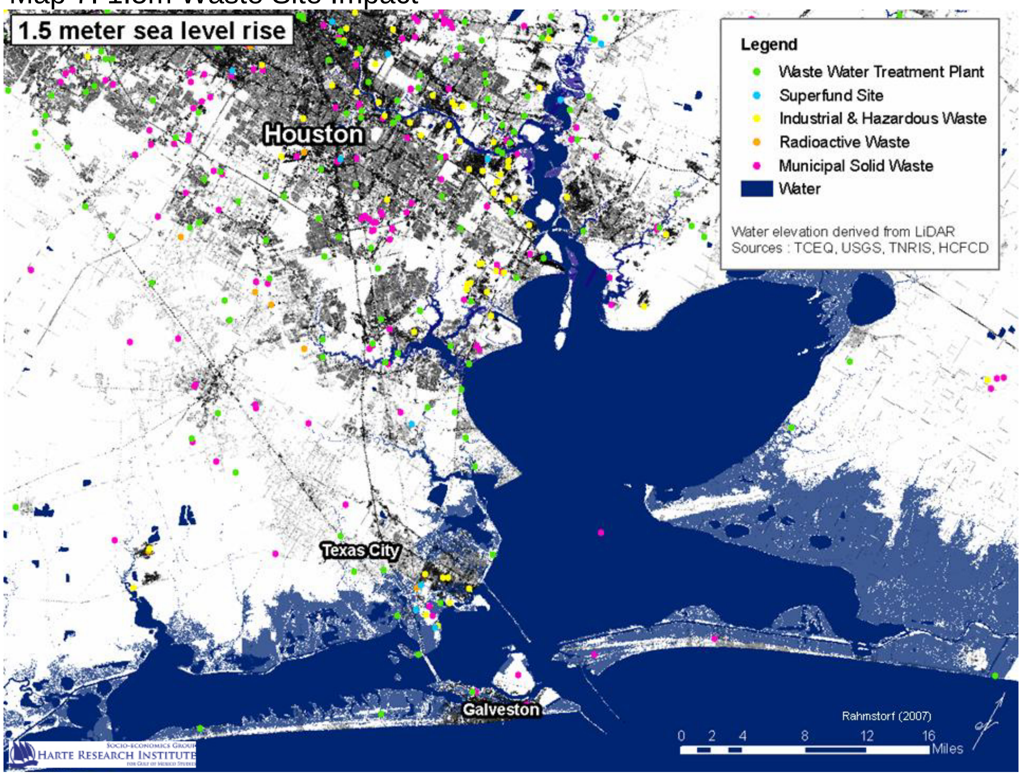
	Waste Water Treatment Plant	Superfund Sites	Industrial and Hazardous Waste Sites	Municipal Solid Waste Sites
0.69 Meter	10	3	5	5
1.5 Meter	16	3	5	9

Map 6. 0.69m Waste Site Impact



Under the 0.69 meter scenario a total of 23 sites would be threatened or impacted. Most prominently waste water treatment plants but also 3 superfund sites. Under the 1.5 meter scenario a total of 33 sites would be impacted or threatened with 16 of those being wastewater treatment plants and 9 being solid waste sites. In order to protect the public from the potential environmental and health impacts government agencies at all levels will be required to expend resources on moving, mitigating, or protecting these sites.

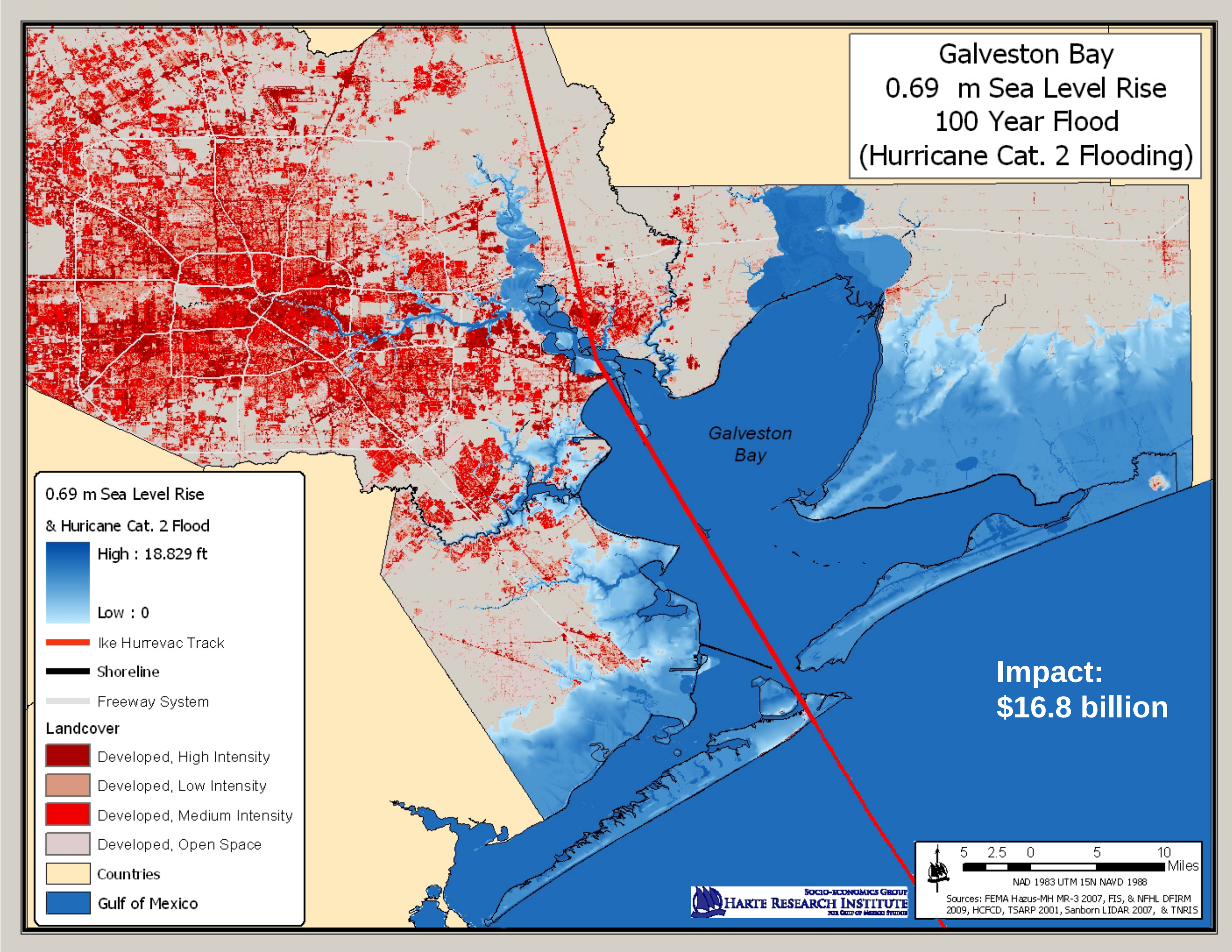
Map 7. 1.5m Waste Site Impact



Hurricane Ike

What would the damage look like if Hurricane Ike were to come ashore, but now with an additional 0.69 meter of relative sea level rise? Once again we employ HAZUS to conduct damage assessment of the storm as it occurred in 2008 and, damage assessment with sea level rise. While damage estimates have changed as time has gone by, we calculated

Map 8. Three county Hurricane Ike impact with 0.69 meter relative sea level rise.



immediate after storm damage to be $15.1 billion for the <u>three county area only</u>. This figure is consistent with the early estimates made by insurance companies and FEMA. Utilizing the same parameters but now adding in 0.69 meter sea level rise, the damage estimate increases by almost $2 billion to a total of $16.8 billion (see Map 8).

To put this in perspective, the total damage amount with sea level rise would equal 1.3% of the Gross State Product of Texas (2008). The additional damage as a result of sea level rise ($1.7 billion) would equate to the sum of median income for 35.7 thousand households in Texas. Also, it is roughly the equivalent of two months of sales tax receipts for the State of

Texas (April, 2009) and almost ten times the 2009 budget for Galveston County ($190 million). Additionally, the Governor had estimated a total of $29.4 billion in unreimbursed costs for all of the 2008 hurricanes. The increased economic impact due to sea level rise would increase that amount by almost 6%.

VII. Conclusions

In an attempt to relate the potential impacts of climate change, in particular sea level rise, we have shown that the greater Galveston Bay region will be adversely impacted by this change. Utilizing and modifying FEMA's HAZUS modeling software and developing two sea level rise scenarios of 0.69m and 1.5m, we estimate conservative impact numbers. For the more aggressive scenario there is the potential of over 98 thousand households being displaced, over 75 thousand builds being impacted at a total economic loss of almost $12.5 billion. Additionally, 33 waste sites will be impacted or threatened, carrying with it a potentially large impact on the environment.

While this study only looked at current socio-economic conditions and transported those 100 years into the future and did not account for any adaptation, mitigation or resiliency measures, the results provide a starting place in which to talk about the long-term impact of climate change in Texas and in particular sea level rise. Also of interest but not addressed here is the impact on municipal and county governments as they deal with infrastructure loss, moving populations, and potentially decreasing tax base.

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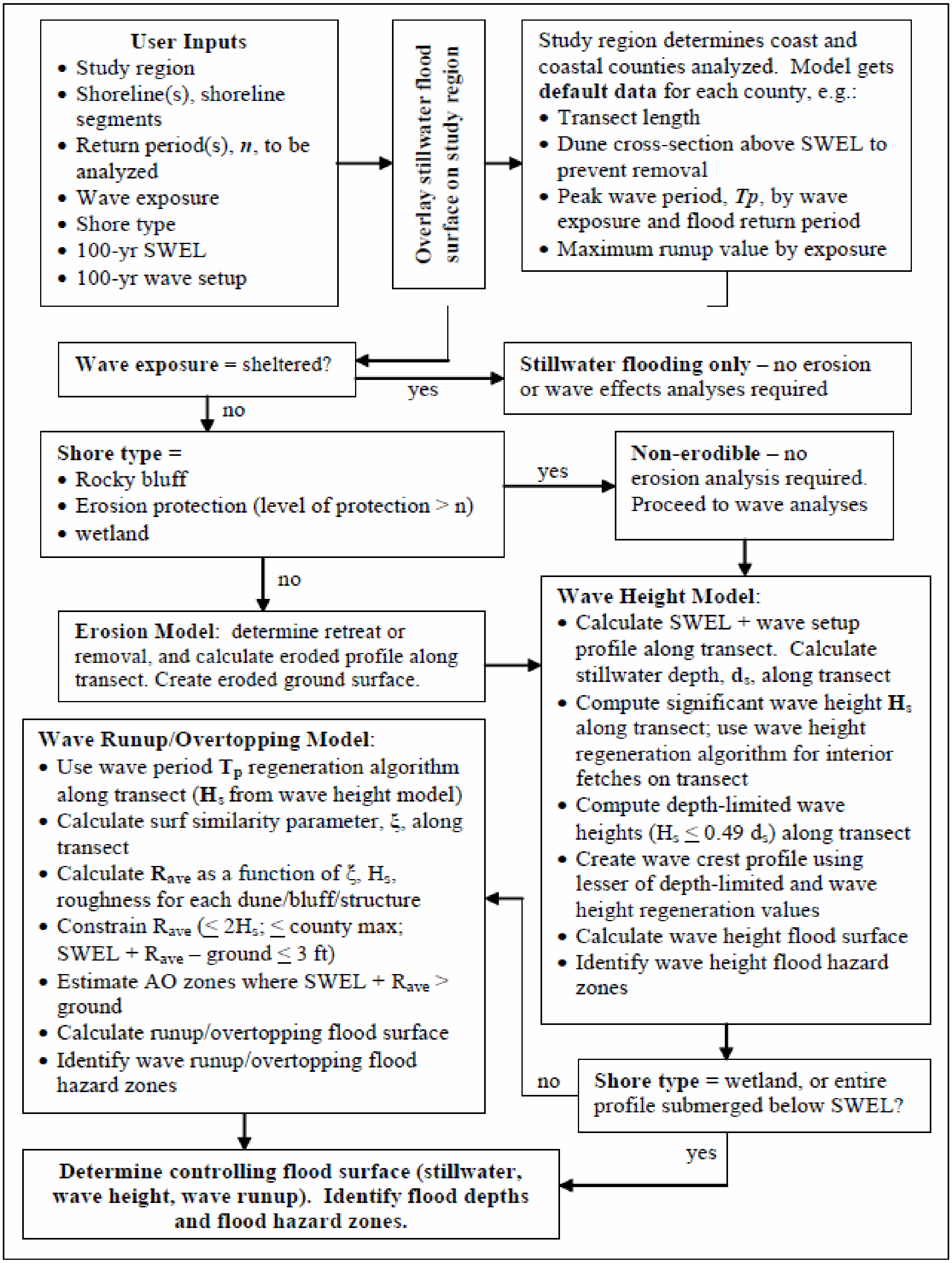
Appendix A

Modeling Process

HAZUS-MH was used as a tool to model 10 and 100 year floods and analyze the effects of sea-level rise to the Galveston Bay community. The study region of the Galveston Bay Region includes Harris, Galveston, and Chambers County was created individually by county using the aggregation level of census block and Flood hazard. During the study region creation process, HAZUS gathers datasets from the Microsoft SQL 2005 Express sever and Microsoft Data Access Components (MDAC 2.8 SP1) engine installed with HAZUS, located on the same computer. Then HAZUS creates a project folder of all the files for the study region that the HAZUS extension will need to use during flood hazard processing. This processing collects, builds, and stores many important aspects of the custom built environment for the study region including a wide range of national databases including a variety of demographic aspects of the population, square footage and valuations for types and occupancies of buildings from 2006. This process also evaluates general building stock, and locations of bridges, medical facilities, shelters, and other data about the local environment. Since these counties are coastal HAZUS also collects data from Gulf of Mexico coastal lookup tables. For each county the study region creator was left to process over night, Harris county took over two days to create (National Institute of Building Sciences, 2007).

Each of these counties were then opened in HAZUS-MH's open region tool which opens ArcGIS Editor, the HAZUS-MH extension, and Coastal Flood Hazard tool set. The layers available are the study area polygon, census blocks, and census tracks. The process is shown in the table "Overview of HAZUS Coastal Flood Hazard Modeling Process" below.

Table A1. **Overview of HAZUS Coastal Flood Hazard Modeling Process (FEMA 2008).**



Next the terrain is created using a Digital Elevation Model (DEM) which is a representation of continuous elevation values over a topographic surface referenced to a common datum. The find area for Digital Elevation Model (DEM) tool within Hazus was used to calculate the latitude and longitude of the top left and bottom right corner of the study region. To improve the terrain a 5 meter LIDAR DEM was used instead of the default National Elevation Dataset (NED) with spatial resolution ArcSecond from the United States Geological Survey (USGS). The LIDAR DEM is from the Tropical Storm Allison Recovery Project by Harris County Flood Control collected in October of 2001 and Sanborn LIDAR from 2000. HAZUS then creates the DEM grid and hill shade from the LIDAR based DEM grid(s).

In order to prepare to enter the shoreline still water elevation data the shoreline transects, effective still water elevation and shoreline characteristics were needed. FEMA's National Flood Hazard Layers (NFHL) GIS Dataset for Texas was used to determine the necessary shoreline limits needed to input the still water flood elevations. The NFHL includes the Digital Flood Insurance Rate Maps (DFIRM) which contains the flood hazard zone, base flood elevations, and depth values for some zones. Since the still water elevations were needed the most recent effective Flood Insurance Studies (FIS) were used, the maps with the still water elevation transects were geo-referenced to the DFRIM (when DFRIM was not available the road layer from Texas Natural Resources Information System (TNRIS) was used). Then the transects were digitized and the still water elevation for 10, 50, 100, and 500 year flood where collected from the FIS Summary of Stillwater Elevations and entered into the attribute table. The changes in still water elevation where identified in the attribute table and the transect layer was symbolized to show only the transects where the still water elevation changed (FEMA, 2008b). The shoreline characteristics were determined using Bureau of Economic Geology at The University of Texas at Austin's shoreline type GIS layer, this layer had a more detailed

Environmental Sensitivity Index than FEMA shoreline type so they were re-categorized to use FEMA categories (BEG, 2009; FEMA, 2008b).

In HAZUS a new scenario is created to identify the coastal shorelines, Hazus uses the TIGER shorelines that it has pre-process and smoothed identify available shorelines and allows the users to select the shoreline(s) to analyze. The shoreline is smoothed to better follow the general shoreline trend, create a better transect layout with less overlap and improve ground and flood surface interpolation between transects. The smoothing process uses a 1/4 mile buffer in and out of the TIGER shoreline. The shoreline limits are created by adding the start line, end line, and break line(s) using the NFHL transects where the still water elevation changes along the shoreline or the shoreline type changes.

Wave Exposure at Shoreline	Typical Location	Wave Height at shoreline (ft)	Typical Peak Wave Period at shoreline (sec)
Exposed, Open Coast, (maximum possible wave conditions -- fully developed waves)	shorelines directly fronting Atlantic, Gulf of Mexico, Pacific, Great Lakes (deepwater with fetches > 50 miles)	$H_s = 0.49$ times local stillwater depth	$T_p \approx$ 2-20 sec (varies by coast and flood return period)
Moderate Exposure (wave conditions somewhat reduced from maximum by fetch)	large bays and water bodies, with fetches between 10 miles and 50 miles	$H_s \leq H_s$ open coast	$T_p \approx$ 0.45 to 0.70 T_p open coast (varies by coast)
Minimal Exposure (wave conditions significantly reduced from maximum)	small bays and water bodies, with fetches between 1 mile and 10 miles	$H_s \leq H_s$ open coast	$T_p \approx$ 0.25 to 0.40 T_p open coast (varies by coast)
Sheltered (no appreciable waves capable of causing erosion or building damage -- essentially stillwater flood conditions)	water bodies, with fetches < 1 mile	$H \approx 0$	$T \approx 0$

1. *Wave heights and periods will vary by region, degree of exposure and flood return period.*

The wave exposure is used to determine whether coastal wave analyses will be run and the peak wave period at the shoreline; Galveston Island was assigned open coast (full exposure with fetches over 50 miles, and moderate on the backside, while shoreline in side the bay was assigned wave exposure of minimal (fetches one to ten mile). Fetch is the over water distance which winds blow and waves develop and grow. Then each shoreline limit is assigned characteristics which determines which coastal models are run along the transects, the average slope, roughness for wave run-up modeling, and erosion.

The FEMA categories used in this study region included sandy beach with small dunes, open wetland, and rigid shore protection structure (Galveston sea wall and protected areas in Harris County). Last the flood conditions of the shorelines were characterized, the 10, 50, 100, and 500 year flood still-water elevations were entered form the Flood Insurance Studies (FIS) (only the 100 year elevation is required), vertical datum, and wave setup if included in the FIS. HAZUS calculates the significant wave height and the peak wave period is added by Hazus using the coastal look-up table. Once the shoreline data in entered Hazus can computer the coastal flood hazards for flood return periods between 10 and 500 years.

Raster Process

Next coastal hazard analysis is run to delineate the flood plain. The user selects the return period of 10, 50, 100, 200, or 500 year flood. Then raster processing begins, this process takes a day or more for each county study region (this time can be reduced by using lower resolution DEM). Hazus automatically smooth the shoreline for transect construction, then creates transects perpendicular to the shoreline at 1,000 foot intervals, their lengths vary from 2 to 30 miles depending on upland elevations and storm surge inundation maps (2003).

Erosion assessment and wave run-up models are applied to sandy beach shoreline, the erosion assessment is only applied to rigid erosion protection structures is the level of protection of the structure is less that the return period of costal flood being analyzed. The erosion model determines dune peak (highest elevation within 500ft from shoreline) and toe (lowest elevation) for erosion analysis. It determines eroded ground elevations along transects by retreat or removal and calculates the eroded profile along each transect and creates a eroded ground surface by interpolating between transects.

Wave height model is applied to all shoreline types; dune erosion and wave effects are calculated along each transect. The wave height model calculates SWEL (stillwater elevation) and wave setup profile along the transect the calculates the stillwater depth along the transect. It also computes the significant wave height along the transect for the regeneration algorithm for interior fetches. Then it computes depth-limits wave heights, wave-crest profiles, calculates wave height flood surface and wave height flood hazard zones.

The wave run-up and overtopping model is run for shore types other than wetland and profiles not submerged below SWEL. Overtopping is when the wave runup excees the freeboard and water passes over a barrier leading to AO zones. The wave period regeneration algorithm is used to calculate surf similarity parameter along the transects which is used to calculate R_{ave}, roughness for each dune, bluff, or structure as a function of the significant wave height and surf similarity parameter. Then the roughness is constrained and A0 zones are estimated where the SWEL and R_{ave} is greater than the ground. Run-up and over topping flood surface is calculated and its hazard zones and identified.

The last step of the raster processing is to determine the controlling flood surface (stillwater, wave height, and/or wave runup) and constraints. The program tests for flooding from adjacent transects and interpolates between the transects to develop the flood surface. These steps are repeated for each flood source. After that the 100-year flood surfaces are merged and the heights flood elevation and most hazard zone for each cell is determined. Then the flood depth grid and vertical erosion grid is calculated. and flood hazard zones are identified. Next the selected return year period flood surfaces are calculates along with depth and vertical erosion grids. Then Hazus determines the flooded census blocks for the return period, and the flood elevation. The end product of raster processing is a delineated flood plain boundary and a raster grid of the flood elevation.

Loss Estimation

The analyze tool allows the user to specify the modules to analyze and runs the analysis. For this project all the available modules were chosen. Modules include estimate potential damage and loss to buildings, essential facilities, transportation lifelines, utility lifelines, vehicles, and agricultural crops. It also asses shelter requirements and debris generation.

The default inventory valuation uses HAZUS default data methodology, enhanced for flood needs; it includes allocation of census block data via statistical analysis, and broad assumptions for first floor elevation. It also includes general land use, lifelines, essential facilities, agriculture, and vehicles inventory. The damage curves are broad regional default curves based on available U.S. Army Core of Engineers (USACE) depth damage curves. Damage estimation and direct loss and impact contains area weighted damage estimates based on the depth of flooding within a given census block. The losses are developed for general building stock, agricultural products, and vehicles. The indirect loss and impact is the cost of repair or replacement of buildings, human shelter needs, temporary housing, vehicles, and crop losses. The results tab allows users to view the current scenario results as reports, tables, and maps.