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Assessing the direct economic costs of sea level rise and storm tide damage in coastal communities using tide gauge data and depth-damage functions

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Abstract

Sea levels are rising as a result of climate change and thereby amplifying the risk of tidal and storm flooding in coastal communities. Flooding is problematic, leading to many types of damages, particularly destruction or degradation of property due to contact with floodwater. The increasing vulnerability of coastal property to permanent inundation and temporary flooding raises concerns about the potential economic damages in coastal communities. Recent literature on the impacts of climate change identifies the economic risks in coastal areas as an important knowledge gap. Numerous studies have provided aggregate estimates of populations and property at risk to various aspects of climate change, yet detailed estimates of economic costs at the local level are limited. The three essays comprising this doctoral dissertation develop a quantitative approach to evaluate the direct economic costs of coastal flooding from sea level rise and storm tide, taking into account local complexities and subtleties in fine detail. Sea level rise losses, storm damages, and future storm damages with sea level rise are projected for two case study areas in Milford, Connecticut using depth-damage functions, high-resolution elevation and spatial data, and local tide gauge data.

The first essay develops a methodology to assess the direct economic impacts of land and structure loss from sea level rise inundation at the local level using depth-damage functions and tide gauge data. Depth-damage functions, traditionally used in flood damage assessment, are derived from historically observed flood damage data to assess structure and content damage. The benefits of using high-resolution topographic data in obtaining an accurate estimation of sea level rise losses are made evident by showing that using both land and structure elevation points takes advantage of detailed data and provides the most accurate estimation of losses to sea level rise. The importance of incorporating the role of tides into the economic damage function for sea level rise is demonstrated, as the baseline sea level from which to measure sea level rise damages is critical in determining accurate damage costs. The paper concludes that the existing flood damage assessment methodology can be modified to calculate the potential economic impacts of sea level rise on structures in coastal communities, but a separate loss function is necessary to estimate land losses. Using detailed elevation data and including the role of the tides are essential to capturing the incremental losses brought on by sea level rise at the local level.

The second essay builds on the methodology and findings of the first essay in utilizing depth-damage functions to estimate flood damage costs, high-resolution topographical data, and tide gauge data to support the analysis of storm flood damages. The role of tides is shown to have a large influence on the height of a storm tide water level and on potential damage costs of coastal flooding. Probability curves are fit to the observed high water data for Bridgeport, Connecticut. The difference between the probability of occurrence and the probability of a storm tide water level causing damage are explored. It is found that storm tide damages increase as water levels increase, but probability of experiencing a flood event decreases as water levels increase.

The third essay combines the ideas developed and discussed throughout the first two essays to support the analysis of storm flooding damages under future conditions of sea level rise. The sea level rise trend is added to the observed storm tide water levels, future probabilities of occurrence are projected, and the direct economic costs of future coastal flooding are estimated. Both sea level rise and storms cause direct economic costs, but permanent losses calculated for sea level rise occur only once, while temporary storm flooding damages can occur repeatedly. Both sea level rise and storm damages are highly dependent on local level details.

Keywords: sea level rise, storm surge, coastal flooding, climate change

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Part I: A methodology for assessing sea level rise inundation costs in coastal communities using local tide gauge data and depth-damage functions

Part I: A methodology for assessing sea level rise inundation costs in coastal communities using local tide gauge data and depth-damage functions

Katie Johnson

Abstract

There is an increasing concern regarding the economic costs of sea level rise in coastal communities. Knowledge about the potential impacts and costs of inaction are necessary to inform decisions on how to manage and protect coastal areas. This essay presents a methodology to assess the direct economic impacts of land and structure loss from sea level rise inundation at the local level. Flood damage assessment methodology is integrated into the framework for assessing the impact costs of climate change, with the aim of quantifying the potential future impacts of sea level rise and valuing them in monetary terms. Historically observed flood damage data is used to derive depth-damage functions to assess coastal flooding damages to structures and contents of structures. The benefits of using high-resolution topographic data in obtaining an accurate estimation of sea level rise losses are made evident; using both land and structure elevation points takes advantage of detailed data and provides the most accurate estimation of losses to sea level rise. It is demonstrated that tides, not only mean sea level, should be included in the economic damage function for sea level rise, as the baseline sea level from which to measure sea level rise damages is critical in determining accurate damage costs, especially at the local level. Future sea level rise losses are projected for two case study areas in Milford, Connecticut using depth-damage functions, high-resolution elevation and spatial data, and local tide gauge data. The paper concludes that the existing flood damage assessment methodology can be modified to calculate the potential economic impacts of sea level rise on structures in coastal communities, but a separate loss function is necessary to estimate land losses. Using detailed elevation data and including the role of the tides are essential to capturing the incremental losses brought on by sea level rise at the local level.

1. Introduction to assessing climate change impacts and flood damages

Climate change is causing sea levels to rise (IPCC 2013). The primary physical impacts on coastal systems include submergence and increased flooding of coastal land, saltwater intrusion, and erosion (Nicholls and Cazenave 2010). Sea level rise and storm flooding pose direct and near-term threats to people, property, infrastructure, and economic activity located in at risk coastal areas. For this reason, much of the recent research on the local economic impacts of climate change focuses on coastal areas (Leichenko and Thomas 2012), where 10% of the world's population lives less than 10 meters above sea level (McGranahan, Balk, and Anderson 2007). Under a business as usual scenario, in the absence of adaptation, hundreds of millions of people will be affected worldwide by coastal flooding and displaced by land loss by the end of this century (IPCC 2013). The threat of climate change has created a sense of urgency to better understand the potential costs associated with coastal hazards and has motivated a flood of research on the topic. In order to effectively and efficiently address the threats induced by rising sea levels, it is first important to understand what the potential impacts are and where they will be realized.

Vulnerability, impact, and adaptation assessments are used to understand how physical climate impacts will affect society, who or what will be affected, and what steps can be taken to adjust to changes and enhance the ability to respond and recover from climatic shocks and stresses. Vulnerability is the susceptibility to adverse effects of climate change, and impacts are the consequences on natural and human systems (IPCC 2007). Vulnerability studies consider why some regions are more likely to be harmed than others. Coastal vulnerability to sea level rise is determined by tidal range, wave height, coastal slope, shoreline erosion rates, geomorphology, and relative sea level rise (Thieler 2000). In the case of a vulnerable coast, an impact assessment can be used to identify and evaluate any positive or negative effects of sea level rise. Adaptations, adjustments in natural or human systems in response to climate change, can be made to moderate harm or exploit beneficial opportunities created by the impacts (IPCC 2007).

The physical impacts of climate change have both direct and indirect socio-economic effects, which appear to be overwhelmingly negative (Nicholls and Cazenave 2010). Understanding the climate impacts is necessary to protect vulnerable social, economic, and environmental systems. Evaluating the costs of impacts in monetary terms provides a metric to help prioritize key areas of concern, and measure and monitor the effects of climate change. Assessing the costs of impacts is useful for informing policy decisions across different geographical scales and time periods, and for different types of policy application. It serves as a way to identify risks and opportunities, and as a baseline reference from which the costs and benefits of different adaptation policies or actions can be evaluated. Cost-efficiency, cost-effectiveness, and equity (Adger et al., 2004; Bosello et al., 2009) are typically used to assess the performance of an adaptation, and require monetization of impacts for comparison with costs of adaptation options.

Potential impacts of climate change are all impacts that would occur from a projected change in climate, without adaptation . The costs of potential impacts are the costs that would be incurred in a business as usual scenario, often called the costs of inaction. The first step in climate change impact assessment is to construct a baseline scenario (Hallegatte, Henriet, and Corfee-Morlot 2011). This involves assessing the current climate and socio-economic conditions to provide information on the present assets at risk, and modeling a future socio-economic scenario for the future assets at risk (Watkiss et al. 2007). The next step is to model a future climate scenario for a future time period (Hallegatte, Henriet, and Corfee-Morlot 2011; Watkiss et al. 2007). This is often done using multiple models or an ensemble of model outputs to account for the many parameters and the confidence levels of models. The climate model is dependent on the socio-economic model in the first step, as socio-economic conditions influence emissions, atmospheric concentrations, and radiative forcing. The third step in assessing impact costs is to quantify the impacts of future socio-economic conditions and climate change (Watkiss et al. 2007). An assessment of the physical impact relationships between climate and impacts or econometric analysis can be used to quantify impacts. Finally, the impacts are valued in monetary terms, using market data or alternate approaches such as contingent valuation when no market data is available (Watkiss et al. 2007). The costs of inaction can them be used to inform decision-makers on the potential impacts associated with future climate change conditions. These costs can be used in cost-benefit analyses to represent the potential benefits, or impacts averted by adapting.

Although impact assessments conducted at the global or national scale are useful for providing insight on the general state of the world or a country, local level assessments are more useful for decision-makers or planners who can take action to reduce impacts or cope with damages. Grounding climate change at the local level provides the benefits of making the associated risks or opportunities more relevant to the public and private agents responsible for designing and implementing responses (Hunt et al, 2011). Not only are people directly affected by climate-induced impacts at the local level, but it is also appropriate for introducing institutional solutions to target a wide number of people (Jabeen, Cassidy, and Allen 2010). A detailed understanding of the potential impacts, where and when they will be realized, is also necessary for constructing any engineering based adaptations. A community based assessment is preferable to one conducted on a larger scale for evaluating adaptation policies (Sterr 2008). Decisions on how to address issues of flooding should be founded on community-based assessments and tailored to local needs, as only coastal populations can make decisions on the possible benefits of adaptation, such as flood insurance or site-specific economic investments, at the micro-scale level.

Many of the risks and hazards confronting communities as a result of climate change are modifications in scale of existing risks and hazards, or the result of a combination of climate dependent and climate independent impacts (Nicholls et al. 2008). Coastal flooding is not a new phenomenon. Before climate change and the additional influence of sea level rise, coastal storms and erosion have brought negative economic impacts to coastal areas. Flood risk management has traditionally been used to limit the damages that occur or will be exceeded within a certain probability in a certain time period. Flood damage assessments assist in decision-making in flood risk management by identifying what is at risk where. Four types of information are generally combined in flood damage assessments: inundation depth, land use, the value of elements at risk, and the susceptibility of the elements at risk to hydrologic conditions (e.g. stage–damage curves) (de Moel and Aerts 2011). Flood damage assessments identify a particular water level, define land and structure value, then find the amount of damage caused by each increment of flood.

To identify the appropriate risk reduction measures, knowledge about the potential impacts is necessary. Flood risk management utilizes damage assessments to provide critical information to decision support and policy development in the fields of natural hazard management and now in adaptation planning to climate change. Damage or impact assessments are essential to flood risk management and have also become essential to adaptation planning for sea level rise. The focus of studies assessing the economic risks of sea level rise as a specific type of coastal flooding hazard is on the potential for physical exposure to sea level rise, identification of property, assets and population at risk to damage, and assessment of adaptation options and costs; these studies draw from an engineering based approach of quantifying assets at risk and the likelihood and costs of damage from sea level rise and storm surge (Leichenko and Thomas 2012). With information on the economic costs of flood risk, cost-benefit analysis can be carried out to assist in decisions on when and where to protect the coastline not only from future storms, but also from sea level rise.

This essay presents a methodology to assess the direct economic impacts from sea level rise inundation in coastal communities. It integrates flood damage assessment methodology into the framework for assessing the costs of inaction against climate change. The aim is to quantify potential climate impacts of sea level rise and value them in monetary terms. Specifically, economic damage functions, spatial scale and topographic detail, and the effect of tides on the flood levels are examined in great detail with respect to sea level rise losses. Some of the other steps in impact assessment that have been covered extensively in the literature are not discussed here. In developing a detailed methodology to assess the costs of sea level rise, approximations that have been used in previous sea level rise damage studies are questioned. Local complexities are considered using depth-damage functions, high-resolution elevation data, and local tide gauge data in the assessment of direct coastal flooding damages due to sea level rise. This essay presents a careful discussion of potential flooding from sea level rise. Adaptation is not considered in the analysis; there is no planned retreat, no depreciation in advance, and no sea walls.

First, a review of existing literature finds that many of the economic principles present in projections of sea level rise costs have been well developed in meso- and macro-scale assessments, while an applicable approach, grounded in readily available data, that can provide local level costs for communities facing sea level rise, is lacking. Second, the case study areas from which local level data is taken to develop the methodology are presented. The third section develops the economic damage functions to estimate sea level rise losses. Historically observed flood damage data is used to derive depth-damage functions to assess coastal flooding structure and content damage. The land and structure data necessary to conduct a local level assessment is described. Fourth, findings from the application of the economic damage functions confirm that high-resolution topographic data is useful in obtaining an accurate estimation of sea level rise losses (and perhaps even more critical in developing an adaptation strategy to protect coastlines). The point at which a property or structure is damaged or lost, based on the choice of elevation point used in the assessment is discussed. The damage functions are applied to show that using both land and structure elevation points takes advantage of the detailed data and provides the most accurate estimation of losses to sea level rise. Next, it is demonstrated that tides, not only mean sea level, should be included in the economic damage function for sea level rise. Findings verify that the choice of the baseline sea level from which to measure sea level rise damages is critical in determining accurate damage costs, especially at the local level. This also includes the decision on when a property or structure actually loses its value. The damage functions are applied to demonstrate the level of accuracy gained in estimating sea level rise losses by including the role of tides. In the sixth section, future water levels are projected using eustatic sea level rise estimates based on the IPCC RCP6.0 scenario to estimate damages. Future sea level rise damages are projected for the two case study areas in Milford, Connecticut using local tide gauge data and high-resolution elevation and spatial data. The general findings of the study are discussed in section seven. Finally, the paper concludes that the existing flood damage assessment methodology can be modified to calculate the potential economic impacts of sea level rise on structures in coastal communities, but a separate loss function is necessary to estimate land losses. Using detailed elevation data and including the role of the tides captures the incremental losses brought on by sea level rise at the local level.

2. Literature review of quantitative approaches for assessing the economic damage of coastal flooding

The earliest economic studies on the costs of sea level rise developed a methodology to project rough estimates at the national level in the United States (Gary Yohe, Neumann, and Ameden 1995). Much of the literature has estimated the annual inundation cost at nation or global scales (Darwin and Tol 2001; Gary Yohe et al. 1996; G Yohe, Neumann, and Marshall 1999) for various sea level rise scenarios using average property values. Yohe et al. (Gary Yohe, Neumann, e Ameden 1995) have provided a conceptual basis for estimating economic costs of sea level rise and many subsequent studies have addressed the issues relevant to assessing sea level rise costs across a large scale. There has since been a more recent shift in the literature on the economic dimensions of climate change towards the local and regional economic impacts; there is a stream of local-level studies researching the economic assets at risk to sea level rise. As studies have begun to take a more local-level focus, they tend consider sea level rise and storm surge (Michael 2007; Lichter and Felsenstein 2012), sea level rise and adaptation (e.g. Neumann et al. 2010), or sea level rise, storm surge, and adaptation (e.g. Hallegatte et al. 2011) together. Literature on the economic impacts and costs of extreme climate events, economic assets at risk to sea level rise, and determinants of economic vulnerability and resilience are overlapping and interconnected (Leichenko and Thomas 2012). Local areas vulnerable to sea level rise are often also vulnerable to storm surge flooding, and consider the costs of inaction and costs of adaptation to both in one comprehensive study. Because this is a newer area of research, the justifications for, resources available to, and expectations of these studies vary depending on each particular case, there has been less progress in developing a transferable methodology.

Yohe (1989) first considered the costs of allowing sea levels to rise in a report for the US EPA. In the report he develops a methodology to catalogue and measure the economic wealth that might be threatened if coasts are not protected from sea level rise. He discusses the costs of sea level rise including the value of lost structures, lost property, and lost social services from the existing coastline. Yohe uses an accounting procedure that attributes all property and structure loss associated with maintaining a coastline to the value of preserving that coastline: the social value of the beach must be at least as high as the beachfront structures that would be abandoned if the beach were to erode. He also assumes that a beachfront structure will be sacrificed to preserve the social value of the coastline whenever a sea level rise scenario brings the water within a certain distance of its foundation.

Regarding water level, Yohe (1989) assumes that the economic value of a structure will be abandoned to sea level rise when the land upon which it sits is inundated during mean spring high tide. Yohe is unable to apply this idea as the inundation scenarios used in his study are not detailed enough, but in a more recent state-wide assessment Neumann et al. (2010) do use mean spring tide to find sea level rise losses. Most other studies use mean sea level or do not explicitly state which water baseline level is used to assess sea level rise inundation.

To assess losses over a larger scale, Yohe (1989) uses a grid layout. He bases sea level rise estimates on inundation scenarios for 500-square meter cells, finding the percentage of developed cells flooded under different sea level rise scenarios. The percentage of a cell that is flooded is used to define the percentage of structures located within a call that will be abandoned. The value of threatened structures within a cell is estimated using the percentages from the inundation scenarios, and summing across cells provides the estimated value of potential structure loss.

2.1. Structure value

Yohe et al. (G. Yohe 1989; Gary Yohe, Neumann, and Ameden 1995; Gary Yohe et al. 1996; G Yohe, Neumann, and Marshall 1999) use aggregate property data, estimating the land and structure values within 500-square meter parcels. Yohe (1989) describes the use of grids, with each cell containing a sample of structure value in terms of current market value. A sampling procedure is used to estimate property and structure costs, looking at strips of land running from the shore inland. Valuations along strips support aggregate estimates. Structure value is estimated from tax records or housing and business census data. Since they do not necessarily reflect true market value, they are translated to reflect market value by noting the percentage of market value reported by the assessor's office and some degree of inflation since the previous assessment.

Neumann et al. (2010) also use a grid system to estimate sea level rise impacts. They developed a GIS-based modeling approach with a 150-meter grid cell network to estimate human response to the threat of sea level rise and the economic impacts of sea level rise on coastal property. The optimal response approach is based on a simplified cost-benefit analysis of protection versus retreat. The cost of sea level rise is the capital cost of construction plus ongoing maintenance when the cost of protection is less than the benefit of avoided property value loss. When the cost is more than the benefit, the impact of sea level rise is the lost value of land and structures. Neumann et al. use assessed land and property values.

Parsons and Powell (2001) adapted Yohe et al's aggregate method to use micro-level data at the level of individual properties in an assessment of inundation from beach erosion. Michael (2007) followed Parsons and Powell's adaptation of Yohe et al's methodology to estimate the costs of property inundation and increased property damage from coastal storm flooding. Parsons and Powell (2001), Michael, (2007), and Bin et al. (2011) use hedonic pricing models to estimate the value of properties at risk to inundation. The hedonic model estimates the implicit values that people place on certain characteristics by determining the extent to which they are capitalized into property values. Hedonic regression results are used to estimate the loss from the inundation of each property at each elevation level.

2.2. Land value

Although land faces the same valuation concerns as structures, land and structures should be considered separately because land can't be depreciated the way a structure can (G. Yohe 1989; Gary Yohe, Neumann, and Ameden 1995; Gary Yohe et al. 1996; G Yohe, Neumann, and Marshall 1999). Yohe et al. claim that the value of land lost to sea level rise should use the value of interior land rather than shoreline land, as coastal land is never actually lost with sea level rise but rather interior land is lost as the coast retreats inland. Coastal amenities of property are transferred to more interior parcels, and therefore the value of land lost to inundation should be measured using the value of inland property. Following this argument first presented by Yohe (1989), other studies (G. Yohe 1989; Gary Yohe, Neumann, and Ameden 1995; Gary Yohe et al. 1996; G. W. Yohe and Schlesinger 1998; G Yohe, Neumann, and Marshall 1999; Parsons and Powell 2001; Michael 2007) have also assumed that the value of inundated coastal land actually has the value of interior land.

2.3. Perfect foresight and no foresight scenarios

Yohe et al. (Gary Yohe, Neumann, and Ameden 1995; Gary Yohe et al. 1996; G Yohe, Neumann, and Marshall 1999) note that if the rate of greenhouse gas induced sea level rise were known with certainty and there were enough time to respond, then it is possible that the economic costs of sea level rise would be confined to the adjustment costs and the value of the inundated land, as structures could be moved and coastal services can be provided by the new coastline. With limited time and imperfect and uncertain foresight the problem is more complicated.

In their studies, Yohe et al. assume efficient adaptation of the property market to a foreseeable rise in sea level. They consider the world as it will likely be and not as it is now. Perfect and no foresight scenarios are used to determine which properties will be lost to inundation and the value of any structures remaining on those properties. In the case of perfect foresight, the cost of losing land and structures to sea level rise is limited to the value of the inundated land. The economic value of structures would depreciate over time as the threat of impending inundation and abandonment became known. True economic depreciation that is modeled to start at some fixed point prior to inundation and to finish just when inundation would occur is the maximally efficient market response to known risk of future sea level rise. With perfect foresight, defensive actions can be employed when the costs of protection are less than the costs of abandonment, at the time that minimizes costs. This is based on the idea that property owners will not invest in structures that will soon be inundated. If physical upkeep is ignored in the time leading up to inundation, then a smaller loss will occur when the structure is inundated. In the case of no foresight, no defensive structures are constructed and the value of inundated structures is estimated as if there were no sea level rise. Michael (2007) also applies both with and without foresight scenarios in his study to find upper and lower bounds of inundation costs in his assessment of the costs of property inundation and increased property damage from coastal storm flooding, but notes that neither of the scenarios are likely in reality.

2.4. Appreciation

Yohe et al. (1995) note that the value of unprotected property lost at a future time should incorporate property value appreciation, exactly what land would be lost (coastal vs. interior), and depreciation in anticipation of abandonment. In assessing sea level rise and storm surge impacts, Hallegatte et al. (Hallegatte et al. 2011) assume that the case study area would remain generally unchanged in the future and that existing properties would be replaced through normal processes and increase in value in response to economic growth. To estimate the loss if the property is inundated at a future date, Michael (2007) first determined the date of inundation, second adjusted the value for the expected appreciation in real property values, third depreciated the structure for age, and forth applied the discount rate to calculate the present value of a future loss.

To estimate real property appreciation, Yohe at al. (Gary Yohe, Neumann, and Ameden 1995; Gary Yohe et al. 1996) and Michael (Michael 2007) use Abraham and Hendershott's (1993) model of real pricing house appreciation as a function of population and income growth. Abraham and Hendershott's model suggests that future property values are well characterized as a function of national population and income. Yohe et al. confirm that Abraham and Hendershott's regression for housing prices can also be applied for land value, assuming that real construction costs and after-tax interest rates will be relatively stable over the very long term. Neumann et al. (2010) reviewed recent literature in an effort to develop a more regional approach to forecasting future property values, and found that property values may be based more on local real estate supply and demand conditions than on economic or demographic conditions.

Neumann et al. (2010) also note that the effect of increasing coastal risk may affect future property values, and that as risks increase, proximity to the shore might decrease property value over time.

2.5. Discounting

The interest rate is a key factor in assessing future costs and benefits, as the present value of assets can change greatly depending on the value of the interest rate. The limitations of cost assessment for climate change have been addressed by inter-temporally weighting future events using the interest rate. Stern (2007) has advocated low social rates of discount, and has argued that the risks of inaction are quite high when compared to the costs of action (Stern 2009). Nordhaus (2007), on the other hand, has supported more standard opportunity cost rates. Lower rates tend to call for action now, whereas higher interest rates have the effect of postponing action on climate change, as future benefits are more heavily discounted. The use of higher interest rates carries the implicit assumption that actions are reversible, which they are not likely to be in transformative circumstances such as sea level rise. The issue of discounting is based on both economic and ethical assumptions about how the future is valued, and in turn provides a great deal of uncertainty to decisions on when and how much to adapt to climate change.

Yohe (1989) proposes the use of current value estimates. Using current value sidesteps the issues of social discounting and the potential that threatened structures will be allowed to deteriorate as it is realized that they may be inundated in the near future. Yohe notes that discounting may be over a short enough timeframe that it is not so significant (i.e. decades rather than half century). Also, growth and inflation trends proceed over the long term at a rate that roughly offsets the effect of discounting on the real value of a threatened structure, so current value and present value match over the long term. Yohe finds that using current value as a measure of future costs misses economic growth and inflation, which for structures tends to increase faster than the consumer price index, and therefore estimates might be conservative.

Discount rates used in other sea level rise inundation assessments range from 2 and 4% (Michael 2007) to 3 and 5% (Gary Yohe, Neumann, and Ameden 1995).

2.6. New contributions of this study

Previous studies confirm that there is a need to assess the economic impacts and climate change response policy at the local scale (Hallegatte et al. 2010), and specifically to refine the method of estimating the increasing costs of coastal flooding (Michael 2007). Bespoke tools have been developed to deal with particular micro situations, and aggregate, analytic frameworks have been created to deal with macro scale issues, but there is a vacuum of applicable approaches grounded in readily available platforms that can provide local level information for communities coping with climate change (Lichter and Felsenstein 2012). This study attempts to fill that gap.

Literature on the economic costs of sea level rise thoroughly covers inland land value, structure depreciation, appreciation, and discounting. While the work of Yohe et al. and others has assessed aggregate social damages, the methodology developed in this essay relates to actual damages to individual coastal properties. As there is an increasing interest in sea level losses and storm surge damages at the local level, primarily to assess the cost and benefits of impacts and adaptations, other issues require further consideration. There is room for improvement in the methodological details and choices when addressing micro-scale cases, and local level studies should take advantage of the most detailed data available. Insufficient consideration has been given to the choice of water level used in the assessments and the question of when a property is actually lost to sea level rise.

The literature has largely relied on low-resolution models of coastlines in order to assess damages to large stretches of coastline. However, when actually defending the coast, such low-resolution models give highly inaccurate estimates of exactly what should be defended, how it should be defended, and how much it would cost. The methodology developed in this study is aimed at the micro level to get at the details of impacts and adaptation needs. This reveals exactly what properties are affected by sea level rise and storms of different heights, the depths of flooding, and the damage to individual properties and buildings. Questions of how to define the elevation of each property and each building are considered, and the importance of using this detailed data is highlighted.

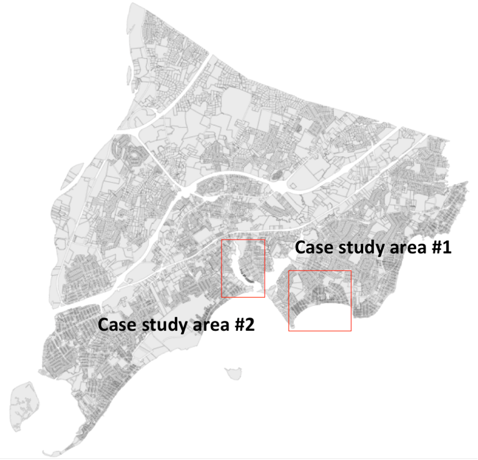
This study provides estimates of direct, private losses associated with sea level rise to illustrate advances made in several aspects of the sea level rise loss and coastal flooding damage assessment methodology. A spatially detailed model of the coastline is developed in order to advance the economics of coastal resilience, which is critical to designing actual coastal defenses. These insights are applied to calculate damages as more realism is brought into the model. Application in a case study demonstrates that the insights are both useful and feasible. Three main contributions are made to the field of sea level rise impact cost assessment: (1) an economic contribution on the use of coastal flooding depth-damage functions for assessing sea level rise losses, (2) a note on the use of high-resolution spatial data in local level assessments, and (3) a scientific contribution on the role of high tides in sea level rise losses.

This essay does not go into great detail on the issues that have been sufficiently covered in the previous studies discussed above. It takes a different approach than those that have assumed that coastal land is not actually lost with sea level rise but rather interior land. The evolving valuation of land is complex and multidimensional, and while there are multiple methods to address this issue, none are perfect. The methodology employed in this study uses parcel specific elevation and value data; the value of a parcel of land always remains for that parcel. Waterfront land may not have the same appeal once sea level rise is realized. It is possible that as the risks of inundation and coastal flooding increase, proximity to the shoreline may actually reduce property value over time. The appeal of the existing waterfront may not be the same if inundated land or structures are abandoned between new waterfront properties and the water. Furthermore, neither sampling nor hedonic pricing is used to derive land and structure values. Hedonic pricing is useful when considering only one classification of property, as the variables that contribute to the value of different classifications of lands vary for residential, commercial, industrial and public properties (i.e. the number of bedrooms is not a useful indicator in determining the value of commercial property). Assessed land and structure values are used and discussed in terms of their 2011 USD amount.

3. Context

Local-level data is derived from two micro-scale case study areas to develop a detailed methodology to assess sea level rise losses in coastal communities. Two geographically diverse neighborhoods are considered: one residential beachfront and one mixed residential-commercial area surrounding a harbor. The two sites are located in the City of Milford, Connecticut, on the north shore of Long Island Sound, an estuary of the Atlantic Ocean. Long Island sound is a 1,320 square mile body of water with over 600 miles of coastline[1], formed by the Laurentide Ice Sheet during the Wisconsin and Holocene glacial and interglacial stages[2] more than 15,000 years ago[3]. It is now bounded by Connecticut to the north, New York to the south and west, and opens up to Block Island Sound to the east. Long Island Sound was designated an Estuary of National Significance in 1987. The coastal communities of Long Island Sound are home to more than four million people, and the uses of Long Island Sound, primarily boating, swimming, commercial fishing and sports fishing, generate about $8.5 billion annually (2009USD) for the regional economy[4]. Due to the coastal location and vicinity to New York City, property around Long Island Sound is both valuable and vulnerable to coastal flooding.

Figure 1 GIS map of Milford, Connecticut. The two case study areas are Bayview Beach (1) and Milford Harbor (2)



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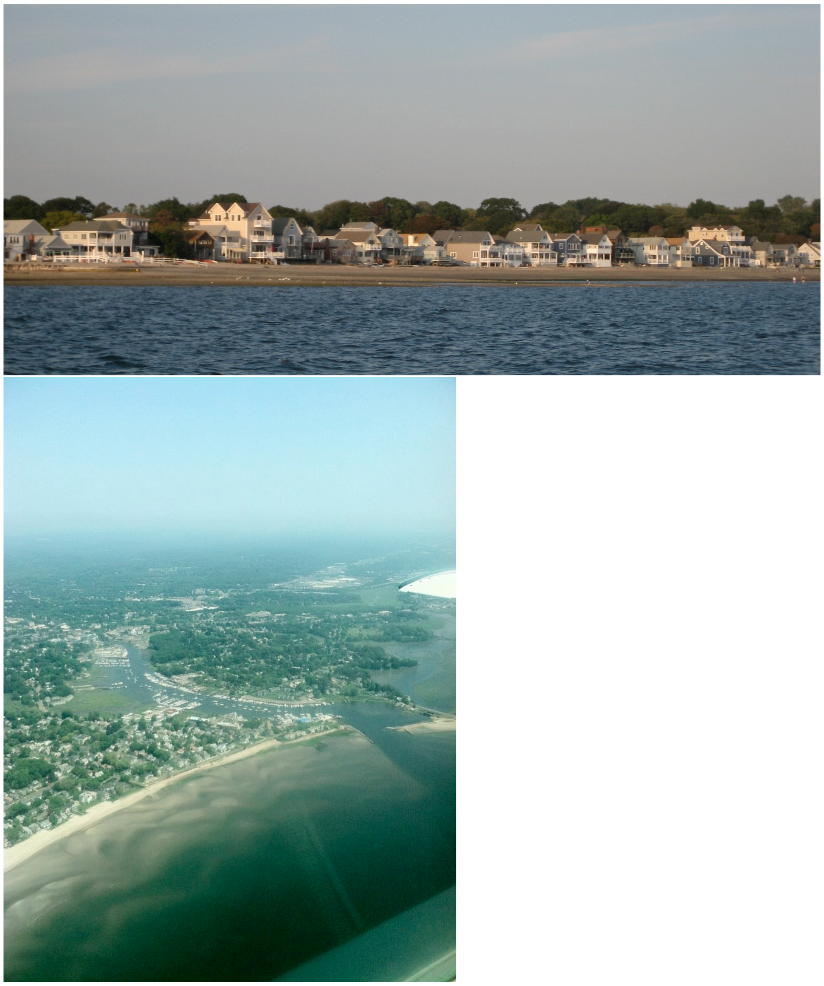
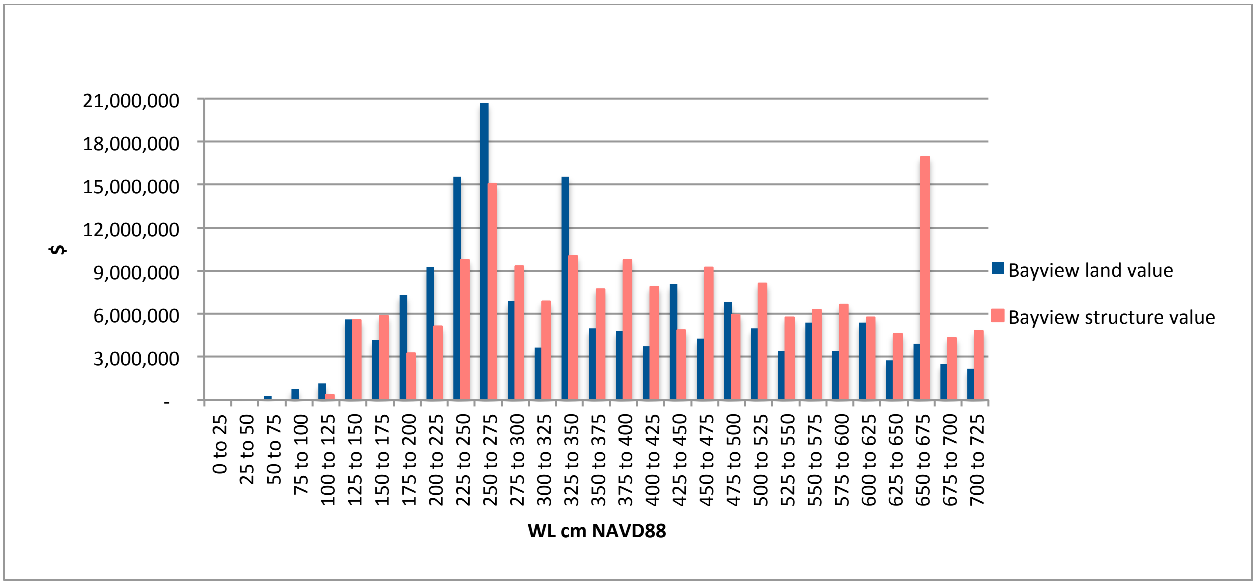
[1] http://longislandsoundstudy.net/about-the-sound/by-the-numbers/
[2] ftp://ftp.nodc.noaa.gov/nodc/archive/arc0001/9900223/1.1/data/0-data/chapt2/2norwalk/chp2num2.htm
[3] http://pubs.usgs.gov/of/2011/1149/html/setting.html
[4] http://longislandsoundstudy.net/about-the-sound/by-the-numbers/

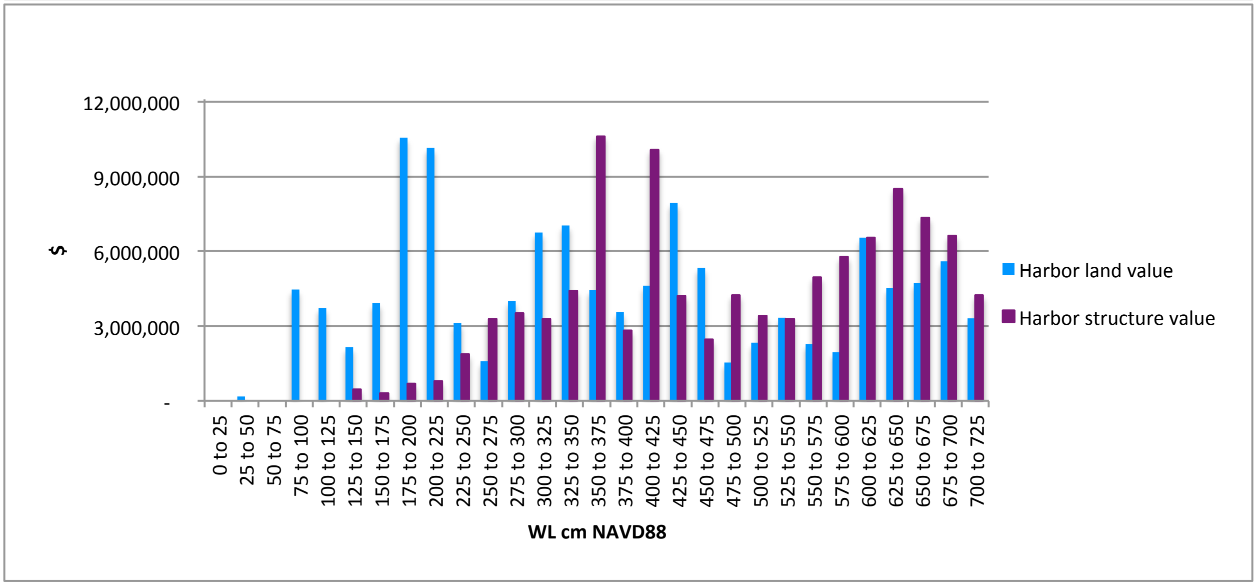
Figure 2 Photos of the case study areas. The Bayview (top) case study area is primarily residential, while Harbor (bottom) has mixed land uses.



Milford was once a seasonal beachside destination that has developed over time into a lively suburban area with approximately 51,000 residents. Milford’s 27.2-kilometer coastline is the longest in the state of Connecticut, with a mixture of residential, public, commercial, and industrialized land uses. The two case study areas include only coastal properties situated between mean sea level and 7.28 meters above mean sea level, due to the limited availability of high resolution elevation data. The first case study, Bayview Beach, includes the area between Welches Point and Point Beach. It is a predominantly residential area situated behind an approximately 1-mile long strip of sandy beach. A small tributary divides the beachfront area, connecting a salt mash to the sea. Many of the properties that surround the marsh currently experience flooding during storm events. There are 993 properties included in the Bayview Beach case study area. The total value of land is approximately $150 million and the total value of structures is about $193 million. The second case study, Milford Harbor, consists of the residential, marine, commercial, and public properties surrounding the approximately 1-mile long harbor. The Harbor case study area includes 379 properties. The total value of land is approximately $210 million and the total value of structures is around $242 million. In both case study areas, the value of structures is higher than the value of the land.

Figure 3 Property value at different elevations for Bayview (top) and Harbor (bottom). The case study areas are situated between 0 and 7.21 meters NAVD88. Land and structure values are displayed at 25-centimeter increments to show where the value at risk to sea level rise is located.





Land accounts for 55% of the total property value in the case study area, while structures represent 45% of the total value. In Harbor, the balance is much different, with land representing 95% of the total value, and structures only representing 5% of the value. In Bayview, there are many expensive beachfront properties, just above the level of current high tides, then total property values decrease slightly as elevation increases and properties are located further inland. In Harbor, the trend in total value is less clear. The land close to sea level is very valuable, whereas total structure value increases at higher elevations, but both values fluctuate at different elevations. In Bayview and Harbor, there are valuable parcels of land and structures at risk to current and future coastal flooding. This study aims to identify the potential direct economic losses to sea level rise in these two areas.

4. Coastal flooding damage assessment for sea level rise losses

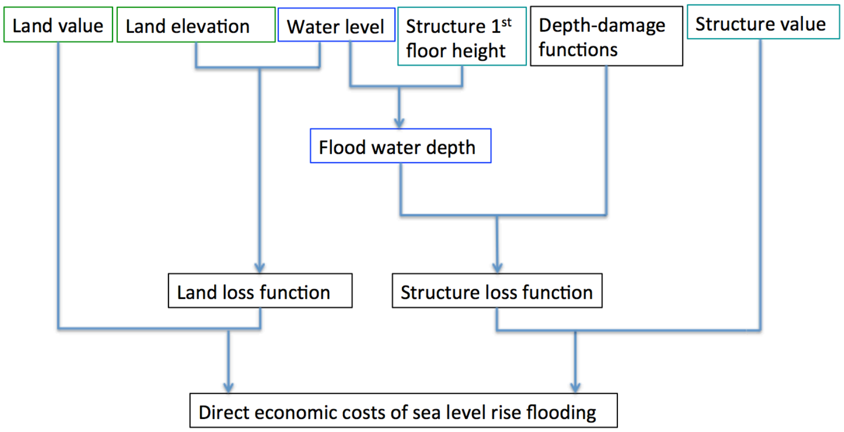
Flooding causes direct and indirect damages. Direct damages occur due to the physical contact of property, people, or any other objects with flood water, while indirect damages are induced by the direct damages but occur outside, temporally or spatially, of the flood event. Both direct and indirect damages can be further classified as tangible or intangible based on whether or not they can be assessed in monetary terms. After a certain threshold of damages, or when occasional flooding becomes permanent inundation, damages can become losses. This section focuses specifically on estimating direct economic damages to land and structures from physical contact with floodwater, and the potential for these damages to become sea level rise losses.

Assessment of direct economic damages consists primarily of three steps: classification of elements at risk, quantification of exposed asset values, and describing susceptibility (Merz et al. 2010). Depending on the spatial extent and level of detail in the inundation assessment, many elements must be considered. These elements are grouped into classes and damage assessment is performed for each class, where the elements in a class are treated equally. Classification is often based on economic sectors (i.e. residential, commercial, industrial, agricultural, public, infrastructure, and service), which can further divided into sub-classes. Susceptibility to experiencing flood damages changes based on the classes and sub-classes of elements.

Assessment of flood damages is often used to weigh the costs of flooding against the benefits of reducing damages. Furthermore, in a context where flooding is one of several natural hazards, flood risk damage assessment allows for a quantitative comparison of risks, and decisions on the allocation of resources. Damage assessments are also pertinent to the insurance and reinsurance sector to calculate premiums and guarantee solvency. In the case of a flood event, knowledge of damage estimates helps managers to budget and coordinate decisions on damage compensation. Damage assessments assist in flood risk mapping, which goes beyond mapping the flood hazard, and includes the potentially adverse effects on asset values, people, and the environment. With information on what is vulnerable where, the potential costs of flood risk and potential benefits of flood management can be quantified and compared. In this way damage assessments are essential for ensuring cost-effective risk management in making optimal decisions in flood mitigation measures. All of the advantages of flood risk management are also pertinent in the case of sea level rise due to climate change.

In this section, the components necessary to construct an economic model to assess coastal flooding damages are presented, and the application to estimate sea level rise losses is explained. There are separate damage functions for estimating structure and content damage and land loss. Damages are found for a business as usual scenario, in the absence of adaptation. These are the costs of inaction against climate change induced sea level rise. First, the use of depth-damage functions is discussed, and observed flood damage data from the United States Army Corps of Engineers (USACE) is used to derive damage functions for residential and non-residential structures and contents. These serve as the economic damage functions for estimating flood damages to structures and contents, following the traditional methodology for assessing coastal flooding damages. Land use and structure characteristics are then used for the classification of elements to determine which damage function should be applied for structures and contents in each case. The use of first floor height rather than ground elevation is explained. Second, the land loss function, unique to sea level rise, is defined. Third, valuation of land and structures is discussed in detail. Lastly, an explanation of how these factors come together to form the basis of the coastal flooding damage assessment, and how they can be used to assess sea level rise losses is presented.

Figure 4 Methodology to assess sea level rise losses.



4.1. Depth-damage functions for structure and content damages

Damage functions are used to relate the damage of an element at risk to the characteristics of inundation. Several factors may affect the amount of damages caused by a flood, including water depth, time of year, velocity of floodwater, duration of flooding, sediment load, warning time, and relief and response. While each of these factors may be relevant to the flood damages incurred, most flood damage models use the element at risk and the inundation depth to find damages, as there is no comprehensive approach to include these additional factors in damage modeling (Merz et al. 2010). Depth-damage curves were first proposed by White (1945; 1964) in the United States, and the first major application of depth-damage curves for buildings was done by the Federal Insurance Agency for the National Flood Insurance Act in the USA in 1968 (Smith 1994). Depth-damage functions are still used as the standard approach to assessing flood damage (Smith 1994).

Damage models can be created from empirical evidence of damage data collected after flood events, or take a more synthetic approach and make assumptions about what damages would occur if a certain flood level were reached. There are obstacles in analyzing observed damage data and deriving damage estimates. Not only is there limited availability of flood damage data, due to the challenges in collecting data, but it is also difficult to construct depth-damage curves as decisions have to be made on what components to include, what values to allocate to those items, and how to classify structures. Direct flood damages are markedly different for individual properties, even when in the same class, making scatter and error of damages an added obstacle; there are also problems of interpolation between data points (Smith 1994). Additionally, as there are not a large number of observed high level floods, often times there is a need to extrapolate data to obtain damage estimates for higher level floods (Smith 1994). However, despite the challenges in creating damage models, they provide useful insight into the potential damages associated with future flooding.

To calculate the damages from coastal flooding due to sea level rise, this study utilizes depth-damage functions created from flood damage data collected by the USACE. The USACE is a US Federal Agency under the Department of Defense that works to deliver vital public and military services to strengthen national security, energize the economy, and reduce risks from disasters. USACE has complied a database of coastal flooding damage data that was collected over several years following flood events, to devise hurricane and storm damage reduction infrastructure. Residential damage data is available in the form of damages incurred in one-foot increments. The non-residential data has been internally analyzed by the USACE and damage models have been derived for non-residential flood damages in the form of depth-damage functions (Kiefer and Willett 1996).

A depth-damage function is a mathematical relationship between the depth of floodwater above or below the first floor of a building and the amount of damage that can be attributed to that water. The basic components covered by depth-damage curves are damage to buildings and contents (Smith 1994). Depth-damage relationships are computed separately for structure and contents. A structure is defined as a permanent building and everything that is permanently attached. Household contents are defined as everything within the building, not permanently installed, such as rugs, portable dishwashers, and freestanding bookshelves. A structure depth-damage equation is used to estimate the structure damage, as a percentage of structure value, based on the depth of floodwater in relation to the first floor. Likewise, content depth-damage functions are used to estimate the percentage of the building contents damaged relative to either the structure or content value, in relation to the depth of floodwater with respect to the first floor.

USACE data on coastal flooding are particularly useful for estimating residential content damages, as the damage functions for residential structures and contents are based off of structure value, thereby eliminating the need to estimate content value. Building and content values should be evaluated as an estimate of depreciated replacement value of the structure (Merz et al. 2010). Appraisal of content values generally requires far more detailed work than structural appraisal because there is no easy way to approximate depreciated value for contents in the same way market value approaches depreciated replacement value for structures.

Both structure and content depth-damage functions are dependent on land use, flood depth, number of stories in the structure, and the presence of a basement. Damage equations derived from the USACE damage data are available for non-residential structures and contents (Kiefer and Willett 1996). Reports by Dawson (2003) and Johnson (2000) on the USACE data for residential structures and contents provide the percentage of damage associated with flood depth at one-foot increments.

4.1.1. Non-residential

Flood damage for commercial and industrial sectors is not well analyzed despite the fact that those losses often far exceed residential losses (Smith 1994). Structure and content depth-damage ratios for non-residential structures are available in the 1996 U.S. Army Corps of Engineers report, Analysis of nonresidential content value and depth-damage data for flood damage reduction studies (Kiefer and Willett 1996). The report finds content-to-structure ratios and depth-damage functions utilizing a database developed from a 1992 survey of businesses in the Wyoming Valley of Northeastern Pennsylvania. The survey was administered to over 600 businesses after record flooding in 1972, when Tropical Storm Agnes produced an extended period of rain sufficient to exceed the design capacities of the local levees. Information was collected regarding building characteristics, value of building contents, building structure value, previous flood damages, and expected damages for hypothetical flood levels.

Structure and content depth-damage functions can be used in conjunction with depreciated building replacement values and content valuation methods to generate total damages resulting from each foot of flooding. In the case of non-residential structures, content damages are calculated as a percentage of content value, based on a content-to-structure value ratio. Content damages are not calculated as a percentage of structure value.

Based on the USACE damage data, structure depth-damage functions show significant damages occurring at low flood levels, with a decreasing rate of damages over each additional foot of floodwater. Specifically, buildings with basements tend to have higher damages for lower flood levels, with differences diminishing as flood levels increase. The number of stories in a building was not found to have an effect on the structure depth-damage relationships. Content depth-damage relationships, however, were found to be dependent on the number of stories in the building, and separate equations are therefore required for single and multi-story buildings.

% Structure damage = $0.72 * (1-e^{-0.1332*depth} * e^{-0.0983*basement})$

% Content damage single story = $0.7102 * (1-e^{-0.3736*depth} * e^{-0.0595*basement})$

% Content damage multiple story = $0.7717 * (1-e^{-0.3223*depth} * e^{-0.1910*basement})$

Where:

e = Euler's number (2.718)

depth = Depth of floodwater relative to the first floor (in feet). This is converted into centimeters in the economic damage model.

basement = Binary variable (0 = no basement present, 1 = basement present)

Based on the survey, damages for non-residential structure and content damages occur when the flood water level reached higher than the first floor elevation. Only structures with first floor height above 0 meters experience damage costs following these equations.

4.1.1.1. Content-to-structure value ratio

Non-residential content depth-damage functions calculate content damages based on content value. Content value is derived through a content-to-structure value ratio. Within the USACE study, content-to-structure value ratios were found in the dataset using the Standard Industrial Classification code, however, due to the small sample size, it is suggested that they are not used to make statistical inferences. Values range significantly depending on the type of commercial business, from 0.5 for eating and drinking places to 2.03 for furniture and home furnishing stores. In both the Federal Emergency Management Agency's HAZUS flood model (Department of Homeland Security and FEMA 2013) and an in economic analysis of flood damage reduction costs and benefits done by the California Natural Resources Agency (The Natural Resources Agency 2012) content value is calculated as a percentage of structure value using content-to-structure value ratios, specifically 50% for residential, 100% for commercial, 150% for industrial, and 100% for public land use. These content-to-structure value ratios are employed herein.

4.1.2. Residential

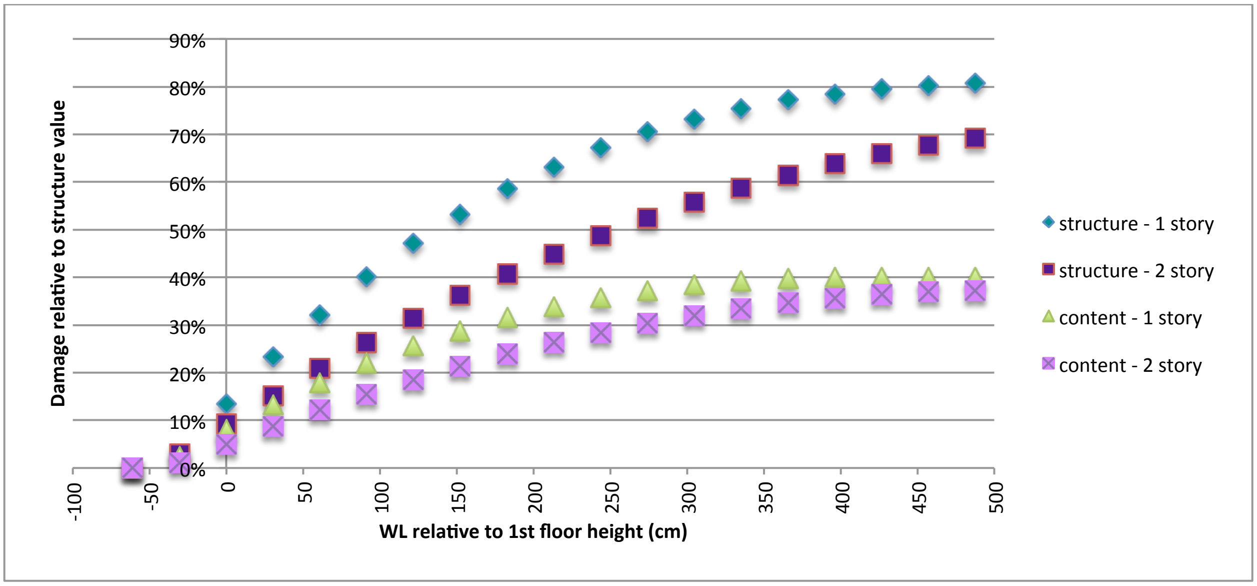
Residential depth-damage data is available in the U.S. Army Corps of Engineers economic guidance memorandum (see Johnson 2000; Dawson 2003). National generic damage functions from the Institute of Water Resources Damage Data Collection Program have been issued for structures without basements (Johnson 2000) and with basements (Dawson 2003). While several independent variables, such as flood duration and flood warning lead-time, were examined in building the models to represent the data, the models that were most efficient in explaining the percent damage to structure and contents were quadratic and cubic forms with depth as the only independent variable. However, only tables with damages at 1-foot increments are available in the memorandum, not the equations. In order to interpolate damages for water level heights falling between the 1-foot increments, damage data are fit with nonlinear regression equations. Both structure and content damages are calculated as a percentage of structure value, so no content-to structure value ratios are required.

Depth-damage functions for residential structures and contents are categorized as having a basement or not having a basement, and furthermore by the number of stories in the building. There are four structure depth-damage functions and four content depth-damage functions. This distinction is due to the finding that structures with basements are more vulnerable to flood damages, as even low-level floods affect the portion of the building below ground. Data shows that damages have been observed at 2.438 meters below the first floor height. Structures without basements face damages when flood levels are within -0.61 meters of the first floor height. For this reason, separate depth-damage functions must be developed for buildings with and without basements. Damages are also dependent on the number of stories that constitute the structure.

4.1.2.1. No basement

The 2000 document, Economic Guidance Memorandum (EGM) 01-03, Generic Depth-Damage Relationships (Johnson 2000), provides generic depth-damage relationships for one-story homes without basements, two or more story homes without basements, and split-level homes[5] without basement. Damage estimates are based on comprehensive accounting of losses from flood victims' records. Data was collected from major flooding that occurred in various parts of the United States in 1996, 1997, and 1998. It has been used to standardize relationships for estimating flood damage and other costs of flooding based on actual losses from flood events. Depth-damage data is limited to 0.61-meters below to 4.877-meters above a given water level for residential buildings and contents with no basements, as damages are averages based on observed flood levels. Damage data is available only for structures with first floor heights within these intervals.

Figure 5 USACE residential depth-damage data for structures and contents of structures without basements.



Structure damages in 1-story structures without basements are 0% of the structure value when the water level is -61 cm below first floor height. The average percentage of damage increases quickly at the lower flood levels then slows a bit at higher levels. At 487.7cm above first floor height, damages reach about 80.7% of the structure value.

Content damages in 1-story structures without basements increase steadily from 0% of the structure value, when the water level is -61 cm below first floor height, until around 396.2 cm, where they then plateau at 40% of the structure value.

Structure damages in 2-story structures without basements are 0% of the structure value when the water level is -61 cm below first floor height. The average percentage of damage increases until reaching 69.2%, when water levels are 487.7cm above first floor height.

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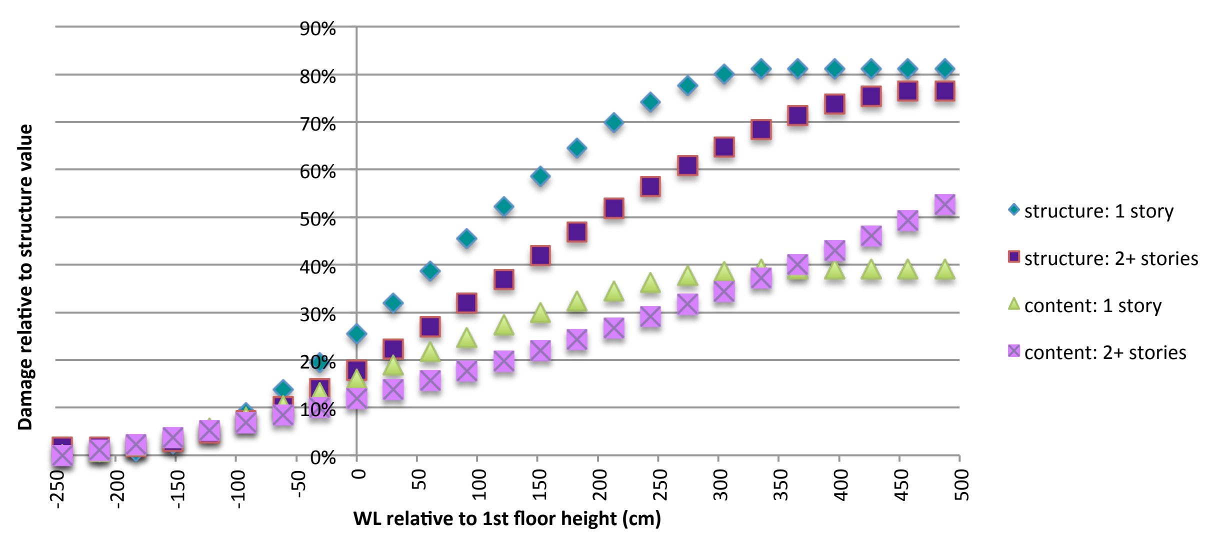
[5] This study excludes the distinction of split-level homes, as data on the number of floors is generally available from the municipal tax assessor, without distinction on the structure layout. The remainder of the discussion on residential structures and content without basement focuses only on one-story or two or more story structures.

Content damages in 2-story structures without basements increase steadily from 0% of the structure value when the water level is -61 cm below first floor height, to 37.2% at 487.7cm.

4.1.2.2. Basement

The 2003 document, Economic Guidance Memorandum (EGM) 01-03, Generic Depth-Damage Relationships for Residential Structures with Basements (Dawson 2003), provides damage data for one-story homes with basements and two or more story homes with basements. Damage data was collected from major flooding events that occurred in various parts of the United States from 1996 to 2001. Damage estimates are based on comprehensive accounting of losses from flood victims' records. Data has been used to standardize relationships for estimating flood damage and other costs of flooding, based on actual losses from flood events. Depth-damage data is limited to 2.438-meters below to 4.877-meters above a given water level for residential buildings and contents in structures with basements, as damages are averages based on observed flood levels. Damage data is available only for structures with first floor heights within these intervals.

Figure 6 USACE residential depth-damage data for structures and contents of structures with basements



Structure damages in 1-story structures with basements are 0% of the structure value when the water level is 243.8-cm below first floor height. Damages form an s-shaped curve, increases until they plateau at 81.1% at 335.3-cm above first floor height.

Content damages in 1-story structures with basements are 0.1% of the structure value when water levels are 243.8-cm below first floor height. Damages form an s-shaped curve, leveling off at 39.1% when the water level reaches 335.3-cm above first floor height.

Structure damages in 2-story structures with basements are 1.7% of the structure value when water levels are 243.8-cm below first floor height. Damages form an s-shaped curve, leveling off at 76.4% when the water level reaches 457.2-cm above first floor height.

Content damages in 2-story structures with basements are 1.6% of the structure value when water level is -243.8-cm relative to first floor height. Damages increase consistently until reaching 52.6% of structure value at 487.7-cm.

4.1.3. Regression analysis for residential depth-damage functions

Given that residential depth-damage data is available from the USACE in 1-foot increments, some method must be employed to find the in-between values. There is no correct solution to interpolation between data points; the common practice is to join straight lines (Smith 1994). Here, nonlinear regression analysis is carried out using the XLSTAT program. The depth-damage data are fit with four-parameter, sigmoidal, logistic functions. A logistic function allows the dependent variable to take on a value between 0 and 1. A four-parameter equation has a minimum asymptote, a hill slope, an infection point, and a maximum asymptote. The form of the regression equation is $F (x) = \alpha_3 / (1 + \exp (- \alpha_1 - \alpha_2^{x}) ^{1 / \alpha_4}$ where α_3 is the maximum asymptote. These equations are used in the economic model for calculating coastal flooding damages for residential structures and contents.

Table 1 4-parameter logistic nonlinear regression equations. The equations are derived from USACE residential structure and content damage data.

Structure	1-story, with basement	=0.837333/(1+exp(-(-0.1409)-0.010585*CM))^(1/0.618069)
	2-story, with basement	=0.849997/(1+exp(-0.239914-0.006585*CM))^(1/0.364565)
	1-story, no basement	=0.809232/(1+exp(-4.408243-0.009813*CM))^(1/0.006679)
	2-story, no basement	=0.728951/(1+exp(-3.831028-0.006897*CM))^(1/0.01058)
Contents	1-story, with basement	=0.406106/(1+exp(-0.401607-0.009052*CM))^(1/0.543833)
	2-story, with basement	=1.03028/(1+exp(-2.215675-0.00247*CM))^(1/0.046456)
	1-story, no basement	=0.405418/(1+exp(-4.375863-0.010879*CM))^(1/0.007458)
	2-story, no basement	=0.383982/(1+exp(-4.014942-0.008115*CM))^(1/0.008879)

The goodness of fit statistics include the R^2 coefficient of determination, the sum of square of errors (SSE), the mean square error (MSE), and root mean square error (RMSE). The R^2 corresponds to the percent of the variability of the dependent variable (damage) that is explained by the explanatory variable (water level). The closer to 1 the R^2 is, the better the fit. R^2 equals 1 minus SSE, and RMSE equals the square root of MSE. The SSE is the criterion used for the model optimization. SSE, MSE, and RMSE are measured in the same units as the dependent variable; the lower the value, the better. Based on the goodness of fit statistics, the derived regression equations are suitable to use for estimating the percentage of structure and content values damaged by sea level rise.

Table 2 Goodness of fit statistics for the residential depth-damage functions derived using XLSTAT nonlinear regression analysis.

	Structure				Contents			
	1-story, with basement	2-story, with basement	1-story, no basement	2-story, no basement	1-story, with basement	2-story, with basement	1-story, no basement	2-story, no basement
Observations	25	25	19	19	25	25	19	19
DF	21	21	15	15	21	21	15	15
R^2	0.9986	0.9995	0.9964	0.9963	0.9982	0.9977	0.9975	0.9968
SSE	0.0036	0.0009	0.0053	0.0037	0.0009	0.0015	0.0009	0.0010
MSE	0.0002	0.0000	0.0004	0.0002	0.0000	0.0001	0.0001	0.0001
RMSE	0.0131	0.0066	0.0188	0.0157	0.0067	0.0085	0.0078	0.0081
Iterations	8	16	200	200	8	200	200	200

4.1.4. First floor height

Depth-damage functions are based on flood height relative to the first floor of a structure. Therefore, the height of the first floor, not the elevation at ground level, is required for damage assessment. Precise information on the first floor height of structures is not currently available for the case study areas. This data is often unknown or unavailable, and can only be determined accurately by a professional surveyor. Although attempts were made to collect this data in the case study areas using a laser, hand-held, indirect measurement device, they proved unsuccessful. This is one limitation of this study that could be improved upon in future application of the methodology. In the US, the National Flood Insurance Program is beginning to collect this information for new or improved structures located in flood zones[6] [7]. Including this detailed data in future applications will only strengthen the methodology.

In order to capture the idea of the first floor height without having specific measurements, a visual approximation was made to classify each structure as either not raised, raised significantly (with the first floor at 2nd story height), or somewhat raised (about ½ story). Buildings that are not raised sit just above ground elevation, with first floor height approximately 30.5 cm (1-foot) above the ground. Buildings that are raised to protect from coastal flooding have a first floor of approximately 243.8 cm (8-feet, the standard ceiling height in a residential structure). Buildings that are slightly raised, falling somewhere in between ground height and 1-story above ground have a first floor height of 121.9 cm (4-feet). These approximations are added to the ground level elevation data to obtain first floor height elevation.

4.1.5. Verification of damage data

To confirm the reliability and relative accuracy of the depth-damage data from the USACE, it is useful to compare it with other flood damage studies. Although this type of data is not widely available, one unpublished European study (Huizinga 2007) has collected and analyzed flood damage data in order to produce flood damage functions relating water depth and economical damage for the assessment of direct damage as a consequence of floods. Damage data for each country was collected from the Internet, available literature at the consultancy that completed the report, and damage assessment experts from various countries. The USACE study, on the other hand, collected observed depth-damage data following actual flood events. Huzinga estimates damages for buildings and the inventory together, as opposed to the USACE damages calculated separately for structures and contents. The damage factors, averaged across all EU countries, were found for flood depths ranging from 0 to 6 meters (see Table 3), ranging from 0 to 100%. USACE depth-damage data is available from -2.44 or -0.61 meters to 4.88 meters, and never reaches 100% for either structures or contents separately. Furthermore, USACE damage data is dependent on the number of stories in a structure and whether or not there is a basement; the construction styles in the US and EU vary thereby limiting comparison of damages. These differences make it impossible to directly compare the US and EU damage data, however some relative comparison can still be made.

Table 3 Average depth-damage data for European Union member states from Huzinga (2007).

WL in cm	Damage factor	
	Residential with inventory	Commercial with inventory
0	0	0
50	0.25	0.15
100	0.4	0.3

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[6] http://www.fema.gov/media-library/assets/documents/160?id=1383

[7] http://www.fema.gov/media-library-data/20130726-1437-20490-0725/f_053_elevcertif_30nov12_fillable.pdf

150	0.5	0.45
200	0.6	0.55
300	0.75	0.75
400	0.85	0.9
500	0.95	1
600	1	1

The average EU residential building with inventory data falls within the range of the US structure damages (1 and 2-story structures with and without basements) but below the range of structure plus content damages for flood levels ranging from 0 to 3 meters. Damages for 4, 5, and 6-meter floods in the EU exceed those observed for the structures alone in the US, but are less than damages for structures plus contents.

EU commercial damage data is within the range of US non-residential damages for structures (with and without basements) only at 0 and 0.5 meters, but is above the range at higher depths. As the content damages in the US data are calculated based on the content values, rather than structure value, it is not possible to compare the EU damages to those of structure plus content for the US non-residential damage data.

Despite the limitations in comparisons, the US and EU depth-damage date are not so dissimilar that one stands out as being inappropriate to use. The USACE data is more detailed and based on actual observations, damages are grouped differently, and construction styles are different in the US than the EU, so it is fitting that damages vary slightly.

4.2. Land loss function

Land cannot be damaged by coastal flooding in the same way that structures and contents of structures can be damaged. When the value of land is lost depends on its use, as land is never actually lost but instead becomes part of the seabed, and previous land uses may not continue. Some uses of a parcel of land may continue if land is submerged only by temporary flooding, however, there becomes a point when the land is regularly inundated by tides and is no longer able to be used in the same way. Coastal land that is regularly inundated by tides due to the rising sea level rise will loses its value. In this model, when a high tide becomes higher than the land elevation, then the total value of that parcel of land is "lost" to sea level rise.

4.3. Valuation of land and structures

In a local level assessment using high-resolution data, valuation of each parcel of land and each structure is necessary to find the value potentially at risk to sea level rise. Damage functions find structure and content damages as a percentage of structure or content value. Percentage of structure or content value is the dependent variable in depth-damage functions. The percentage is then multiplied by the value of the structure or contents to find the potential damage costs. While the damage cost to land is not typically captured by coastal flooding damage estimates, land loss is a potential consequence of sea level rise, and therefore the value of land is required in assessing sea level rise losses.

Land and structures must be considered separately as structures face direct damages costs from coastal flooding, while land does not. Nevertheless, both land and structure can be lost to sea level rise. In a detailed assessment these potential impact costs should be calculated separately.

Detailed, 2011, parcel-level data from the municipal tax assessor on individual property characteristics is used to assess sea level rise losses in the case study areas. Appraised land and structure value, number of stories, absence or presence of a basement in structures, and land use zoning are used together with the corresponding depth-damage function to estimate coastal flooding damages and in turn sea level rise inundation loss estimates.

4.3.1. Appraised value

The depth-damage equations call for the use of depreciated replacement values of structures, defined as the costs of restoring or replacing a property with something of equivalent value accounting for physical deterioration and functional obsolescence brought on by age or lack of maintenance. Here, the tax assessor's appraised value for each structure is used. Appraised value is an evaluation of a property's value based on a given point in time, and is very similar to the idea of depreciated replacement value. As all values are 2011 USD, and costs are discussed in terms of current value (appreciation, depreciation and discounting are not included in the assessment), using appraised value is appropriate here.

4.3.2. More than one building on a property

There are multiple buildings located on some properties. For example, residential properties often have a detached garage or a shed. Outbuildings are given separate values in the assessor's records (but included in the total improvements value, and therefore must be subtracted out to find the value/s of the primary building/s). If there is more than one primary improvement, the total improvement value is divided by the combined area (square footage) of the structures located on the property to find the structure value per square foot. The square footage of each building is then multiplied by the value per square foot to find the structure value of each individual building. Having the assessed value for each building adds another level of detail and accuracy in estimating coastal flooding damages.

4.3.3. Condominiums

Condominiums are unique in that they have individually owned units with shared structures on shared property. In the tax assessor's database, individual condominium units are listed separately. Therefore a value for the common land area (or extra/utility buildings) is not explicitly provided as it is accounted for as a portion of each unit's value. In order to find the land value, which is necessary in considering sea level rise losses, the average values of Milford's waterfront and non-waterfront land per acre are used to make an estimate. According to the tax assessor, waterfront land is worth approximately $1,493,980 per acre and non-waterfront land is worth approximately $315,900 per acre. The number of acres on a condo lot is multiplied by the appropriate waterfront or non-waterfront value to make an estimate of land value.

Since the land and building values are lumped together in the assessor's database, it is necessary to adjust the condominium unit values to reflect the values for buildings only. To do this, the total land value is divided evenly amongst the number of condominium units and subtracted out from each unit price to find the structure value.

For condos, the values of units located in the same building are summed together and treated as one property. This addresses the issue of not knowing which floor a unit is located on in a condominium building, because, for example, a condo unit on the second floor of the building does not experience the same flooding damages that it would if it were located on the first floor. Likewise, a second floor unit will not maintain its value if the first floor of the building is flooded by sea level rise.

4.3.4. Docks

Public and private docks are often located along coastal properties, especially in harbors. Here, docks are considered only if they are located at a commercial property (i.e. marina). Residential docks are included in the primary structure value because of the lack of detailed data on the appraised value of each individual dock. However, there are five commercial properties with docks in Milford Harbor:

Milford Yacht Club, Milford Boat Works, Port Milford Marina, Milford Harbor Marina, and Spencer's Marina. All docks are assumed to have the same piling/bulkhead height (10 feet or 304.8 cm above the elevation at edge of the coastline nearest to the dock) since the individual docks at each location were not surveyed separately; approximations were made at a few locations. Sea level rise or storm surge water levels above that height mean that the value of the docks will be lost. Storm damages are not calculated as a percentage of the dock value relative to water height in the same way that buildings are, instead the total value is lost if the sea level rise or storm surge water level is above the piling height. The values of docks on these commercial properties are provided as outbuilding values in the tax assessor's records.

4.3.5. Dockominiums

A dockominium is a boat slip that is owned, not rented, as a condominium. There is one area in Milford Harbor where there is a shared parcel of land housing a parking lot and ramps to the docks, and each dock slip is privately owned as an individual unit. To find the value of land associated with the dockominiums, the average value per square foot of the five commercial docks (noted above) is used to find the average structure value. The square footage of each dockominium is listed on each of the tax assessor's property records[8], and is multiplied by this average value per square foot derived from the commercial dock values. The derived structure value is then subtracted from the total unit value to find the land value for each unit.

It is assumed that land value of dockominiums is not lost to sea level rise as long as the elevation of the inland edge of the property is above the sea level so that the dock can be attached to land. Therefore, to calculate sea level rise land value loss for dockominiums, the elevation of the center point of the inland edge of the property is used. Like with all docks, the value of the dock structure is lost when sea level rise or storm surge water levels are above the height of the pilings.

4.4. Structure loss function

The value of structures lost to sea level rise is estimated using a threshold value of coastal flooding damages. One major benefit of this approach is the ability to assess not only sea level rise losses, but also storm surge damages, and sea level rise and storm surge together, in future applications of the model. The value of land is not damaged by storms and is lost to sea level rise only if the water level is higher than the ground elevation.

The depth-damage functions, land use data, structure characteristics, and structure value discussed in this section are several of the components necessary to estimate coastal flooding damages for structures and contents. The land use classification, residential or non-residential, determines which type of damage functions to choose, and then the number of stories and presence of a basement determines the specific function. The method for determining land loss is much simpler and relies only on land value. Land value is lost if land is inundated by sea level rise.

Assessing sea level rise losses requires a few adjustments to the existing coastal flooding damage assessment methodology. The use of depth-damage functions works well for structures and contents, but ignores land. Additionally, structure and content damages can become losses, not only if damages reach 100%, but also if structures are submerged by sea level rise. Structure values can potentially be lost to sea level rise if damages reach a certain threshold at a specific interval of recurrence, whereas land is generally not lost in storm flooding. The threshold at which structure damages become losses is dependent on two things. One, the willingness for communities or even individual property owners to

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[8] http://gis.vgsi.com/milfordct/

experiences damages, and two, at which interval of recurrence they are willing to experience this level of damages.

To determine a threshold for damages to become losses, the concept of rent is applied. A property generates a certain rent per year, and rent is typically about 10% of property value per year (Shelton 1968). The structure has value if the rent is greater than the maintenance costs. In this case, maintenance costs are flood damages. So, 10% flood damage costs per year drive the value of the structure to 0 if the rent is 10%. In this economic model, structure values are lost when damages exceed 10% of the structure value per flood event.

This 10% threshold can also be considered in a different way. If a community is more willing to relocate, then this number can be lowered, and conversely if a community is particularly attached to their neighborhood, then the number can be raised to reflect this sentiment.

Contents can be damaged, but not lost to sea level rise. If a structure is going to be lost to sea level rise it will be a gradual process and the owners will presumable be able to relocate their belongings. Although content losses do not factor in the calculation of sea level rise losses, the content depth-damage functions were developed here to be consistent with structure damages for future application in studies including storm surge flooding.

Land elevation and water level are notably missing from the discussion thus far. Exposure analysis is the next step in which the elements affected under a given flooding scenario are identified by intersecting elevation and inundation data in a geographic information system (GIS). Once elevation and water level height are determined, then the independent variable in the structure and content depth-damage functions and land loss function is found, and the percentage of damage relative to structure value is evaluated. The independent variable in the structure and content damage function is the flood level minus the land elevation plus first floor height. In the land loss function it is the flood level minus the ground elevation. The value of affected land and structures is summed to estimate damage costs.

For structures and contents, damages are incurred at water levels below the level where structures are lost to sea level rise. Therefore, for each water level scenario there can be both damages and losses. Losses are a one-time occurrence, and once a structure is lost to sea level rise it cannot be damaged or lost again as water levels continue to increase. If a structure and its contents are not lost but damaged, then they experience those damages every time that that water level is reached. For this reason damages and losses cannot be summed to describe total costs for a sea level rise scenario; one is a stock and one a flow. Only losses are presented herein.

All calculations in the study use 2011 USD. The study assumes no human adaptation to reduce expected inundation or flood costs, and no future development inside the case study areas. It is assumed that the coast will not change in the future (locations of properties and structures) as it is already developed.

5. Topographic detail and spatial resolution

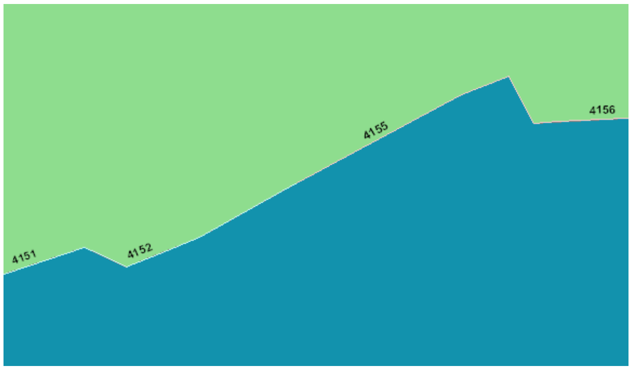
Flood damage assessments can be performed on the micro, meso, or macro spatial scale. Micro-scale assessments are based on single elements at risk, meso-scale assessments are based on spatial aggregations, such as land or administrative units, and macro-scale assessments use large-scale units such as municipalities, regions or countries for damage estimation. Meso and macro-scale assessments require aggregation, and up-scaling or downscaling methods are necessary for comparing different scale methods.

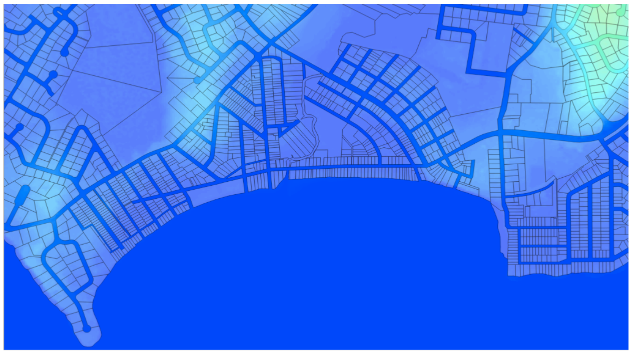
The context of the damage assessment is relative to the spatial scale of the assessment. Local studies generally apply micro-scale analysis, for which detailed local level data is required. Meso and macro-scale assessments are often chosen when larger areas are considered, as the data requirements are of these types of assessments are less intensive. Topographic detail is associated with the spatial scale of a coastal flooding assessment. High resolution spatial data is needed for rational decision making at the local level (Lichter and Felsenstein 2012). The level of detail affects the accuracy of damage estimates as well as the types of adaptation options to protect against coastal flooding. With lower resolution data it is likely that inaccuracies or problems average out over large areas, but more precise data is necessary for local scale impact and adaptation assessments.

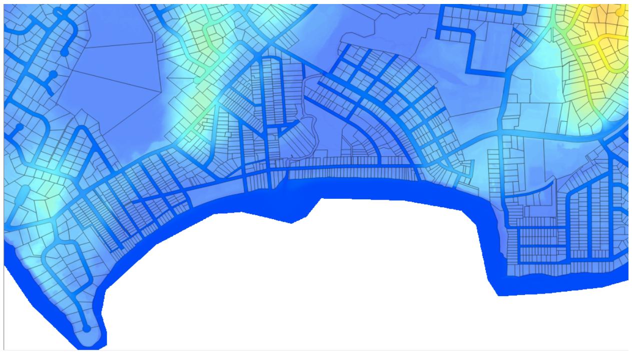
Lower resolution data fails to capture the intricacies of the coastline. The changes in topography and elevation are too small and the coastline in turn resembles a flat line with a uniform slope. Based on this type of low-resolution data, it appears that a coastline will experience losses in a uniform way and often be able to be protected by a simple, straight seawall. This type of assessment functions well on the global or national scales, but is not appropriate for local level assessments.

High-resolution digital elevation models (DEM) provide a more precise level of mathematical detail than lower resolution models that project the coast as a straight line. Increasing the data resolution essentially increases the length of the coast by adding the details of the curvature of the coastline. High-resolution data allows for more accurate damage assessment. In making adaptation decisions, higher resolution DEMs will initially provide better insight for the construction of more detailed adaptations. For example, there can be a lower area in between two higher elevation areas, and by simply building a small wall to connect the two points of higher elevation a large area behind the wall can be protected. However the higher sea level rises, the less important intricate details will become as the whole coast will eventually need to be protected.

Figure 7 DEM data resolution. The resolution of DEM data affects the level of detail in sea level rise assessment. The DIVA global DEM has 12,148 segments homogenous in terms of coastal characteristics with an average length of about 70 km. The DIVA DEM (top) shows Bridgeport to New Haven, Connecticut with Milford located between 4152-4155. The Bayview case study area can be seen in much greater detail using the 10-foot DEM (middle) and 3-foot LiDAR DEM (bottom).







High-resolution topographic LiDAR (light detection and ranging) data is available for the costal zone in Milford, Connecticut and provides extremely accurate elevation information for the case study areas. The 3-foot (0.9144-meter) LiDAR digital elevation model (DEM) was created by the Federal Emergency Management Agency (FEMA) in 2006 and has a vertical accuracy of +/- 1-foot (0.3048-meter), and a horizontal accuracy of +/- 3-feet (0.9144-meters). High resolution LiDAR data is a useful indicator of land vulnerability (Burkett and Davidson 2012), particularly in the case of sea level rise and coastal flooding. The center point of each property and structure in Milford is identified using the centroid function within the Quantum GIS Geospatial Data Abstraction Library (QGIS GDAL) and the Milford tax maps with property boundaries and structure locations (in 2011). Elevation data is linked to each land and building center point. The elevation at the center point of each property and each building is used to represent the elevation of the entire parcel of land or building. This high-resolution data is appropriate for assessing potential impacts of coastal flooding or sea level rise, as well as project based engineering solutions for the case study areas.

Figure 8 Land parcel and structure locations on the GIS map in the Harbor case study area. Property outline and building position (left) are used to derive the centroid point of each parcel of land (green dot) and each structure (black dot) to collect elevation information for the analysis.

5.1. Choice of elevation point

To calculate the coastal flooding damages and losses from sea level rise, it is necessary to determine whether the elevation of each parcel of land and its associated structures are above or below the water level in a sea level rise scenario. There are several different ways to determine if a property will be inundated and the value of that land and its structures will be lost using the elevation of the land and structures. Depending on the data available, there are several options for using land, structure, or land and structure elevations to estimate damages.

5.1.1. Land

The simplest approach to select an elevation point for the inundation loss estimate is to use the center point of a property. This approach can be applied even without data on the exact location of any structures on the property. If the elevation of the center point of the property is lower than a given sea level, then the value of both land and structures are lost. This ignores the possibility that (on a larger property) a structure might be situated on a portion of the land that is higher than the land center point, and therefore the structure might still be accessible and useable. Using the land center point will accurately capture inundated land value, but will overestimate structure loss.

5.1.2. Structure

Using the elevation of the structure requires data on the location of structures. If the elevation of the center point of the primary structure on a property is lower than a given sea level, then the value of both land and structures are lost. For properties without buildings, the center point of land is used. This approach accurately captures the value of structure loss, but underestimates land loss.

5.1.3. Land and structure

The most precise approach to estimating sea level rise damages and losses is to treat each property and each structure independently. This requires data on the location of all properties and all structures. If the elevation of the center point of the property is lower than a given sea level, then the value of land is lost; and if the elevation of the center point of a structure is lower than a given sea level, then the value of that structure is lost. It is possible that a property is sloping and the structure is located on the higher end. In this case, the center point of the land being below sea level may not affect the value and usability of the structure. This approach of using both land and building elevation separately best takes advantage of the most detailed elevation and spatial data.

5.2. Damages for choice of elevation point

Direct damages from coastal flooding and sea level rise losses are estimated in this study using the structure and content damage functions and land loss function developed in section 4 for the various combinations of land and structure elevation points discussed above. The water levels used here is the mean perigean spring tide (discussed in detail in section 6; section 7 explains future projections of sea level rise).

As predicted, using the land center point accurately captures inundated land value, but overestimates structure loss, and using the structure center point accurately captures the value of structure loss, but underestimates land loss. For example, in Bayview in 2025, using land elevation suggests that land losses will be about $7.7 million and structure losses will be about $8.9 million, whereas structure elevation suggests much lower losses for both, around $0.7 million for land and around $1 million for structures. The actual value lost, found using both land and structure elevations includes land loss calculated using land values and the structure loss calculated using structure values; $7.7 million and $1 million for land and structures, respectively. Using both land and structure elevation points separately gives the best estimation of sea level rise losses as only the individual land and structure units that are submerged are damaged or lost. The other two methods group the land and structure value for a property together. This method takes advantage of the most detailed high-resolution data available. Both land and structure elevation points are used throughout the remainder of this study to take advantage of the detailed elevation and topographic data in developing a methodology for local level assessment.

Table 4 Sea level rise losses calculated using land (A), structure (B), and land and structure (C) elevation points. Using both land and structure elevation points takes advantage of the most detailed data and provides the most accurate loss estimates.

Datum & year	Damage function	Bayview land loss $	Bayview structure loss $	Harbor land loss $	Harbor structure loss $
MPST 2025	A	7,716,290	8,937,980	10,503,220	2,475,960
	B	739,740	1,022,420	-	-
	C	7,716,290	1,022,420	10,503,220	-
MPST 2050	A	10,821,050	12,267,320	12,661,579	6,113,212
	B	1,522,670	2,281,160	-	-
	C	10,821,050	2,281,160	12,661,579	-
MPST 2075	A	12,318,040	13,694,260	15,256,479	6,428,722
	B	3,381,200	4,522,915	-	-
	C	12,318,040	4,522,915	15,256,479	-
MPST 2100	A	16,218,320	17,190,610	23,770,273	9,898,797
	B	5,721,185	7,263,014	1,029,760	223,090
	C	16,218,320	7,263,014	23,770,273	223,090

6. Evaluating the coastal flooding hazard using tide gauge data

The choice of which water level to use in coastal flooding assessments is crucial in determining the potential damages. The inundated area is defined as the connected area between the sea and the intersection of the water level and the DEM. A property is flooded when the water level rises higher than the elevation of the land or structures. However, the sea level is not stable, but is constantly in flux due to the relative locations of the earth, moon, and sun. The simplest method to assess the risk of inundation is to consider the elevation of land relative to mean sea level: a property is submerged when the mean sea level rises above the elevation of that piece of property. Using mean sea level is problematic as it ignores the rise and fall in sea level due to tides. As high tides occur regularly, using mean sea level ignores the possibility that properties situated only slightly above mean sea level are inundated, if only temporarily, regularly. A more precise method to assess inundation risk is to consider the elevation of a property relative to the high tide.

The heights of the various tides can be determined through an analysis of tide gauge data. The risk of inundation is affected by the tidal cycle, as the types and heights of tides vary with different reoccurrence intervals. This study improves upon the existing literature by basing coastal flooding damage assessment on water levels obtained from an assessment of local tide gauge data. Sea level rise assessments often base damage calculations on the water level height at mean sea level, as this data is readily available and easily applicable in all locations. At a more detailed scale, and particularly when adaptation is the goal of damage assessment, more precise information on the natural fluctuation of the water level is very relevant and has the potential to significantly impact the projected flood damages.

This section includes an overview of the availability and usability of tide gauge data and a description of the tidal cycle and tidal datum. It provides an analysis of tide gauge data for Bridgeport, Connecticut to demonstrate importance of the role of tides in choosing a water level to assess coastal flooding damages. Previous literature assessing the economic costs of sea level rise has not based damage estimates on tide gauge analysis or included a detailed analysis of the role of tides in damage estimates. The importance of including the effect of tides in damage estimates is demonstrated here using the Bridgeport tide gauge data and the Milford case study areas. Bridgeport is located about 16-kilometers southwest of Milford.

6.1. Tide gauge data

In the US, the National Oceanic and Atmospheric Administration's National Ocean Service (NOAA NOS) maintains numerous tide stations across the country where tidal and other water level data are collected. NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) provides the infrastructure, science and technical expertise to monitor, assess and distribute this data. CO-OPS collects, studies and provides access to historical and real-time observations as well as predictions of water levels and other coastal data, which is available on the NOAA Tides and Currents website (tidesandcurrents.noaa.gov). Analysis of water level data can provide insight into the height and reoccurrence intervals of tidal cycle and storm surges.

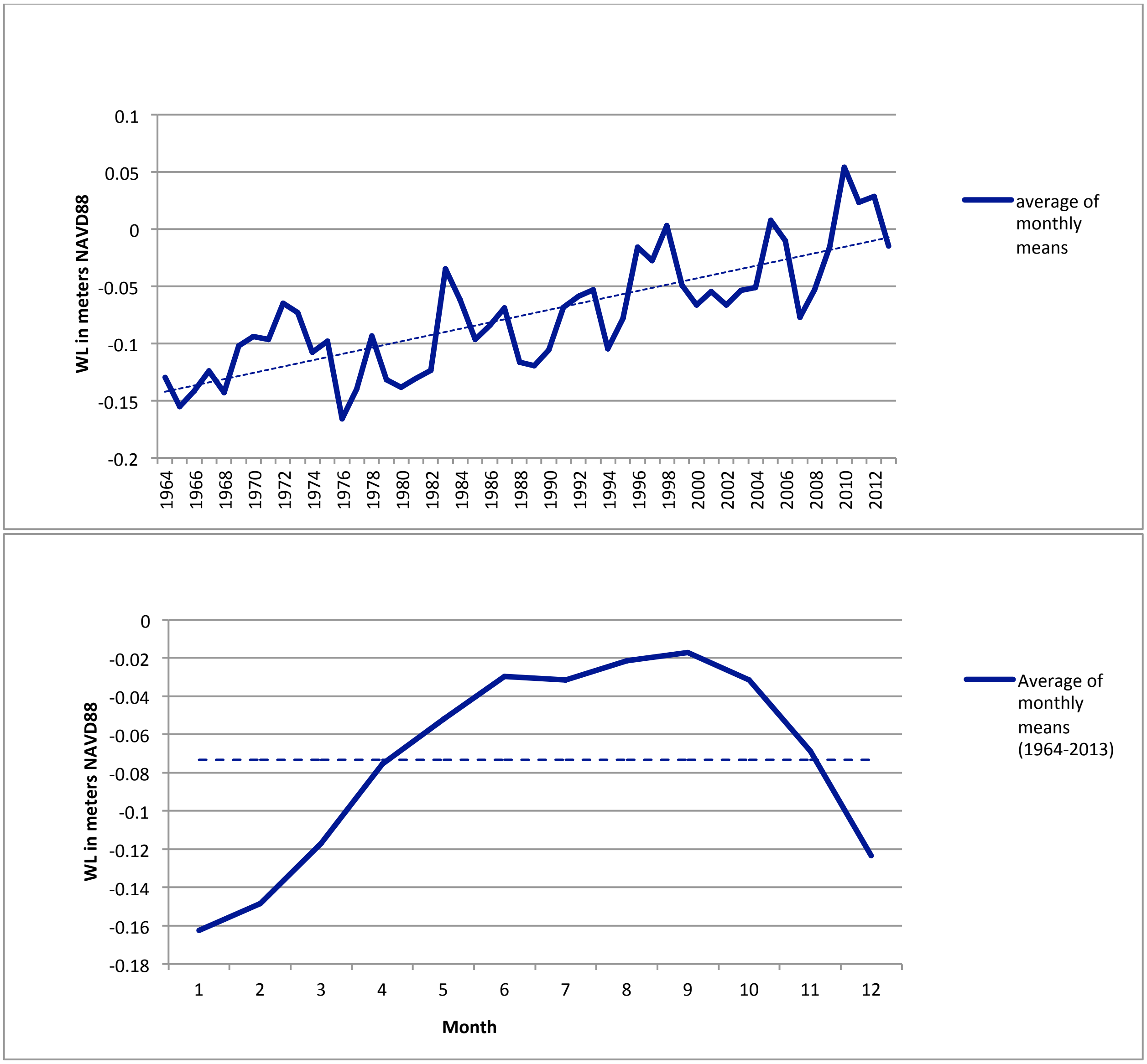
Water level data is collected relative to a tidal datum. Each tidal station has a Station Datum of 0.00 meters from which all tidal levels are recorded. To allow for easy comparison of water level data across different locations in North America, each tidal station also has a geodetic datum. The current national geodetic vertical datum is The North American Vertical Datum of 1988 (NAVD 88). NAVD 88 is the vertical control datum established in 1991 by the minimum-constraint adjustment of the Canadian-Mexican-U.S. leveling observations. NOS's National Geodetic Survey (NGS) develops and maintains NAVD 88. CO-OPS publishes tidal benchmark information and the relationship between NAVD 88 and various water level datum, such as mean lower low water, mean low water, mean sea level, mean tide level, mean high water, and mean higher high water.

Bridgeport, Connecticut water level data is used to develop the methodology presented in this study. Verified and predicted water level data for Bridgeport is available from NOAA. Monthly mean data dates from October 1964 to present, while high/low tide, hourly, and 6-minute data dates back only to 1996. Predicted water level data is available on an hourly or 6-minute basis for Bridgeport. Predicted water level data is useful in analyzing the fluctuation in the tidal cycle from factors such as the angles and distance between the earth, moon and sun. Observed and verified data captures the deviations from the predictions, which may be influenced by winds or storms.

6.2. Mean sea level

Mean sea level (MSL) is the arithmetic mean of hourly water level heights calculated using observed water level data sets. MSL is not a fixed level, but rather a fluctuating level with inter-annual variation and a seasonal cycle. Figure # shows the inter-annual variation in MSL using the average yearly MSL from 1964-2013 calculated from mean monthly MSL data. The average seasonal cycle of MSL is caused by regular fluctuations in coastal temperatures, salinities, winds, atmospheric pressures, and ocean currents. Figure # shows the seasonal cycle using mean monthly data from 1964-2013.

Figure 9 Bridgeport mean sea level. Yearly MSL (top) from 1964 to 2013 calculated using a yearly average of monthly data shows an increasing trend. Monthly MSL (bottom) was also calculated using monthly data from 1964 to 2013. It shows a seasonal trend in MSL, higher in the summer and lower in the winter months.



In Bridgeport, MSL has shown an increasing trend over the last half century, and has been higher in the summer and lower in the winter months. There is inter-annual variation in the yearly average of monthly mean data, and an increasing trend in MSL over the period 1964 to 2013, rising from 3.4185 to 3.5334 meters NAVD88. During this time, the average of monthly MSLs was 3.4747 meters. The seasonal cycle of MSL ranged from 3.3855 meters at its lowest point in January to 3.5307 meters at its highest point in September, with a difference of 14.52 centimeters. The lowest MSL in January was 8.92 centimeters below the average, and the highest MSL was 5.6 centimeters above the average MSL in September.

6.3. High tides

Using MSL in sea level rise inundation assessments ignores the significant influence of tides on the water level. Tides are the alternating rise and fall of the sea level with respect to land, and tidal ranges vary in different parts of the world. The tidal cycle naturally fluctuates in accordance with gravitational pulls exercised by both the moon and the sun. The tide-generating forces are differential forces between the gravitational attraction of the bodies (Earth-sun and Earth-moon) and the centrifugal forces on the Earth produced by the Earth's orbit around the sun and the moon's orbit around the Earth. The gravitational force on Earth holds the ocean water to the surface, but tractive forces of the moon and sun act externally on Earth's ocean waters. High tides are created in two points of maximum lunar and solar gravitational attraction where water piles up, and low tides are created by the withdrawal of water at the midpoint between the two heaps of water. High tides are created by the moon's gravity being dominant on the earth's near side and centrifugal force being dominant on earth's far side. The diurnal rotation of the earth with respect to the two tidal humps and two tidal depressions is responsible for the alteration between high and low tides (Bowditch 2002; R. E. White 2012). The earth rotates in the same direction as the moon, but with a period of 24 hours compared to 27.3 days. The tidal bulges follow the orbiting moon, which takes 24 hours and 50 minutes (one lunar day) to circle Earth, so each day the tides occur 50 minutes later than the previous day. Highs and lows average 6 hours and 12.5 minutes apart; high tide occurs every 12 hours and 25 minutes (R. E. White 2012).

Overall, the tidal range is influenced first by the moon's phase, with the highest tides occurring at Full and New Moon; second by the moon's distance from earth in its elliptical orbit, with highest tides occurring when the moon is closest at perigee; and third, by the moon's declination to the north or south, which creates tides of different heights on the same day.

6.3.1. Mean high water

Mean high water (MHW) is the average of all high tides. In Bridgeport, the average monthly MHW from October 1964 to July 2013 was 4.5009 meters; 2.8002 meters above the MSL for that same period (mean monthly data from October 1964 to July 2013). Daily high/low data shows similar results for MHW, although it extends over a shorter observation period. The average daily MHW from January 1996 to July 2013 was 4.5592 meters, 2.8107 meters above the mean tidal level (MTL, calculated from high and low tide values) for that period (daily high/low tide data from January 1996 to July 2013). Results differ slightly between the monthly and daily data sets because of the time frame and format of data (MSL versus MTL). Over the same time period, 1996 to 2013, the average monthly MHW was 4.5567 meters, 2.8007 meters above the MSL (mean monthly data from October 1964 to July 2013).

6.3.2. Mean higher high water

The plane of the moon's orbit around earth furthermore affects tidal heights. The plane of the moon's orbit is inclined to the plane of the equator, traveling above and below the equator and only sitting directly above the equator twice a month. When over the equator, the day's two high tides have approximately the same height. When the moon is north (northern declination) or south (southern declination) of the equator the high water marks on the same day will be of different heights; the effect is semidiurnal inequality. Diurnal inequality is the difference in the height of the two daily high and two daily low water levels, which occurs as a result of the moon and sun's changing declination above and below the equator (R. E. White 2012). If the moon has northern declination and is over the US, this tide will be the higher of the two daily tides. When the moon is over Asia during the second tide of the day, the water will be less high because the far side tidal bulge will be greatest over South America and less over the northern hemisphere. The higher of the two high tides is a tidal datum referred to as higher high water and the lower of the two low tides is called lower low water (Thurman; Ross 1995; Sumich 1996).

MHHW is the average of the higher of the two daily high tides. Daily high/low data shows the average daily MHHW was 4.6596 meters, 2.9111 meters above the MTL for January 1996 to July 2013 (daily high/low tide data from January 1996 to July 2013).

6.3.3. Mean spring tide

The gravitational effects of the moon and sun alter the tides on a monthly basis due to their respective positions. Solar tides are only half the strength of lunar tides and are expressed as a variation of lunar tidal patterns. During a full moon or new moon, when the sun, moon and earth are aligned, high tides are extra high and low tides are extra low. This occurs as the solar tide has an additive effect on the lunar tide, referred to as a spring tide. Neap tides occur one week later when the sun and moon are at right angles to one another (first quarter or last quarter) and the sun has a moderating effect by partially canceling out the lunar tide. Two sets of spring tides and two sets of neap tides occur each lunar month (Sumich 1996). As there are approximately 13 lunar months, there are 26 spring tides and 26 neap tides in each calendar year (R. E. White 2012). This means that there are 26 occasions when tidal levels are extra high due to astronomical forces.

The dates of spring tides are listed on lunar calendars. To find the MST for Bridgeport, the average water level is computed for these dates. Mean spring tide (MST) is the average of the spring tides. In Bridgeport, the MST was 4.7590 meters from January 1996 to July 2013.

6.3.4. Mean perigean spring tide

Distance between the earth, sun and moon also affect tides. Once a month, when the moon is at its perigee, closest to the earth at 221,000 miles, tide-generating forces are stronger than usual and produce above average ranges in tides. When the moon is at its apogee two weeks later, farthest from earth at 252,000 miles, the moon exhibits less force and the tidal ranges are less than average.

The perigean tide overlaps with the spring tide a few times each year and is called the perigean spring tide. During these events, the moon is in alignment with the sun, and the Earth is between the moon and the sun. An average of the high tides during these events is the mean perigean spring tide (MPST). Dates when the moon is at perigee can be found on a lunar calendar. An average of water levels is taken for days when both spring tide and the perigee are occurring simultaneously. In Bridgeport, from January 1996 to July 2013, the MPST was 4.9561 meters.

6.3.5. Highest annual astronomical tide

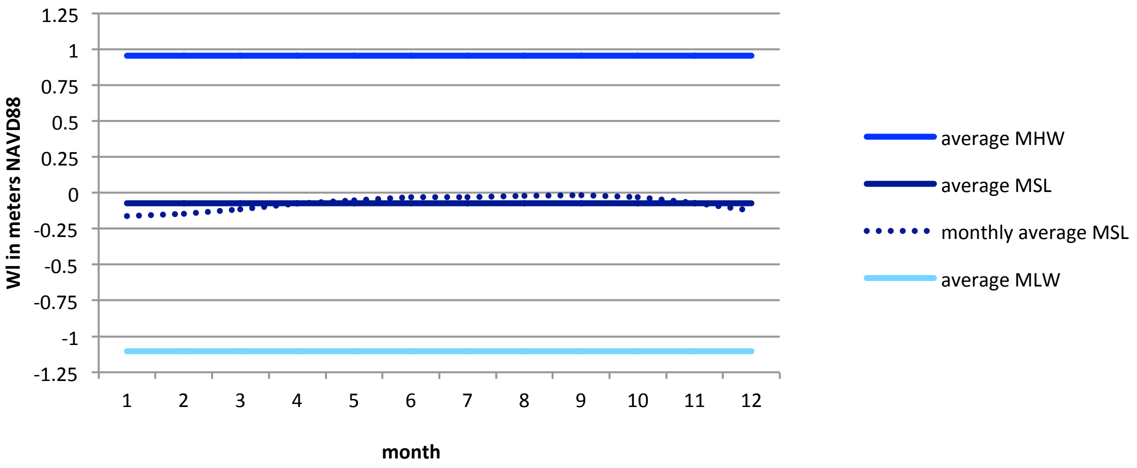
The highest annual astronomical tide (HAAT) is the highest predicted tide in a given year. Predicted tides can be used to capture high waters attributable only to tidal conditions, unlike observed water levels, which may be influenced by other factors such as low-pressure, wind, rain, or storms. Predicted water levels can be used to identify the greatest possible tidal contribution to an inundation event. The highest monthly or yearly-observed tidal level cannot be used, as it would have undoubtedly occurred during a storm event.

The average HAAT from January 1983 to July 2013 was 4.9961 meters (hourly water level predictions for 30+ years, January 1983 to July 2013). From January 1996 to July 2013 the HAALT was 4.9977 meters. Monthly data shows that from 1996 to 2013 the MSL was 3.5230 meters relative to the station datum (mean monthly data October 1964 to July 2013). Daily data from the shorter time period of January 1996 to July 2013 shows that the MTL was 3.5225 meters (daily high/low tide data from January 1996 to July 2013).) HAAT is therefore about 3.2540 meters higher than MSL.

6.4. Comparing tidal levels and identifying when property or structure value is lost

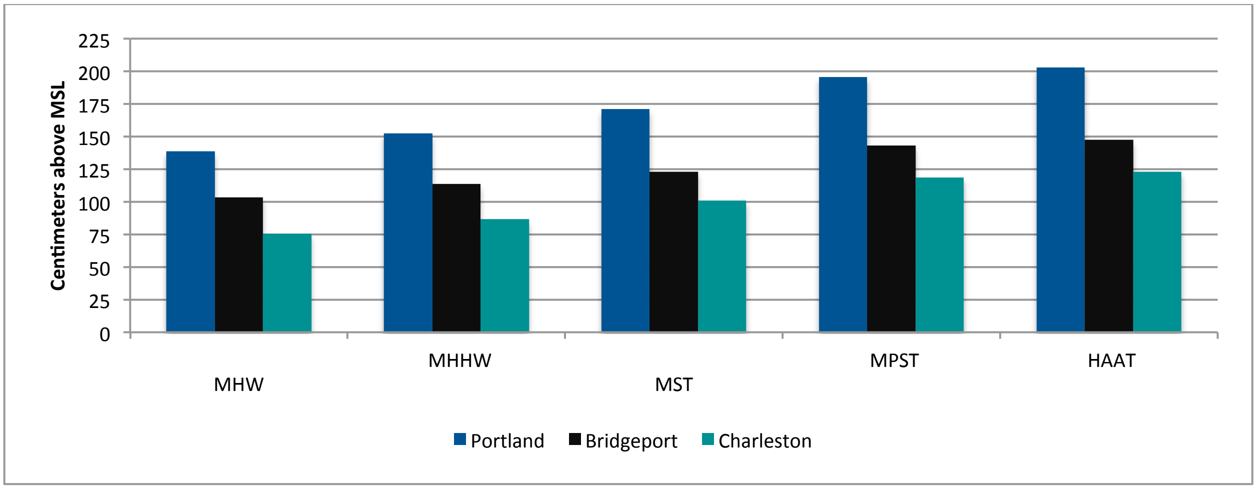
This tide gauge analysis shows that the time frame for calculating MSL is important, as there is an increasing trend in MSL due to the observed effect of sea level rise. Analysis of tide gauge data for Bridgeport shows that the seasonal cycle in MSL is much less significant than influence of the tides (see Figure 10) as it stays within +/-10 centimeters of the yearly average. Tides fluctuate over a much larger range of water levels. Both observed and predicted data show that considering tides rather than MSL alone makes a significant difference in water level height for use in inundation estimates. The sea level rise damage function used in coastal flooding damage assessments should therefore account for the increase in water level above MSL due to tides. These findings for Bridgeport are confirmed with additional analyses of Portland, Maine and Charleston, South Carolina tide gauge data. This analysis has also been carried out for Portland and Charleston to confirm that these relative findings do not change based on latitude, tidal range, or openness to the ocean (in this region of the world) (see Figure 11).

Figure 10 Average mean high water, mean sea level and mean low water for Bridgeport from 1964-2013. An average of mean monthly data from 1964 to 2013 shows that the MHW is about 1 meter higher and the MLW about 1 meter lower than MSL. The monthly average MSL fluctuates within about 10 centimeters of MSL depending on the phase of the seasonal cycle.



The difference between MHW, MHHW, MST, MPST, and HAAT is smaller than the difference between MSL and MHW in Bridgeport, Portland, and Charleston (1996-2013 data). While the incremental increases in the tidal datum above MHW are less than the jump from MSL to MHW, the difference between MHW and MPST or HAAT is also important to consider.

Figure 11 Tidal data for Bridgeport, Portland, and Charleston. Tidal ranges are slightly higher in Portland and lower in Charleston than for Bridgeport, yet the relative difference between tidal heights remains the same.



Depending on the coastal flooding assessment, different choices in tidal height can be made. In Connecticut, the property line for a parcel of oceanfront land is technically at the mean high tide line. Although one could argue that the land value is lost when mean high tide inundates the land, it is likely that any value associated with a parcel of land would be lost before the time at which it becomes regularly flooded twice a day. Which tide to use is essentially a question of return rate. High tides are each associated with a probability; high high tide occurs once daily, high tide occurs twice daily, mean spring tide occurs about twice a month, mean perigean tide occurs about once a month, and mean perigean spring tide occurs about three times a year. In the 6385 days of Bridgeport water level data analyzed here, there were 6385 higher high tides, 3192 high tides, 433 spring tides, 233 perigean tides, and 37 perigean spring tides. There is a 12.5% a perigean spring tide will not occur in a year, a 18.75% chance 1 will occur, a 37.5% chance 2 will occur, and 18.75 % chance that either 3 or 4 perigean spring tides will occur. Depending on the willingness to accept some level of flooding, different tides can be used in the assessment, each associated with a different probability or recurrence.

6.5. Losses using mean sea level compared to tides

Land and structure loss estimates using MSL are compared to loss estimates using tidal data. Losses are calculated using MSL, MHW, MHHW, MST, MPST, and HAAT to demonstrate the importance of including tides in sea level rise flood damages for 2025, 2050, 2075 and 2100. Future water levels with sea level rise are discussed in section 7. Results confirm the importance of considering tides in sea level rise damage cost estimates.

When using MSL to assess sea level rise damages, Bayview does not experience any land or structure losses in 2025, 2050, or 2075, and in 2100 one small piece of land is lost to sea level rise. Land and structure losses are realized in all four years under each of the high tide conditions for Bayview land and structures and Harbor land. Harbor structure losses are not experienced until 2075 when MPST and HAAT water levels are reached, and 2100 when MST, MPST and HAAT are reached. Land losses increase by millions of dollars depending on the choice of tidal datum used in the assessment, as higher a datum captures more of the potential losses. The increase in losses moving from higher probability to lower probability tidal levels is notable and confirms the importance of the careful consideration of which water level to use in sea level rise loss assessments. The choice of tidal datum significantly affects estimates for the potential economic losses to coastal flooding and climate change induced sea level rise.

Table 5 Sea level rise losses calculated using MSL and high tides. This table measures the damage to properties at each tidal elevation. It highlights the difference between using MSL to assess damages as opposed to including the role of the tides in the assessment of flood damages. Damage depends on where a property is actually located, not on the definition of sea level, however some damages may not be captured when insufficient consideration is given to the choice of water level. Previous studies that used low resolution data did not know the exact elevation of each property and assumed that some properties were located at mean sea level.

Year	Datum	Bayview land loss $	Bayview structure loss $	Harbor land loss $	Harbor structure loss $
2025	MSL	-	-	1,660	-
	MHW	1,023,220	96,170	5,204,150	-
	MHHW	1,574,540	254,240	7,861,750	-
	MST	2,967,890	258,310	8,416,550	-
	MPST	7,716,290	1,036,570	10,503,220	-
	HAAT	7,860,110	1,149,490	10,766,310	-
2050	MSL	-	-	1,660	-
	MHW	1,135,760	254,240	7,671,750	-
	MHHW	3,315,920	258,310	8,416,550	-
	MST	5,834,010	892,090	9,095,480	-
	MPST	10,821,050	2,558,785	12,661,579	-
	HAAT	10,988,110	2,944,355	12,764,569	-
2075	MSL	-	-	1,660	-
	MHW	3,315,920	258,310	8,416,550	-
	MHHW	7,017,040	899,540	9,604,420	-
	MST	9,281,710	1,243,850	11,136,310	-
	MPST	13,201,340	4,597,515	15,406,479	3,040
	HAAT	14,011,240	5,368,707	15,696,479	3,040
2100	MSL	2,700	-	176,290	-
	MHW	7,716,290	1,036,570	10,503,220	-
	MHHW	10,988,110	2,944,355	12,764,569	-
	MST	12,318,040	4,180,915	15,256,479	3,040
	MPST	17,221,340	7,917,365	24,698,558	223,090
	HAAT	19,210,760	8,691,018	24,976,208	223,090

7. Climate change and sea level rise

Sea level rise is increasing the water level height at all phases of the tidal cycle, leading to more temporary and permanent flooding of coastal properties. Sea level rise can occur both globally and locally due to changes in the shape of the ocean basins, changes in the total mass of water, and changes in water density (Baede 2007). At the global scale, over the time frame of decades or longer, global (eustatic) mean sea level change and geographically non-uniform sea level change results from the thermal expansion of ocean waters and the exchange of water between oceans and other reservoirs, such as land based ice (Solomon et al. 2007). At a regional level, there are spatial variations of sea level rise, dependent on dynamic processes occurring from circulation and variations in temperature and salinity, as well as static equilibrium processes occurring from mass redistributions that change gravity and Earth's rotation and shape (Sallenger, Doran, and Howd 2012). Vertical land movements resulting from glacial isostatic adjustment, tectonics, subsidence and sedimentation influence local sea level measurements. Although these regional discrepancies do not alter the volume of ocean water, they do affect global mean sea level through their alteration of the shape and hence the volume of the ocean basins containing the water (Solomon et al. 2007). The IPCC provides historical records and future projections of sea level rise at the global level, and in some cases these global projections have been downscaled in light of local conditions to form regional sea level projections. By considering relative sea level rise, the specific contribution of local processes are accounted for in assessments of future impacts (Nicholls et al. 2008). Regional sea level rise, however, is not covered in this study. Instead, IPCC global projections are used.

7.1. Observed sea level rise

Tide gauge records and satellite data confirm that the global mean sea level is rising. The IPCC (IPCC 2013) estimates that the mean rate of global sea level rise was 1.7 mm/year from 1901 to 2010, with an increased rate of 3.2 mm/year between 1993 and 2010, and a similarly high rate between 1930 and 1950. Over the same period of 1993 to 2010, monthly tide gauge data for Bridgeport shows a trend in MSL rise of 3.12 mm/yr. Over the 25-year period on which the IPCC projections are based, from 1986 to 2005, monthly tide gauge analysis shows an increase in MSL of 3.69 mm/yr. From 1964 to 2013, the extent of the observed monthly tide gauge data, MSL increased at a rate of 2.75 mm/yr. Observed regional sea level rise is close to the global level, particularly for 1993-2010, so IPCC future projections are used in this analysis.

Relative sea level rise in Connecticut is still influenced by a large ice sheet, several miles thick, which covered the state and spread south as far as Long Island during the height of the last glacial period, around 20,000 to 25,000 years ago. At that time the sea level was about 400 feet (122 meters) lower than it is now. Around 18,000 years ago the glacier began to melt causing sea level to rise until approximately 6,000 years ago. The weight of the ice sheet warped Earth's crust and caused Connecticut to become slightly uplifted. Since the ice has melted, the crust is now evening out and Connecticut is subsiding at approximately 0.76 to 0.89 mm/yr (Peltier 2001). This is called glacial isostatic adjustment (Gornitz et al. 2004). However, instead of making assumptions about the future rate of relative sea level rise in Connecticut, only eustatic levels are considered.

7.2. Future sea level rise

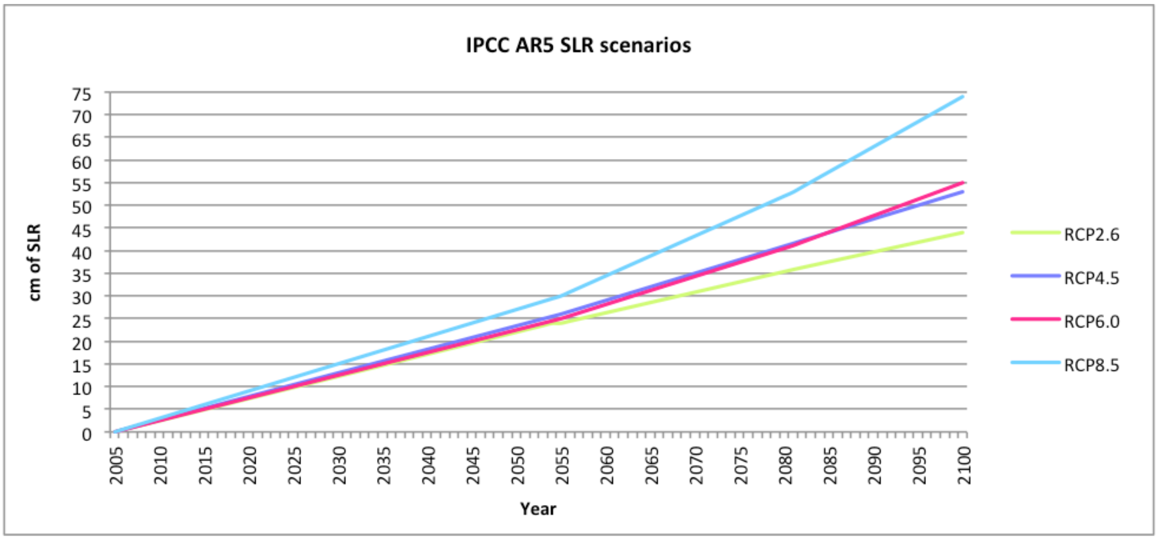
There is no discussion in the IPCC AR5 that climate change may alter the levels of tides, excluding the effect of sea level rise. It is currently unknown if this will be an issue. It is assumed that relative heights of the tidal datum will remain the same, even with future sea level rise. Sea level rise will only increase the height of the water level at all tides, high or low.

The IPCC (IPCC 2013) projects that the rate of global mean sea level rise over the 21st century will be higher than that observed from 1971 to 2010 for all representative concentration pathways (RCP) considered. At mid-century all projections are within a range of 5 centimeters, as the divergence of projections has a delayed effect due to the time integrating characteristics of sea level (IPCC 2013). In 2046-2065, global MSL is projected to be 0.24 meters for RCP2.6, 0.26 meters for RCP4.5, 0.25 meters for RCP6.0, and 0.30 meters for RCP8.5. The rate of sea level rise is anticipated to increase over the last two decades of the century, with rates of 4.4 millimeters per year for RCP2.6, 6.1 millimeters per year for RCP4.5, 7.4 millimeters per year for RCP6.0, and 11.2 millimeters per year for RCP8.5. By 2100, global mean sea level rise is therefore anticipated to be 0.44 meters for RCP2.6, 0.53 meters for RCP4.5, 0.55 meters for RCP6.0, and 0.74 meters for RCP8.5.

Table 6 Global sea level rise to 2100. IPCC projections and rates (bolded columns) were used to calculate interim rates.

Sea level rise scenario	Sea level rise rate 2006-2055 (cm/yr)	**Sea level rise 2046-2065 (cm)**	Sea level rise rate 2056-2080 (cm/yr)	**Sea level rise rate 2081-2100 (cm/yr)**	**Sea level rise 2100 (cm)**
RCP2.6	0.48	24	0.4165	0.44	44
RCP4.5	0.52	26	0.5615	0.61	53
RCP6.0	0.50	25	0.5819	0.74	55
RCP8.5	0.60	30	0.8812	1.12	74

Figure 12 IPCC AR5 global sea level rise scenarios.



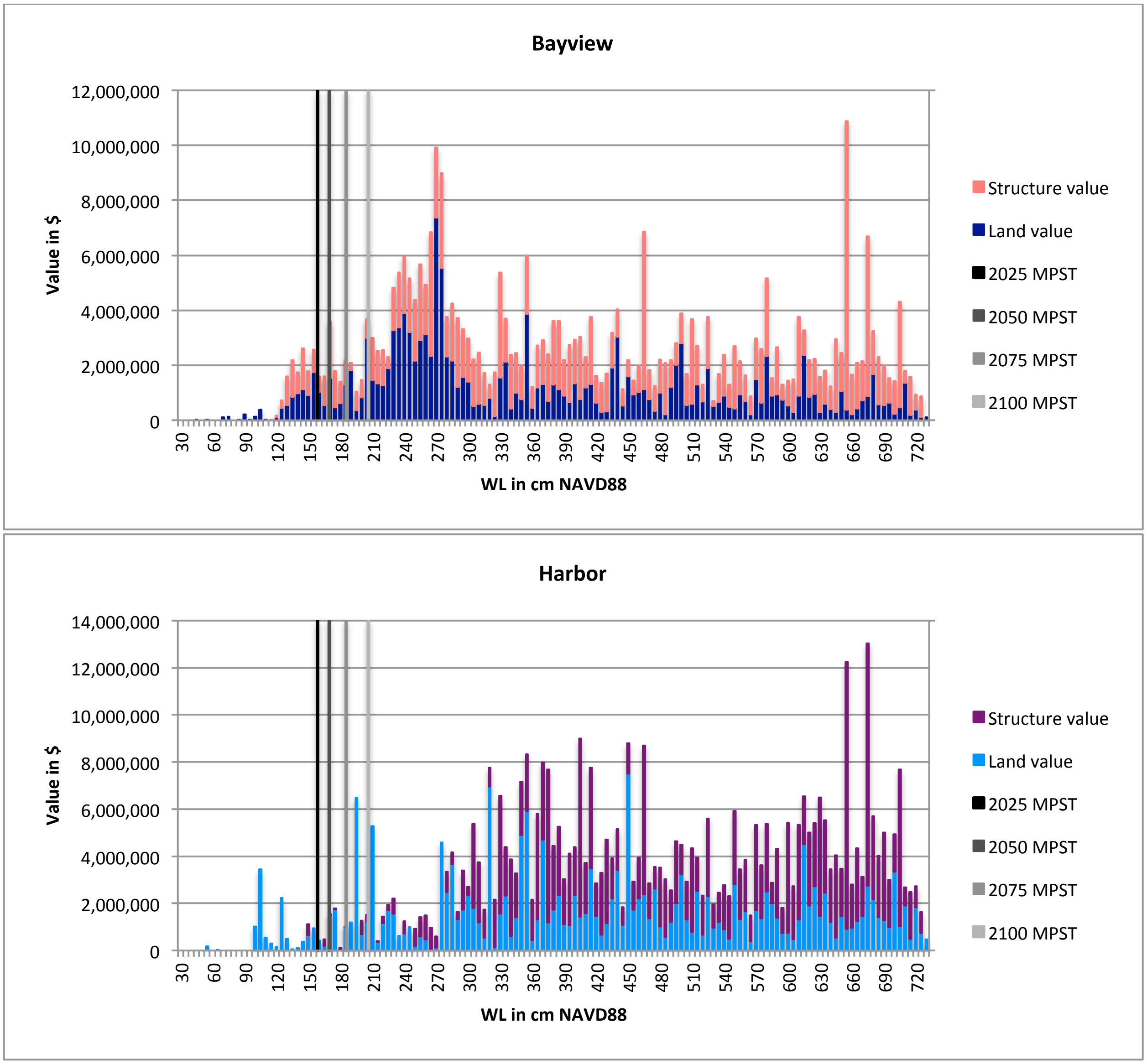
IPCC's RCP6.0 emission scenario uses a level of radiative forcing corresponding to many baseline (no climate policy) scenarios used in the literature (Vuuren et al. 2011). RCP6.0 is therefore like a business as usual (BAU) scenario. Future water levels discussed in this study use sea level rise projections based on the IPCC RCP6.0 scenario. Adding the increase in sea level height to the current tidal datum discussed in section 6 gives the height of future mean sea level and high tide levels.

7.3. Damages and losses with sea level rise

The damage and loss functions, high-resolution spatial data, and water level datum presented in this essay are combined and applied to assess the expected coastal flooding damages with sea level rise in the case study areas. MPST with both land and structure elevation points are used to estimate future losses to sea level rise. MPST is used as it represents a water level that will be reached on average two or three times per year, often enough that property owners will begin to feel the economic impacts of sea level rise. MPST is chosen rather than MSP or mean perigean tide, as it is likely that property owners will abandon their land or structures before they begin to experience damages on a monthly basis, as is the case with MST and mean perigean tide. As MPST occurs less frequently but is still predictable and regularly occurring based on astronomical factors, it is used here for sea level rise loss assessment.

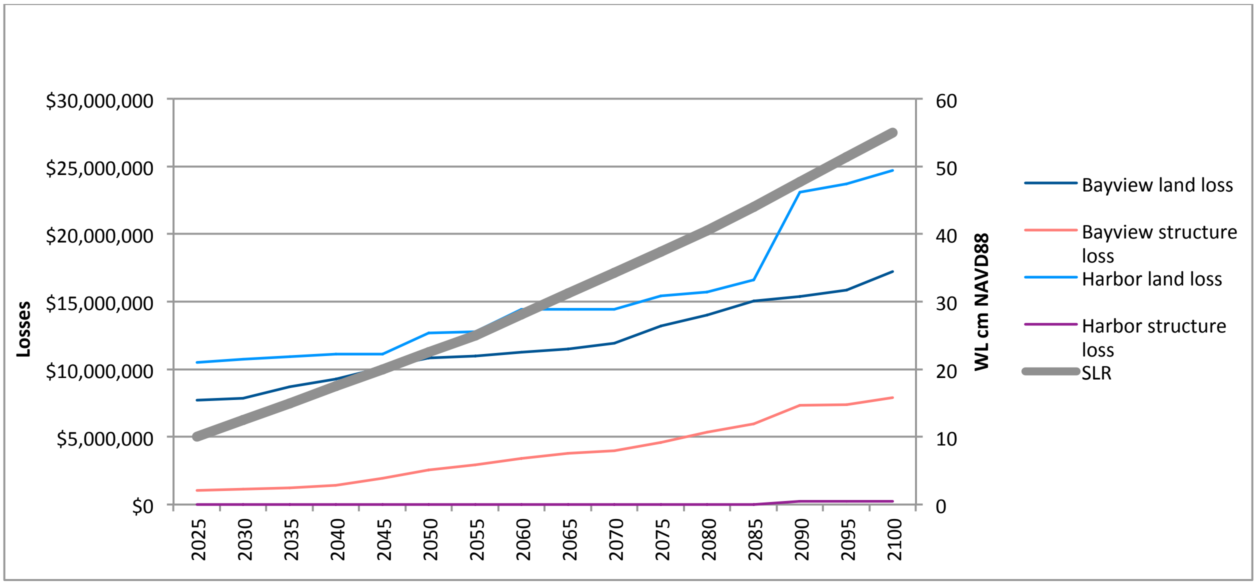
In Bayview, the total value of property (land and structures) at risk to SLR (i.e. below the MPST) is about \$15.5 million in 2025, \$19.2 million in 2050, \$25.7 million in 2075, and 34.2 million in 2100. The value at risk to SLR flooding in Harbor is about \$11.4 million in 2025, \$13.4 million in 2050, \$16.2 million in 2075, and \$26.4 million in 2100. These are the values at risk to sea level rise flooding.

Figure 13 Property value at risk of flooding. Land and structure values for Bayview (top) and Harbor (bottom) are shown in 5-centimeter increments with the MPST water level under future sea level rise conditions. The value at risk to sea level rise includes anything located to the left of the water level line.



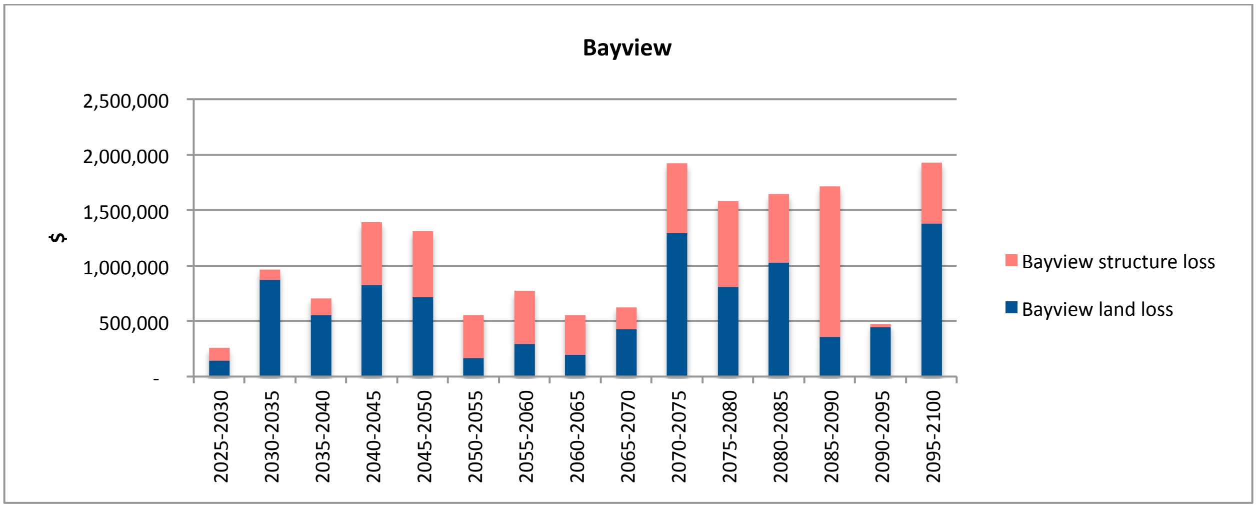
Land value is estimated to be lost when the center point is inundated at MPST. The value of a structure is estimated to be lost when the structure damages are greater than 10% of the structure value at MPST. This value of 10% reflects upon the willingness of a community to experience damages or relocate. Contents are damaged when the structure is damaged, but are not lost when a structure is lost. Damages costs are not presented here, only the value of structures and land lost to sea level rise.

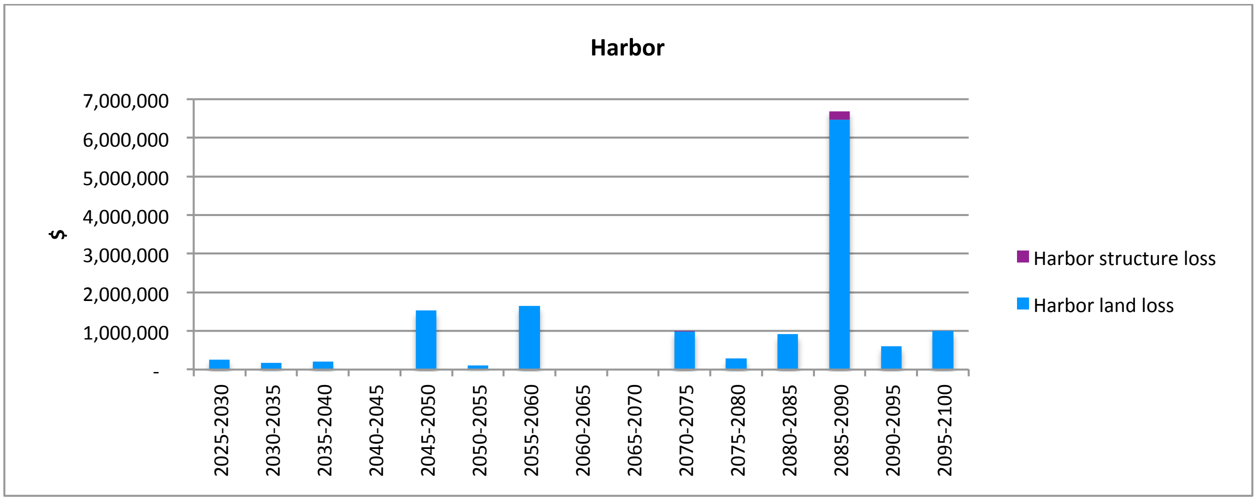
Figure 14 Cumulative sea level rise losses from 2025 to 2100.



As sea level rises and the value of land and structures at risk rises, sea level rise losses increase. Cumulative losses of Bayview land and structures increase consistently over the 75-year period. Both land and structure losses are experienced in each 5-year increment considered. Incremental land losses range from $144,000 to $1,380,000, with the greatest losses occurring in 2095-2100. High land losses, above $1,000,000 are also projected for 2070-2075 and 2080-2085. Land losses are highest between 2095-2100 when sea level rise is 51-55 cm above the baseline levels. All periods between 2030 and 2050, 2070-2085, and 2090-2095 land losses are projected to exceed $500,000; the remaining periods will face lower losses. Bayview structure losses range from $25,600 to $1,358,000. Structure losses are highest in 2085-2090, corresponding with 44-48 cm of sea level rise. Structure losses are also particularly high in 2070-2065, as damages exceed $600,000, when sea level rise is between 19-22 cm and 34-44 cm above baseline levels.

Figure 15 Sea level rise losses per 5-year period from 2025 to 2100 for Bayview (top) and Harbor (bottom). The values of structures are lost to sea level rise when MPST water levels cause greater than 10% structure damage. Land is lost when MPST is higher than land elevation.





Cumulative Harbor land loss increases in all 5-year periods, excluding 2040-2045 and 2060-2070. Land losses exceed $1,000,000 in 2095-2100, $1,500,000 in 2045-2050 and 2055-2060, and $6,000,000 in 2085-2090. These high land loss costs occur at 51-55 cm, 20-23 and 25-28 cm, and 44-48 cm of sea level rise relative to baseline levels, respectively. Harbor structure losses remain at $0 until 2075-2080, when sea level rise is 37-41 cm higher than the baseline level. Structure losses are also projected for the 5-year periods from 2085-2090. The highest structure losses occur in 2085-2090, with 44-48 cm of sea level rise, and are $220,000.

Land and structures will be lost to sea level rise in both the Bayview Beach and Milford Harbor case study areas by 2100. The highest combined land and structure losses in Bayview are projected to occur in 2080-2085. Land losses account for about $1,026,000 and structure losses for $1,201,000 of the total for that 5-year period. The highest total losses for Milford Harbor are $6,700,000; they will occur in 2085-2090 and are more than three times the losses projected for any other 5-year period.

In Bayview, 5%, 7%, 9%, and 11% of the total $150 million land value will be lost to SLR in 2025, 2050, 2075, and 2100, respectively. Structures losses will be 1%, 1%, 2%, and 4% of the total structure value of $193 million in 2025, 2050, 2075, and 2100, respectively. Harbor land losses, like in Bayview, outweigh the structure losses. In Harbor, 5,6,7,and 12% of the $210 million total land value will be lost to SLR in 2025, 2050, 2075, and 2100, respectively. Harbor structure losses will total less than 1% of the $242 million in total structure value in 2075 and 2100.

Table 7 Percent of land or structure value lost to sea level rise. Land losses are given as a percentage of total land value; structure losses are given as a percentage of total structure value.

Year	Bayview land loss	Bayview structure loss	Harbor land loss	Harbor structure loss
2025	5%	1%	5%	0%
2050	7%	1%	6%	0%
2075	9%	2%	7%	0.001%
2100	11%	4%	12%	0.092%

7.3.1. Spatial dimensions of sea level rise flooding

Future sea level rise flooding scenarios are visualized using the high-resolution data in GIS to see what properties will be inundated when. In Figure 26, lighter blue areas will be flooded sooner, while darker blue colors indicate that flooding will occur later, with the darkest blue areas experiencing flooding nearer to the end of the century. Green dots represent the center point of land parcels and black dots represent the center point of structures.

Figure 16 GIS maps of sea level rise at MPST in 2025, 2050, 2075, and 2100 in the Bayview (left) and Harbor (right) case study areas. Green dots represent the center point of each parcel of land and black dots represent structures.

8. Discussion

Following the stages of a traditional flood damage assessment, this study has derived damage functions for the amount of damage caused by each increment of flooding, identified the water levels at which damage will occur, and defined land and structure value. These elements have been supplemented with a land loss function to construct an economic model to assess direct economic losses to sea level rise. Aspects of impact assessment have also been included in constructing a baseline and projecting future climate conditions. The model has been applied to local level data for two case study areas in Milford, Connecticut to provide loss estimates for future sea level rise due to climate change. Tide gauge analysis highlights the influence of tides on sea level rise losses. The increased accuracy of loss estimates when using separate land and structure elevation points, and the enhanced spatial visualization of future inundation are proven advantages of using high-resolution data for local level assessment.

8.1. Damage functions

The use of depth-damage functions to determine structure damage and loss has several advantages. First, the existing flood damage assessment methodology is well defined. Second, the parameters for structure loss can be modified based on local sentiment and attachment to a particular location through the percentage of damages that will be tolerated before the structure is abandoned and the value is lost. Ten percent is used in this study as a starting point, justified by the discussion of rent, but can be adapted to reflect local conditions. Third, it allows for further application of the model, beyond sea level rise losses, to both storm flooding and storm flooding with future sea level rise. Using damage functions, with a threshold level of damages before losses are occurred, allows for the model to be used in many different contexts.

The decision to abandon a property once the height or reoccurrence interval of flooding is no longer acceptable is also represented in the model by the choice of water level. This reflects on the willingness or unwillingness of landowners or communities to stay or relocate as the choice of tidal data has an associated probability of recurrence. This is an important factor as some neighborhoods have an attachment to the property (or perhaps the land and structures hold a cultural significance) that is greater then the monetary value, thereby making residents less likely to leave despite damages. On the other hand, others may be less attached to a property and may have no problem relocating once damages or the real threat of damages are immediately realized.

This choice in tidal level height is much more flexible than using an elevation cutoff for losing a structure. Different structure characteristics make them more or less vulnerable to flooding, so using percentage of structure damage presents a better alternative. For a 1-story residential structure without a basement, damages reach 10% of structure value a few centimeters before the water level reaches the first floor height; and for a 2-story residential structure without a basement, damages reach 10% of structure value a few centimeters after the water level exceeds the first floor height. For both 1 and 2-story residential structures with basements, damages reach 10% of structure value around 92 and 61 cm below first floor height, respectively. Buildings with basements will be lost to sea level rise sooner as they will experience greater damages to the low elevation of the basement and foundation. Structure characteristics are captured in the depth-damage functions and more accurately represent the value of damages and eventual losses.

This methodology for calculating sea level rise losses also finds the damages that will occur every time a specific water level is reached. These damages were not discussed here, as the focus of this study is to assess sea level rise losses. It should be noted however, that these losses are not the only costs incurred when a high water level is reached. All structure and content damages below the 10% structure value threshold are damages that will occur even though they are not reported here.

As using coastal flooding damage functions to assess sea level rise losses has not been done before, there is no literature to draw from indicating how much coastal flooding from sea level rise property owners are willing to accept before abandoning their buildings. For this reason, 10% was chosen to represent a conservative approach, based loosely on the concept of rent. Experiencing structure damages worth 10% of the structure value even one time a year will drive the value of a property to 0, and MPST, the threshold water level for assessing damages, occurs on average 2 or 3 times per year. It should be noted that although MPST may occur multiple times per year, and cause damages totaling less than 10% of structure value to some properties, these smaller damage percentages are not summed together to cause structure losses when 10% is exceeded. With this methodology, damages only become losses when the MPST water level causes damages greater than 10% of structure value, as the water level return rate is not accounted for directly in the model, but instead projects damages and losses for single flood events. The return rate is inherently captured in the choice of the water level threshold.

8.2. High-resolution topographic data

High-resolution spatial and elevation data is essential for conducting a local level assessment where damages are estimated for individual properties. Use of high-resolution data provides real evidence to individual property owners on how much damage will occur and at what water level. The sea level rise assessment becomes much more real when a property owner sees how and when sea level rise will affect them, and most importantly, the associated costs of flooding. This is not the social cost of climate change that has been estimated in pervious literature on the economic costs of sea level rise (as done by Yohe and others, see Section 2). These are not the aggregate costs for the state or the city, but the costs at the local, neighborhood level, where it is possible to identify who specifically will bear the burden of sea level rise losses.

Analysis of when and where losses are experienced is also valuable for planning and management of coastal communities. It is very useful in deciding the most effective timing and placement for engineering based adaptations to climate change. Being able to visualize how much damage will manifest spatially is very enlightening and calls for action from those property owners who will be affected.

Furthermore, high-resolution data and the choice of elevation data point bring into light the issue of public roads and access to land and structures. This idea of access to a structure within the boundaries of a property also brings into question the problem of public access (streets) to private property as it may be affected by sea levels. This along with the valuation of roads and infrastructure warrant further consideration in a future study.

8.3. Water level

Each tidal datum and water level has an associated probability of recurrence. Perigean spring tide occurs approximately two to three times per year. This is the highest, regularly occurring, astronomically observed tidal level. While the MPST water level is higher than other high tides, the probability that it will be reached is lower. Using this level to estimate structure losses means that structure and content damages may also be incurred at even lower water levels, i.e. spring tide. The method of using percentage of structure damage captures all damages from water levels up to the MPST; it is possible that some structures are lost when water levels lower tidal datum heights depending on the elevation of the structure and structure characteristics. Other tidal data can be used in the assessment, but the damage threshold would have to be changed to reflect the acceptable level of damages. For example, if MST is used, the damage threshold would have to decrease significantly, as no property owner could realistically face 10% structure damages twice a month. In any case, considering the role of tides is essential to accurately capture future water levels and the damages and losses for both land and structures.

8.4. Sea level rise losses in the case study areas

The figures describing cumulative and 5-year sea level rise losses for the case study areas are not smooth. Although the sea level is consistently rising, there are years with low damages followed by high damages and vice versa. This is because the value of land and structures at risk to sea level rise at different elevations varies considerably. Therefore, precise information on the location and value of assets at risk is essential to assessment of direct damage costs and should be studied together with sea level rise changes when considering management options.

The value of land and structures lost to sea level rise is relatively low compared to the total property value in the case study areas, which include properties connected to the sea, ranging from 0 to 7.21-meters NAVD88. However, the cumulative land and structure losses are projected to be in the millions of dollars in both the Bayview Beach and Milford Harbor case study areas. In Bayview, the beachfront properties and properties surrounding the salt mash and tributary are most vulnerable; without adaptation, land losses will reach 11% (over $17 million) of the total land value and structure losses 4% (nearly $8 million) of total structure value by 2100. In Milford Harbor, although land losses will only reach 12% of total land value, the monetary loss is high (nearly $25 million) due to the high value of land in that area. Structure losses, on the other hand, will reach less than 1% of total structure value by 2100, as limited values are at risk to experiencing greater than 10% damages under MPST conditions.

9. Conclusions

Coastal communities are increasingly vulnerable to climate change induced sea level rise and the potential economic effects are a growing concern. An understanding of the costs of inaction provides local property owners, decision makers, and planners with a baseline from which to compare the costs and benefits of taking action to protect coastlines. This study develops a methodology to assess the value of land and structures that will be lost under future sea level rise scenarios. Local level conditions are incorporated into the assessment to increase the accuracy of loss estimates. The use of coastal flooding depth-damage curves is adapted to determine at which point structures will be abandoned to sea level rise. Depth-damage functions for structures and contents take into account the land use and structure characteristics to provide the most accurate estimation of damages for each individual structure for each water level scenario. Straightforward land loss functions are used to determine when a parcel will be inundated and what value will be lost. This methodology for calculating sea level rise losses can easily be adapted to assess storm surge damages and storm surge damages with sea level rise in future research applications.

An analysis of local tide gauge data highlights the role of tides and the effect that high tides have on the potential for sea level rise inundation. This is a key point in assessing the direct economic damages caused by sea level rise. A property will not suddenly become submerged. It will be a slow process where the property becomes flooded more and more frequently during high tide events. Incorporating tides into the sea level rise loss methodology captures this intricacy and increases the accuracy of loss estimates.

High-resolution topographic data provides the accurate elevation and spatial data necessary to determine which individual parcels of land and structures will be affected under future sea level rise scenarios. An accurate DEM is indispensible as it provides information on whether low-lying properties will be flooded or not. This type of information is crucial to develop appropriate adaptation measures in the near term. It allows for visualization of what properties will be affected by specific water levels at future dates, and what might be done to protect them. Additionally, sea level rise maps indicating areas that are potentially prone to future inundation are valuable tools for policy makers and decision makers.

The methodology to assess sea level rise losses developed in this study combines depth-damage functions, tide-gauge analysis, and high-resolution topographic and spatial data to assess sea level rise losses at the neighborhood level. The type of information generated from this level of assessment, on when, where, and at which water level sea level rise inundation will occur, and the associated costs, is critical for understanding the economic risks and for effective adaptation planning for all coastal communities. The methodology developed in this study generates information on the costs of inaction necessary to make efficient and cost effective decisions on management and protection of properties. Consideration of when and also where these losses will occur, and at which water level, are critical for flood management and adaptation planning. Furthermore, the methodology is applicable to both assessments of storm flooding damages and future storm flooding damages with sea level rise. When coupled with applications of the methodology to estimate storm flooding damages and future storm flooding damages with sea level rise, results will provide a comprehensive picture of current and future economic risks facing coastal communities.

Part II: Assessing the costs of storm tide flooding in coastal communities

Katie Johnson

Abstract

This is the second of three essays comprising a doctoral dissertation on the economic costs of local level damages and losses to sea level rise and storm surge flooding in coastal communities. This essay builds on the methodology and findings of the first paper. Depth-damage functions, high-resolution topographical data, and tide gauge data support the analysis of storm tide flooding damages using the local level data from the two case study areas presented in the preceding essay. The role of tides has a large influence on the height of a storm tide water level and on potential damage costs of coastal flooding. It is found that the probability that a water level will be reached and the probability that it will cause damage are not the same. Storm tide damages increase as water levels increase, but probability of experiencing a flood event decreases as water levels increase. Expected damages decrease with increasing water levels, as the probability of reaching higher water levels decreases.

1. Coastal storm flooding

Sea levels fluctuate regularly due to astronomical tides and storms. Storms occur less frequently, but can have a more significant effect on the height of the water level than tides. Coastal flooding is often caused by storm surges, which can be intensified by high tides. This essay presents a methodology for estimating storm tide damages using depth-damage functions and tide gauge data. The direct economic impacts of temporary flooding are estimated for structures and contents of structures. The high-resolution topographical dataset compiled for the two case study areas in Milford, Connecticut in the previous essay is used again here. First, the role of tides and storm surges in coastal flooding is discussed. Next, the damage functions for estimating coastal flooding costs are presented. Third, the tide gauge data is analyzed to find the probability of storm tides occurring and the probability of storm tides causing damages. Finally damages are estimated for observed storm tide water levels.

1.1. Storms

Nor'easters and hurricanes are two types of storms that cause coastal flooding in the northeast United States. A nor'easter is a type of cyclone that has leading winds blowing in from the northeast. Though they can occur anytime during the year, nor'easters are most common between October and April. They affect the northeast coast of North America – from Canada south to Virginia, bringing hurricane force winds and large quantities of rain or snow. Nor'easters form around low-pressure systems in the atmosphere and are fueled by cold air. They can become even more devastating when the cold artic air collides with the warmer winds of the Gulf Stream, thereby intensifying the storm.[9] Similar to cyclones, nor'easters cause storm surges and coastal flooding due to the associated low-pressure system and high winds.

Hurricanes are major tropical cyclones that develop over oceans warmer than 26 degrees Celsius. The Atlantic hurricane season goes from June 1st through November 30th. Cyclones form over tropical or subtropical waters and have a closed, low-level circulation of clouds and thunderstorms, rotating counterclockwise in the northern hemisphere. Cyclones, depending on wind speed, can be classified as tropical depressions (max sustained winds of 62 km/hr), tropical storms (max sustained winds 63 to 118 km/hr), hurricanes (max sustained winds 119 km/hr or greater), or major hurricanes (max sustained winds 179 km/hr or greater). The latitude where the cyclone forms influences the direction that the cyclone travels. Tropical cyclones that form between 5 and 30 degrees north usually travel west, although sometimes the winds in the middle and upper atmosphere steer the cyclone north or northwest. North of 30 degrees latitude, cyclones often move northeast.[10] The associated low-pressure system and high winds associated with cyclones are often times responsible for storm surges and coastal flooding events. The surge is a dome of high water created by low atmospheric pressure and strong winds. The height of the surge at landfall depends on the track and strength of the storm, and the height of the storm tide depends on the phase of the tidal cycle. Additionally, waves can contribute to the storm tide height.

Nor'easters are the most common type of coastal storm affecting Connecticut, and although the wind speeds and surges are lower than for hurricanes, they typically extend over a much broader area and last through several tidal cycles. Both types of storms cause direct economic damages to properties due to storm flooding in Connecticut.

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[9] http://news.discovery.com/earth/weather-extreme-events/what-is-a-noreaster-130208.htm

[10] http://www.nhc.noaa.gov/climo/

1.2. Storm surges and storm tides

A storm surge is the rise of shallow coastal water driven by a storm's surface winds and pressure gradient forces. The magnitude of a storm surge is determined by the characteristics of the storm, together with the geometry and bathymetry of the coast. Often times a tropical cyclone or nor'easter will cause a surge over and above the normal astronomical tide, where water levels are raised due to strong onshore winds combined with low pressure, which drives water onshore. The combined storm surge and astronomical tide is a storm tide. A storm surge occurs when there is an abnormal surge of water that is higher then the predicted astronomical tide, whereas a storm tide is the rise in water level due to the combination of storm surge and astronomical tide. The combination of storms and tides can lead to temporary flooding of normally dry, low-lying coastal land, which can affect populations, activities and infrastructures located in vulnerable areas.

The height of the storm tide depends on the phase of the tidal cycle and the height of the storm surge. If a storm surge arrives at low tide, then the storm tide will be much lower than if the same storm arrives at high tide. A big storm at high tide can lead to coastal flooding, while the same size storm surge at low tide may not even arrive at the height of the mean high tide. The role of tides in storm flooding can be seen simply by considering the difference in storm tide height if a 1, 2 or 3-meter storm surge arrives at the lower of the two low tides of the day (LL), low tide (L), mean sea level (MSL), high tide (H), or higher of the two high tides of the day (HH). Figure 1 shows that a 1-meter surge at high tide would cause about the same level of flooding as a 3-meter storm low tide. At lower low tide, a 1-meter surge is below mean sea level, a 2-meter surge is below high tide, and a 3-meter storm only reaches the level of a 1-meter storm at higher high tide.

The tide at which a storm surge arrives not only affects the water level height, but also the associated flooding damage costs. The economic impacts of the same size storm surge arriving at low tide versus high tide will vary significantly. The importance of the role of the tides was demonstrated in the previous essay in regards to sea level rise. Tidal levels are equally important in determining storm-flooding damages.

Figure 17 Storm tide levels when surges arrive at MLLW, MLW, MSL, MHW and MHHW.

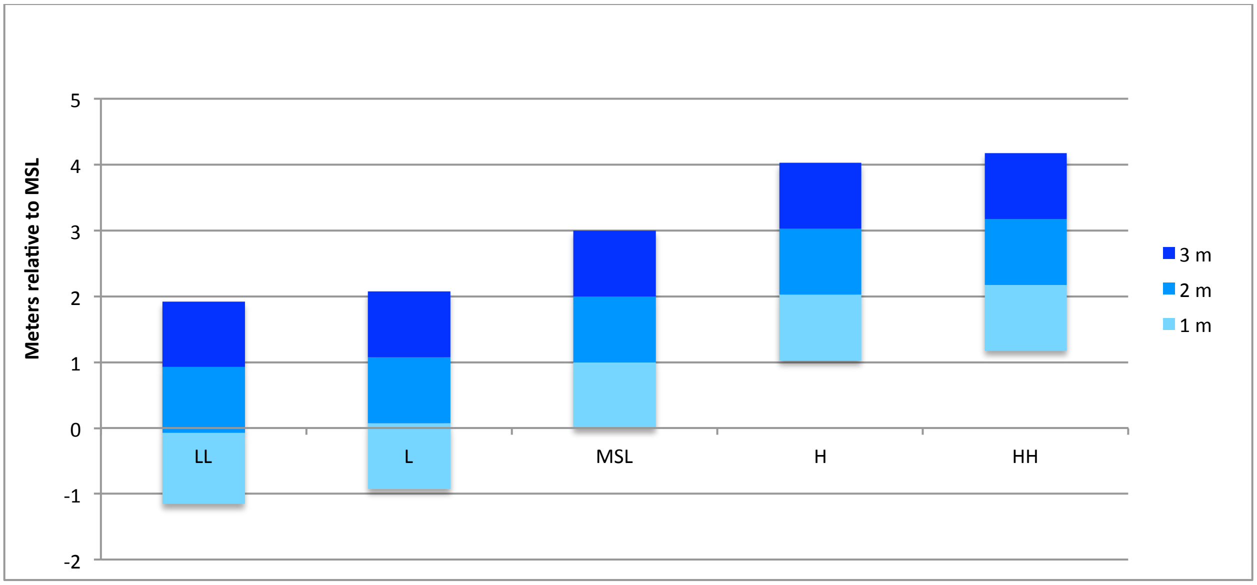
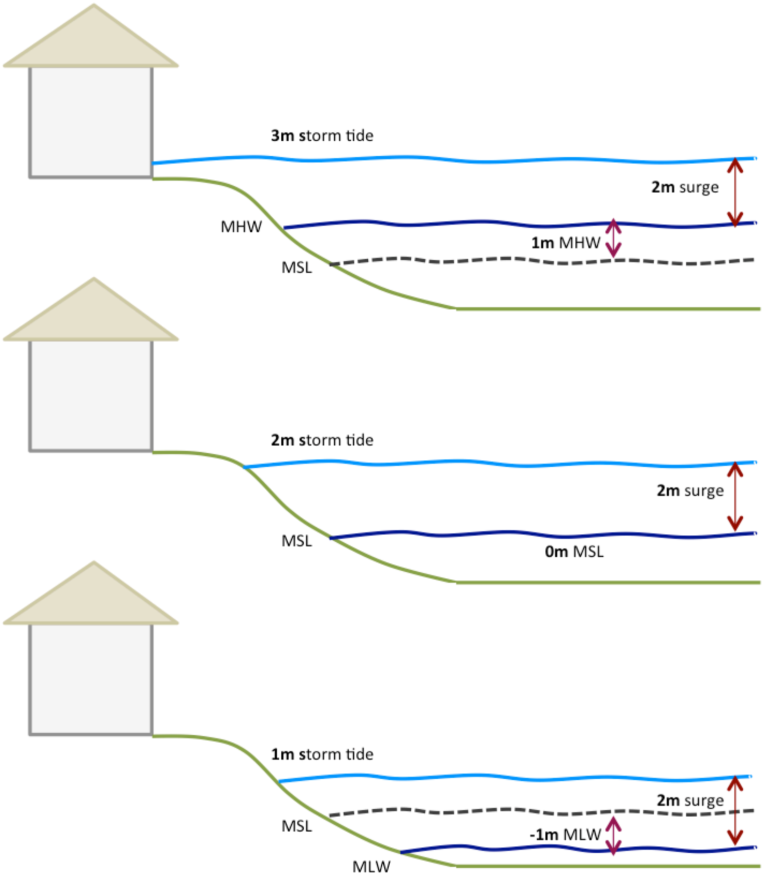


Figure 18 Effects of a 2-meter surge arriving at MHW (top), MSL (middle), or MLW (bottom). Combining tides and storms changes outcomes. The probability that the surge will arrive around MSL is 50%, while there is a 25% chance that it will arrive at MHW and a 25% chance that it will arrive at MLW.



1.2.1. Probability of a storm arriving at high, mid, or low tide

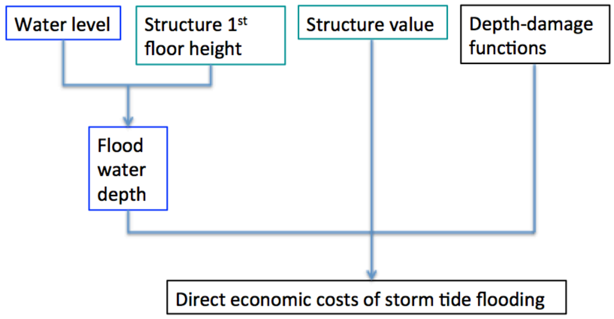
Combining tides and storms changes outcomes. Consider a storm that comes four times a year and causes a surge of 2-meters. Even if the expected height of the surge remains the same, the water level height changes depending on the phase of the tidal cycle. If damages are a nonlinear function of height, then the expected damages rise if the 2-meter surge arrives at high tide versus low tide.

The probability that a storm surge arrives at a high or low tide is lower than the probability that a storm surge arrives at mean sea level. This is due to the fluctuation of the tidal cycle. Between every high and every low tide, the cycle passes back through the mean sea level. So, in every tidal cycle, one lunar day or 24 hours and 50 minutes, there are two high tides, two low tides, and four times when mean sea level is reached. This means that if a storm arrives, there is a 50% chance that it will come when tides are near the mean, a 25% chance that it will come near high tide, and a 25% chance that it will come near low tide.

2. Coastal flooding damage assessment

Depth-damage functions provide a corresponding direct monetary damage for a flood of certain water level, and can be used to estimate the damage costs of storm surges (Smith 1994; Boettle et al. 2011). The methodology applied to assess flood damages and losses in this essay follows that developed in the previous essay on sea level rise. Functions to estimate direct damages, incurred due to direct contact with floodwater, were derived for structures and contents of structures. Land is not considered in this assessment, as it does not experience direct damage costs from temporary flooding in the same way as structures and contents; land uses can resume once temporary floodwaters have subsided. Impact cost estimates include damages caused to structures and contents by direct contact with floodwater, not storm damages due to wind or waves.

Figure 19 Methodology to assess storm tide flooding costs



The components necessary to construct an economic model to assess coastal flooding damages are a subset of those presented in the previous essay. There are separate damage functions for estimating structure and content damage and land loss. Damages are found for the case study areas under current conditions. These are the costs of inaction against storm tide flooding. Depth-damage functions are based on observed flood damage data compiled by the United States Army Corps of Engineers (USACE) for residential and non-residential structures and contents. These serve as the economic damage functions for estimating flood damages to structures and contents. Land use and structure characteristics are used for the classification of elements to determine which damage function to apply for structures and contents in each individual case.

2.1. Storm damage functions

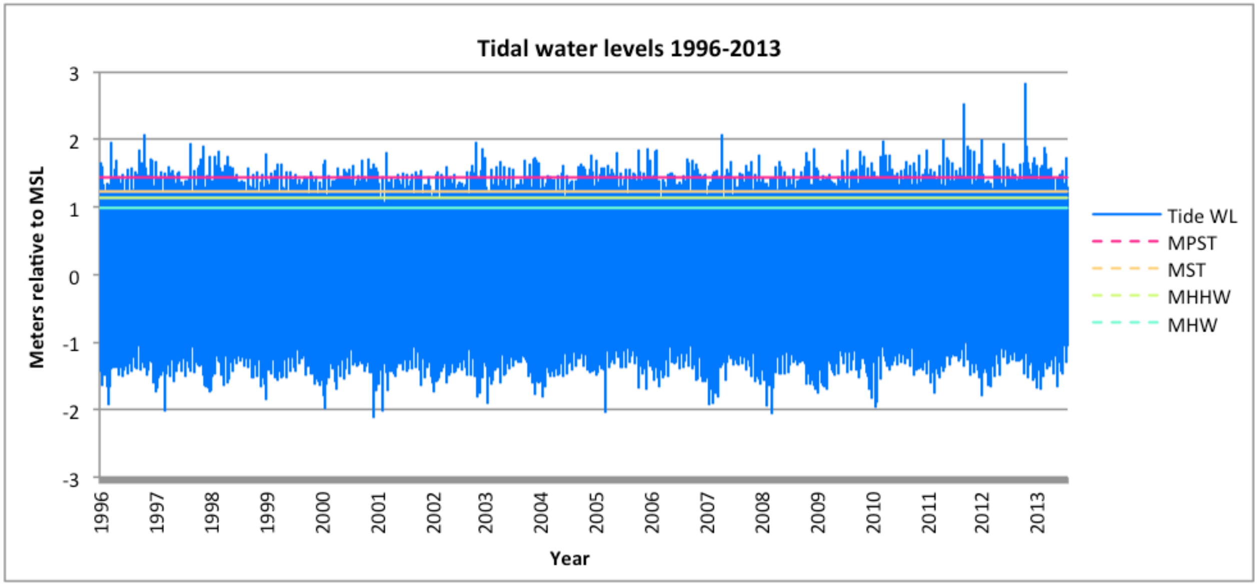
There are two sets of depth-damage functions, one for residential and one for non-residential structures and contents. The depth-damage functions developed in the previous essay using USACE data are employed again here. Non-residential structure and content depth-damage data is based on a 1996 USACE report (Kiefer and Willett 1996). As these functions find content damage as a percentage of content value, content-to-structure value ratios used are 100% for commercial, 150% for industrial, and 100% for public land. Residential depth-damage data for structures and contents find damages as a percentage of structure value. Residential data is obtained from 2000 and 2003 USACE reports (see Johnson 2000; Dawson 2003). See the previous essay for further information and explanation on the derivation of the damage functions.

Damages are found only for flooding only. Other storm characteristics such as wind and water velocity are not captured in depth-damage functions, as discussed in the previous paper – water level is the only independent variable. Land is not damaged from storm flooding, only structures and contents aDamages are based on water level relative to first floor height. Appraised value (2011 USD) is used for structures and contents. Damages are reported in terms of their current value. It is assumed that for each storm structure and content values are in 2011 USD and damages are based on those values. If structures and contents are damaged in more than one storm, the structure and contents are always assumed to have their original 2011 value, and subsequent damages are based again on the 2011 value.

3. Tide gauge data to assess storm water levels

Tide gauge data from the National Oceanic and Atmospheric Administration (NOAA) is useful for understanding the heights and recurrence intervals of tides, as well as storm tide levels. Tide gauge data captures the height of the storm tide rather than the storm surge; both astronomical tides and storm surges are captured in the tide gauge data. The probability of a storm surge arriving at a specific tidal level does not require separate consideration here as it is inherently captured in the tide gauge data. As in the first essay, Bridgeport, Connecticut water level data is used to develop the methodology presented herein. Verified water level data for Bridgeport is available from NOAA. Monthly mean data dates from October 1964 to present, while high/low tide, hourly and 6-minute data dates back only to 1996. Observed and verified data captures water levels, not only as they include the role of tides, but also as they are influenced by storms.

Figure 20 Daily tidal water levels 1996-2013. Daily high and low tide levels are plotted with mean tidal data relative to MSL. The highest peaks in the data series capture storms.

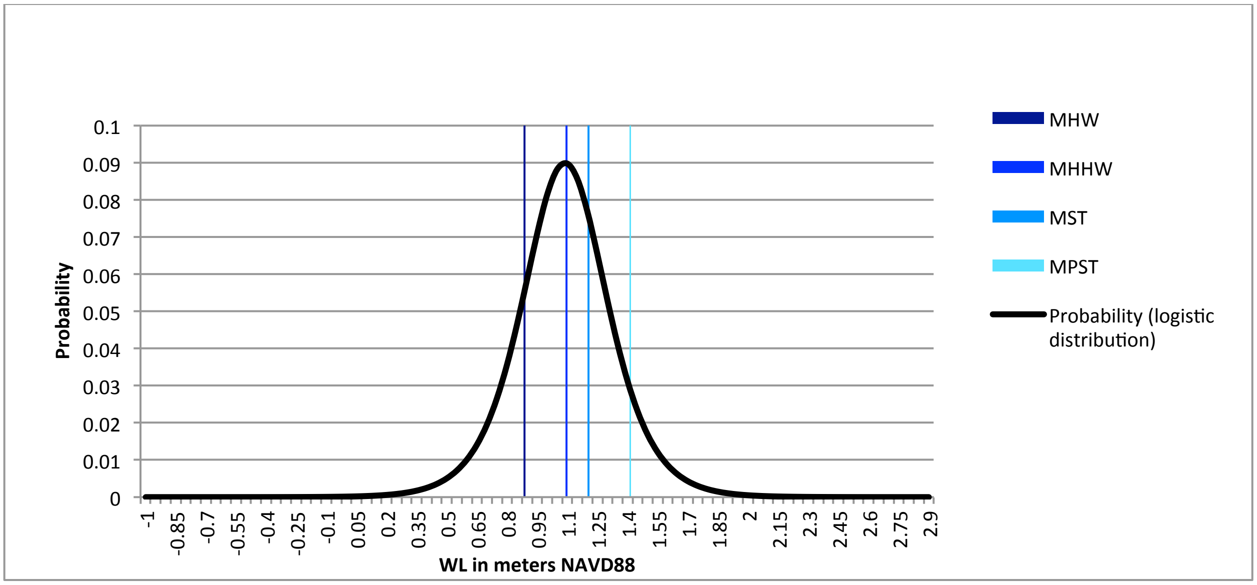


3.1. Probability and return rate

Tide gauge data for the highest water level observed each day provides information on storms, including storm tide height, and the probability and frequency of occurring. Daily mean higher high water (MHHW) data from 1996-2013 is analyzed to find the probability associated with the highest water level observed on any given day. Water level data (relative to NAVD88) is fit with a probability distribution curve using the XLSTAT program. A logistic distribution is found to best fit the highest daily water level data and account for the heavy-tailed distribution that includes storms. The density distribution gives the probability of the highest daily water level. The daily return rate of each water level is found by dividing 1 by the daily probability of occurrence. The yearly return rate is found by multiplying the daily return rate by 365.

The MHHW level has the highest probability of being the highest daily water level observed, and lowest return rate. Higher and lower water levels are less frequent. This is expected, as the MHHW is an average of the daily highest water levels. The water level heights of the mean spring tide (MST) and mean perigean spring tide (MPST) have slightly lower probabilities, as they are generally reached due to the influence of astronomical tide about two times per month and two or three time per year, respectively; any other instance is due to storm influence. As this essay is focused on storm flooding damages, the discussion is limited to the higher than average water levels. This includes water levels equal to or greater than MPST. The probability of occurring decreases and the return rate increases as water levels increase.

Figure 21 Probability of highest daily water level. Higher high water data fit with a probability distribution curve shows the likelihood and height of the highest water level on any given day.

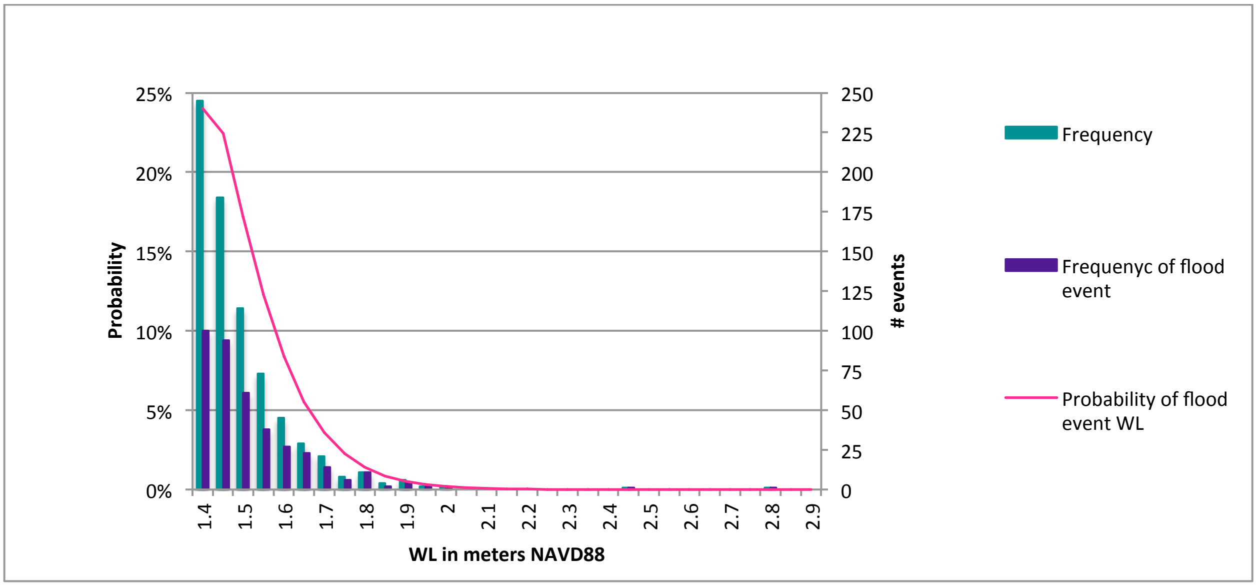


3.2. Probability of occurring versus probability of causing damage

Water levels slightly higher than the MPST occur often due to any combination of astronomical, storm, wind, rain, or pressure conditions. Daily HHW measurements capture this data. However, using daily data to estimate the probability of experiencing flood damages can lead to an overestimate of expected damages. For example, if a large storm brings higher than average water levels on back-to-back days, daily data can lead to a double counting of flood events. For example, Hurricane Sandy in 2012 and the April 2007 nor'easter both caused 2 days with extremely high WLs, amongst the top 20 observed over the 1996-2013 data set. In cases such as these, flood damages are not incurred two separate times, but rather only once.

To address this issue of potentially overestimating flood damage costs, the daily HHW data (observations higher than the MPST only) is "cleaned" by keeping only non-consecutive flood days, eliminating back-to-back days of flooding. Flood events are defined here as non-consecutive days with water levels above MPST; flood events cause flood damages. In the case that two or more days in a row have HHW greater than MPST, the day with the highest water level is kept in the data set and the others are eliminated. Figure # shows the frequency of the daily and daily sorted data in the 1996-2013 data set, highlighting the potential of over counting flood events. From January 1996 through July 2013, there were 708 days and 369 flood events where water the HHW level exceeded the MPST. At lower water levels, the daily number of observations is the highest, far greater then daily-sorted data, and the number of observations decreases rapidly as the water level height increases. The higher the water level, the closer the number of observations in each data set. The highest 6 observed water levels, above 1.95 meters NAVD88 are captured by both data sets. This analysis shows that daily data may overestimate the number of storm water levels (and damage costs) by counting back-to-back floods as separate events, especially for lower water levels. Using daily-sorted data to define flood events provides the most accurate estimate of the number of flood events causing damage.

Figure 22 Daily and daily sorted data for storm tide frequency. The graph shows the frequency of water levels observed with the frequency and probability of flood events in Bridgeport, Connecticut from 1996 to 2013. Daily-sorted data has been cleaned to eliminate consecutive days with high water levels, to isolate flood events. The probability curve shows the likelihood of a water level being reached during a flood event.

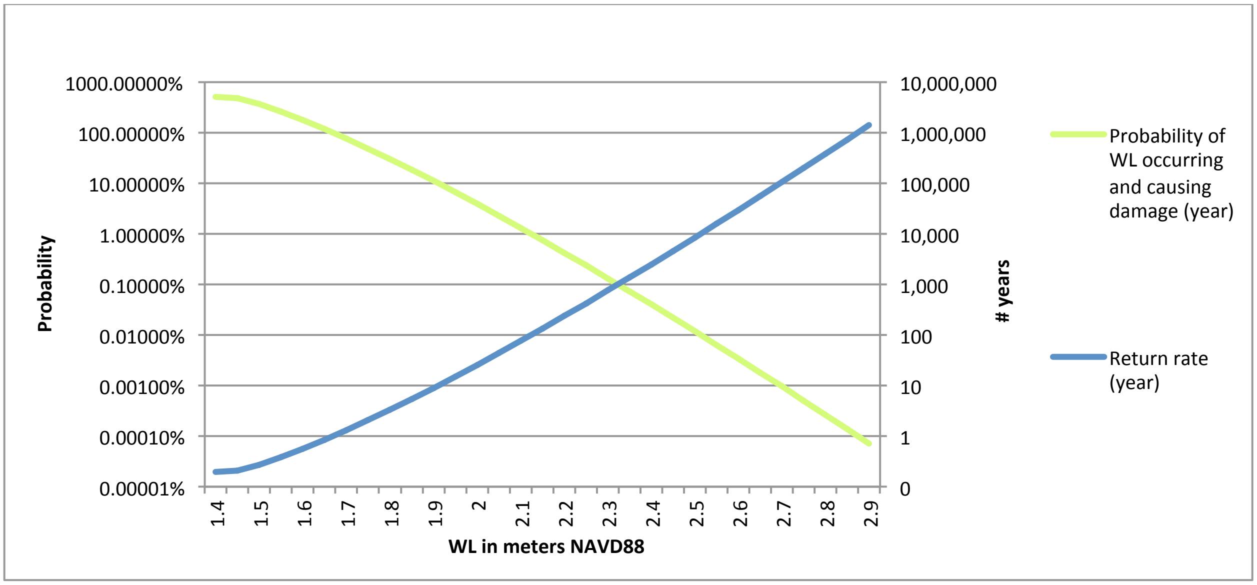


The daily HHW sorted data set of non-consecutive flood events represents the high water events causing economic damages. This new data set is fit with a probability distribution curve using the XLSTAT program. The distribution that fits best the data for the goodness of fit test is the three-parameter Weinbull distribution.

Flood events above 1.4 meters have a decreasing probability of occurring. The daily probability of any high water level above 1.4 meters NAVD88 occurring is about 11%. This is the sum of the probabilities of all high water levels, from 1.4 to 3 meters NAVD88. The probability that a high water level will cause damage if it occurs is about 52%; this is the frequency of flood events divided by the frequency daily of high water levels. There is a 6% probability that a flood event will occur and cause damage on any day, found by multiplying these two probabilities together. The probability of a specific water level occurring and causing damage on any given day is found by multiplying this 6% by the probability of a water level occurring and causing damage. The yearly return rate of water levels causing damage is found by dividing 1 by the daily probability times 365 days per year.

Lower water levels have high probabilities and low return rates; high water levels have low probabilities and high return rates. Probabilities greater than 100% mean that the water level will be reached multiple times per year; water levels lower than 1.65 meters NAVD88 are reached yearly, while higher levels are reached less frequently.

Figure 23 Probability and return rate of flood events. This is the probability that a water level will be reached in a year.



4. Storm tide damages

The depth-damage functions are applied to estimate the storm damages to structures and contents from water levels greater than MPST. Flood event water levels between 1.4 to 3 meters NAVD88 (MPST to 2.6 meters above MPST) are used to calculate damages at 5-centimeter increments. The water level height at the lower end of the 5-centimeter range is used to calculate damages.

The higher the storm tide water level, the higher the coastal flooding damage costs to structures and contents. In Bayview, content damages are higher than structure damages at lower water levels until 3.3 meters, then structure damages become more significant with higher water levels. In Harbor, structure and content damages are nearly the same at each storm tide flood level. Potential damages increase as return rate increases.

Figure 24 Probability of storm tide and associated damages. This is the probability that a water level will arrive in a year. Damages are not cumulative; damages for each water level are calculated individually.

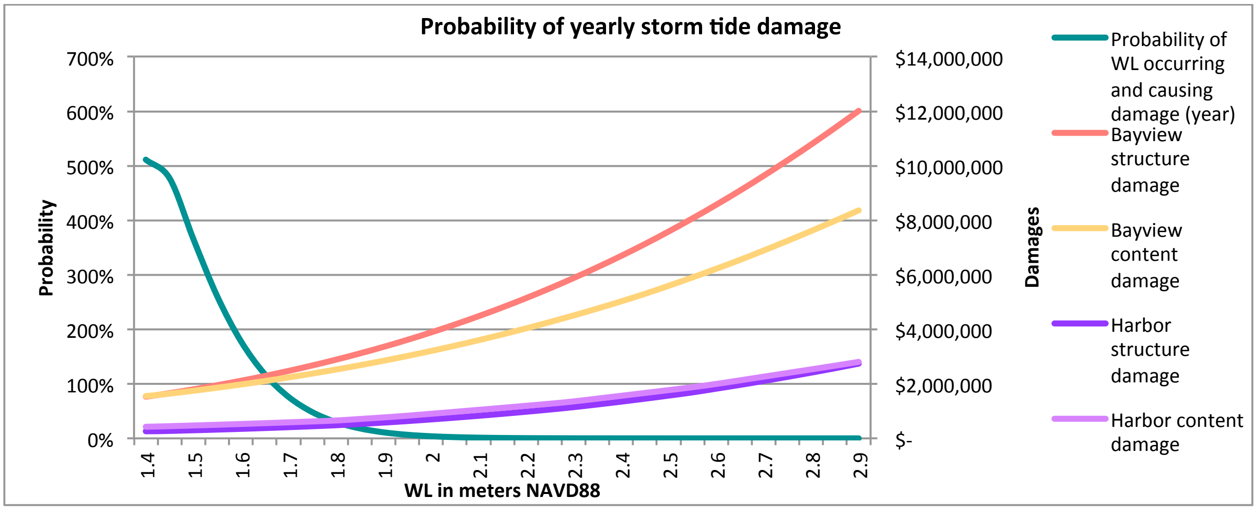
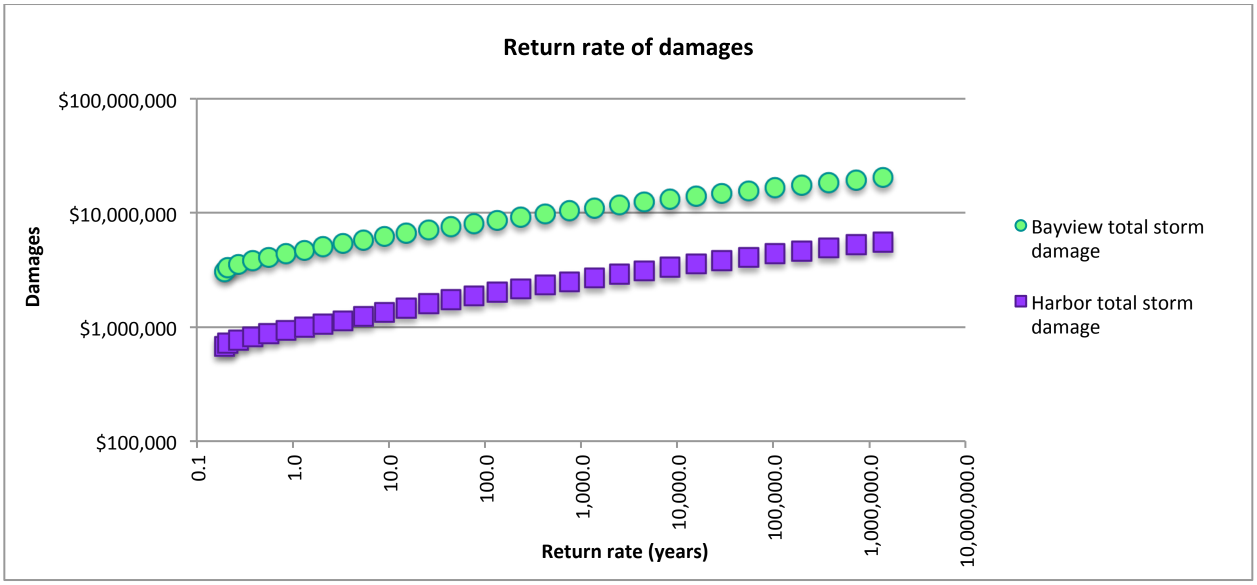


Figure 25 Return rate of damages. Damages for each water level are graphed against the associated return rate.



4.1. Expected damages

Expected annual storm flooding damages are found by multiplying the probability of a flood event occurring times the associated potential damages. Expected damages for both Bayview and Harbor decrease with water levels above 1.4 meters NAVD88. Total yearly-expected damages for Bayview are over $77 million, and nearly $17 million for Harbor. Expected damages are highest at the lower water levels because the probability of occurrence is very high and the rate of return is very low. The highest storm tide water levels have very low expected damages because the probability that they will occur is so small. Lower water levels have higher expected damages even though damages per event are lower, as they occur multiple times per year. In Bayview, expected damages for a low-level, 1.5 meter storm with a 365% chance of occurring each year are about $13 million dollars, whereas a high-level, 2.5 meter storm with a 0.01% probability only has yearly expected damages of $1,500.

The structure damages from each increment of storm tide flooding are a relative small percentage of total structure value in both case study areas. In Bayview, structure damages are 0.8% of total structure value with a flood level of 1.4 meters NAVD88, and 6.3% of property value for a storm tide of 2.5 meters NAVD88. The percentages of damage are slightly lower in Harbor as there are fewer structures located at lower elevations. Structure damages are 0.11% of total structure value with a flood level of 1.4 meters NAVD88, and 1.1% of property value for a storm tide of 2.5 meters NAVD88.

5. Discussion

The role of tides in storm flooding is inherently captured in tide gauge data. Tide gauges record the storm tide, which is a combination of the astronomical tide plus the storm surge. While the height of the storm surge is important, the height of the tidal cycle at the time that the storm hits can have an equally important or even greater influence on the water level of the storm tide. The highest observed storm tide since 1964 was 2.8645 meters above MSL. Assuming that this storm surge arrived at MHHW, the storm tide could have been only 1.73 meters above MSL if it had arrived at MSL, less than the MHW of 1.83 meters that occurs twice daily. The tidal cycle has a significant influence on the water level and costs of storm flooding.

In analyzing tide gauge data to find the height of storm tides, daily HHW data is appropriate to find the probability of the highest daily water level and the associated return rate. It does not however accurately capture the probability that the water level is representative of a storm tide that will cause damages. Based on the nature of nor'easters and hurricanes affecting the Connecticut coast, storms will often have an effect that lasts throughout several tidal cycles. If a storm event triggers back-to-back days of flooding, the damages will not be experienced as separate events, but rather as one flooding event with the highest observed water level causing the damage. Daily MHHW data above MPST can be cleaned to eliminate consecutive days of flooding, to better represent the idea that damages will likely be incurred one time for each flooding event (i.e. a nor'easter with back to back high tides exceeding MPST will not cause damages twice, but the highest level of flooding will result in damages).

The return rate of a storm tide is different than the return rate of a storm surge. Using storm tide data it is not possible to separate out the probability of a certain level storm surge occurring in tandem with a certain phase of the tidal cycle. The probabilities cannot be considered separately – this is one limitation of using tide gauge data.

The cost estimates of observed storm tides calculated using depth-damage functions and high resolution spatial and elevation data provide insight into the damages experienced over the past 18 years in the case study areas. These calculations show that damage costs increase at higher water levels. However, the difference in structure and content damages is less straightforward. Harbor structure and content damages are nearly the same and increase at nearly the same rate for all surge levels, while Bayview structure damages grow larger than content damages at higher water levels. This is due in part to the depth-damage functions that find residential structures with basements experience more content damages than structure damages when water levels are within the range of -183 to -121 cm below first floor height for 1 story structures and -244 to -121 cm below first floor height for 2 or more story structures. More damages are incurred for non-residential contents than structures in all cases except single store with basement when the water level is at 0 cm relative to first floor height. Since there are more residential properties at Bayview and more commercial properties around Harbor this finding seems reasonable.

6. Conclusions

The methodology developed to assess sea level rise losses in the previous essay has been applied here to assess coastal flooding storm tide damage costs. Analysis of tide gauge data provides insight into the storm tide height, probability of being reached, and probability of causing damages. Depth-damage functions are useful in estimating the direct damages to structures and contents from storm tide flooding. These functions take advantage of the detailed data on water level, elevation, land use, and structure characteristics and value. Here depth-damage functions have been used to estimate storm tide damage costs from observed water levels. Because this analysis is based on such detailed, local level data, it is possible to identify which structures, where they are located, at what water level, how often they will be flooded, and what the potential damage costs will be under different storm tide conditions. This information is useful in planning to protect structures against storm flooding damage

Part III: Assessing the future costs of storm tide flooding with sea level rise in coastal communities

Katie Johnson

Abstract

This is the third of three essays comprising a doctoral dissertation on the economic costs of local level damages and losses to sea level rise and storm surge flooding in coastal communities. This essay builds on the methodology and findings of the previous two essays. It utilizes depth-damage functions for estimating damages and losses, high-resolution topographical and spatial data, and tide gauge data to support the analysis of storm flooding damages under future conditions of sea level rise. The two case study areas presented in the first essay provide the local level data necessary to assess sea level rise losses and storm tide flooding damages. Storm water levels analyzed in the second essay are used here to construct the dataset of future storm tide levels. The IPCC RCP6.0 sea level rise trend is added to the observed storm tide water levels to project changes in the probabilities and return rates of storm tide water level being reached. The future direct economic costs of permanent and temporary coastal flooding are estimated.

1. Sea level rise and storm surge flooding

Coastal communities are vulnerable to sea level rise and storm surge flooding. Sea level rise is one of the most evident impacts of climate change and it is increasing the vulnerability of coastal property to storm flooding. While even current storms cause damages, coastal areas have the potential to incur higher economic costs due to the enhanced coastal flooding from sea level rise. Sea level rise will change the probability that a high water level will be reached or exceeded. Sea level rise will increase the damages caused by storms as the base level for storm effects becomes higher.

Sea level rise increases the frequency, extent, and height of coastal flooding. This analysis of coastal flooding is based solely on present-day storms and sea level rise. It does not consider changes in other factors that could influence coastal flooding, including future changes in storm characteristics, geomorphology, erosion, and sediment transport, subsurface water flows and subterranean infrastructure, aboveground infrastructure (e.g., sea walls), or coastal wetlands.

The Intergovernmental Panel on Climate Change (IPCC) (IPCC 2013) finds that an increase in the occurrence of sea level extremes is likely in the 21st century and very likely by 2100 as a result of an increase in the mean sea level. The effect of climate change on storm surge is less certain. It is difficult to detect long-term trends and to distinguish the attribution of climate change to tropical cyclones due to the large amplitude fluctuations in frequency and intensity, and the limited availability and quality of global historical records (Knutson et al. 2010). There remains uncertainty as to whether past changes have exceeded the expected natural variability of tropical cyclones, however future projections based on theory and high-resolution dynamical models consistently indicate that climate change will affect the frequency and intensity of tropical cyclones. Knutson et al. (Knutson et al. 2010) find that the globally averaged intensity of tropical cyclones is projected to shift towards stronger storms, with intensity increases of 2-11% by 2100, while frequency decreases by 6-34%. They also project that there will be an increased frequency of the most intense cyclones, and that precipitation rates will increase by 20% within 100 km of the storm center. While studies predict an increase in the global mean of maximum winds and rainfall rates of tropical cyclones due to climate change, the effect on storm surges still requires more research. The effect of sea level rise, rather than changes in storm characteristics, and thereby storm surge levels, has been the focus of most studies on the impact of climate change on coastal flooding risk (Lin et al. 2012) as this is more certain.

Coastal flooding caused by storm surges can be exacerbated by high tides, as was demonstrated in the second essay. As we look further into the future, sea level rise will increasingly play a role in this equation by raising the height of the sea level under all tidal and storm conditions. The purpose of this paper is to combine the sea level damage estimation methodology developed in the first essay with the storm tide water levels from the second essay, to estimate future sea level rise losses and storm tide damages in the two case study areas in Milford, Connecticut. First, the sea level rise and storm damage functions are reviewed briefly. Next, the sea level rise trend is added to the observed storm tide levels. The storm tide levels identified through the tide gauge analysis in the second essay are used to project the future storm tide levels, probabilities and return rates. No additional changes in storminess or storm surge frequency or intensity are considered in this analysis. Third, the storm damages are calculated for the two case study areas using the depth-damage functions and tide gauge water level data. Results are discussed and the paper concludes that sea level rise losses and storm tide damages will increase with sea level rise. The methodology of using depth-damage functions to assess both sea level rise losses and storm damages together provides estimates of the costs of inaction based on local level conditions and detailed data.

2. Storm damage and sea level rise loss functions

The value of some land and structures will be lost to future sea level rise, as demonstrated in the first essay. Storm surges will be higher as the base water level will be higher due to sea level rise. In this case there will be losses to sea level rise and damages from storms. To find the future costs, the methodology applied to assess flood damages and losses in this paper follows that developed in the first paper and applied to assess storm flooding damages in the second paper. Separate damage functions are used to estimate land loss and structure and content damage, incurred due to direct contact with floodwater. These are the costs of inaction against climate change induced sea level rise and the increased occurrence of high storm water levels due only to the influence of sea level rise. Depth-damage functions are based on observed flood damage data from the United States Army Corps of Engineers (USACE) for residential and non-residential structures and contents. These serve as the economic damage functions for estimating flood damages to structures and contents, and land use and structure characteristics are the used for the classification of elements to determine which damage function should be applied for structures and contents in each case. Damages are found under a business as usual scenario. These are the costs of inaction against climate change induced sea level rise and the increased occurrence of high water levels due only to the influence of sea level rise without any adaptation or flood protection measures. Damages are based on water levels relative to first floor height. All economic costs are reported in 2011 United States dollars (USD).

The difference here is that damages and losses can be incurred due to both sea level rise and storm surge flooding in any given year. Only structures and contents, not land, are damaged from storm flooding. Both land and structure can be lost to sea level rise. First, sea level rise losses are calculated following the methodology detailed in the first paper. Land inundated at mean perigean spring tide (MPST) loses its value in the year when the water height of MPST exceeds the ground elevation of that parcel of land. Structures that experience damages greater than 10% from MPST flooding also lose their value in that year when damages exceed 10%. Second, after calculating sea level rise losses, structure and content damages for structures not lost to sea level rise during that year are calculated. If for a given year the structure value is already lost to MPST, then it is not possible for the structure or contents to face damage costs, as the value is already zero. If a structure is not lost, then the damages costs are calculated based on the original 2011 value.

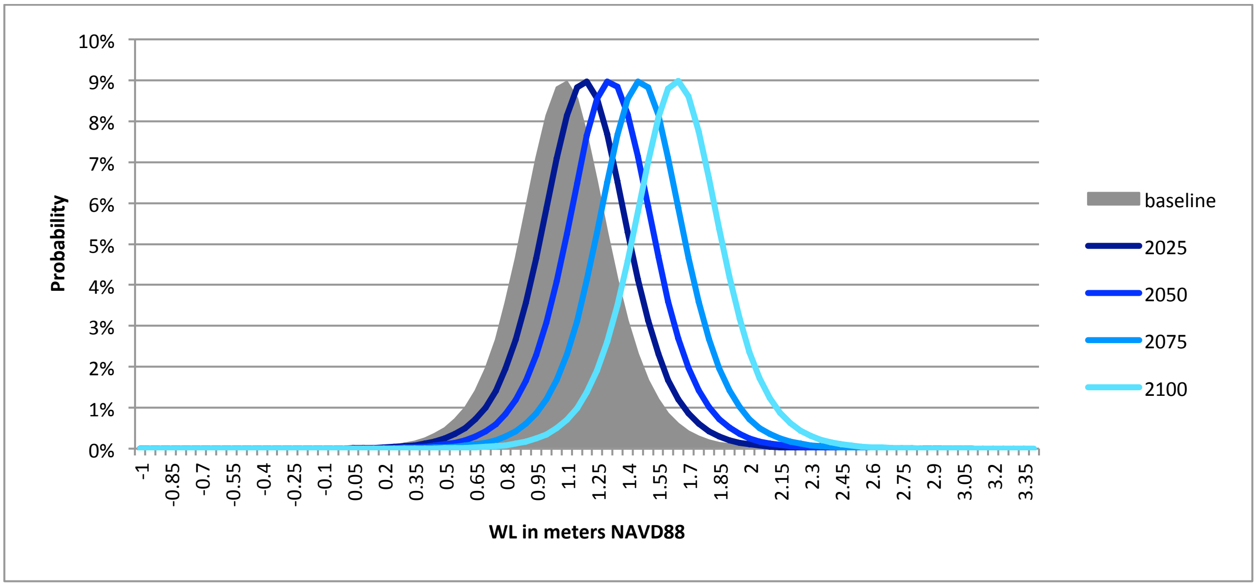
3. Storm tides with sea level rise

This study captures the effect of sea level rise on storm flooding in terms of the increase in storm tide height, rather than changes in storm characteristics. It considers the historically observed storm tide water levels and makes no assumptions about the changes that will occur in the intensity of future storms because of the uncertainty in the science. This study assumes that storm surge risk is changed only by sea level rise and not through changes in storminess.

To estimate the water level height of future storm tides with sea level rise, the range and probability of storm tides observed from 1996 to 2013 are projected into the future to reflect the changes in water level height due to sea level rise. The full daily higher high water (HHW) data set presented in the second essay is joined with the IPCC RCP6.0 sea level rise scenario presented in the first essay to project the future water level heights, probabilities, and return rates. The storm tide water levels are divided into categories covering 5-centimeter increments of flooding.

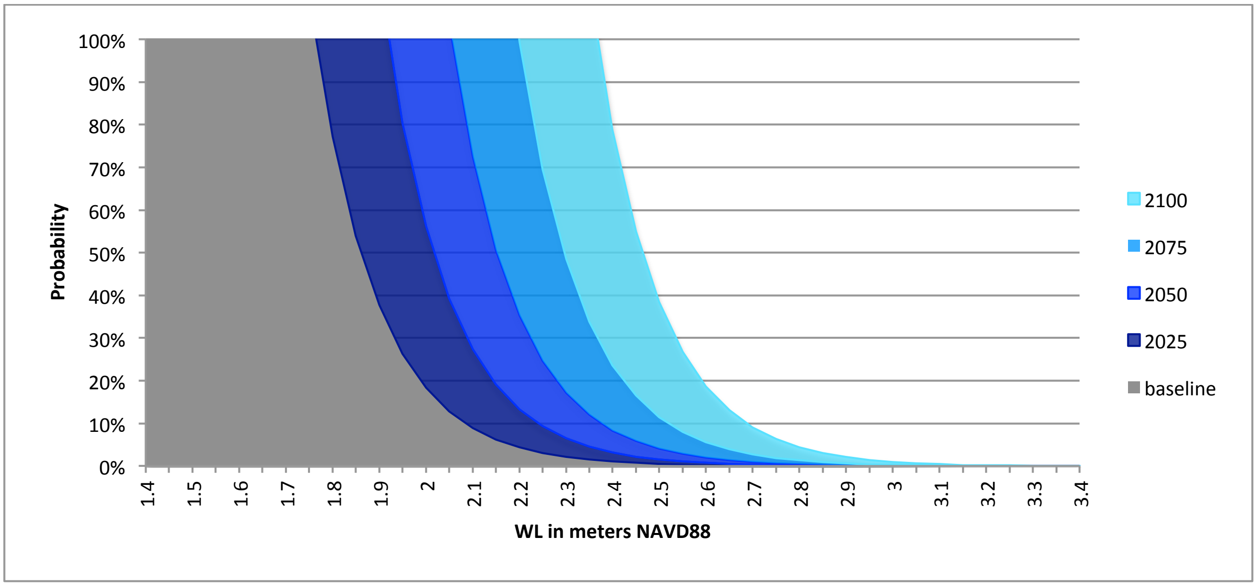
In the 1996 to 2013 daily data set, there was a 9% chance that the highest daily water level would be 1.1 meters NAVD88. With sea level rise, the probability distribution of the highest daily water level shifts to the right. The most probable highest daily water level becomes 1.2 meters in 2025, 1.3 meters in 2050, 1.45 meters in 2075, and 1.65 meters in 2100. The probability and frequency of higher level storm tides increase with sea level rise.

Figure 26 Probability of highest daily water level with sea level rise. This graph shows the shift in the probability of highest daily water level with sea level rise in 2025, 2050, 2075, and 2100, based on 1996 to 2013 daily-sorted data above MPST.



The probability of a high storm tide water level being reached in any given year increases drastically with sea level rise. For example, a storm tide that is 2.5 meters NAVD88 has a 6% chance of being reached in 2025, and 15% chance of being reached in 2050, a 45% chance of being reached in 2075, and more than a 100% chance of being reached in 2100. The probability of high storm tides increases and the return rate decreases in the future.

Figure 27 Yearly probability of a water level being reached with sea level rise.

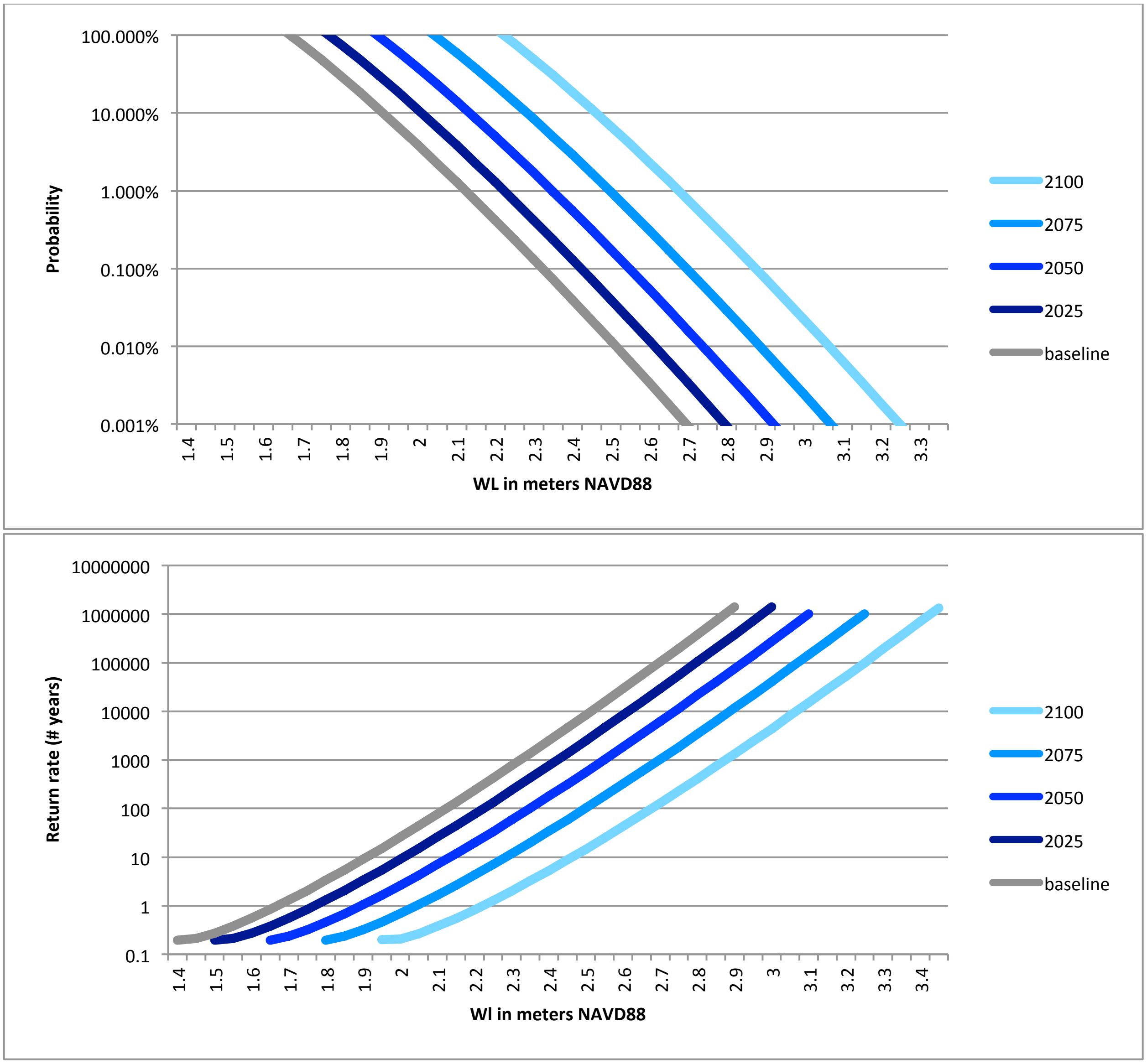


3.1. Storm tides causing damage with sea level rise

The second essay on storm tide damage presented the idea that flood damages will not be incurred every time that a high water level is reached, but rather only for flood events. Flood events are defined as non-consecutive days with water levels in exceedance of the MPST. The daily highest water level data set was cleaned to eliminate consecutive days with high water levels above MPST, likely caused by the same storm system, so as not to overestimate damages. In the case of consecutive days with high water levels above MPST, the day with the highest water level was kept and the others discarded. The resulting data set are the flood events or water levels in exceedance of MPST that cause flood damages.

To find the yearly probability and return rate of these flood events, the baseline probability of water level being reached is multiplied by the baseline probability of a high water level causing damages and the probability of each flood event water level height. The return rate is 1 divided by the probability.

Figure 28 Probability and return rate of flood events with sea level rise. The top graph shows the yearly probability of a storm tide occurring and causing damage. The graph on return rate (bottom) shows how often each flood level will occur.

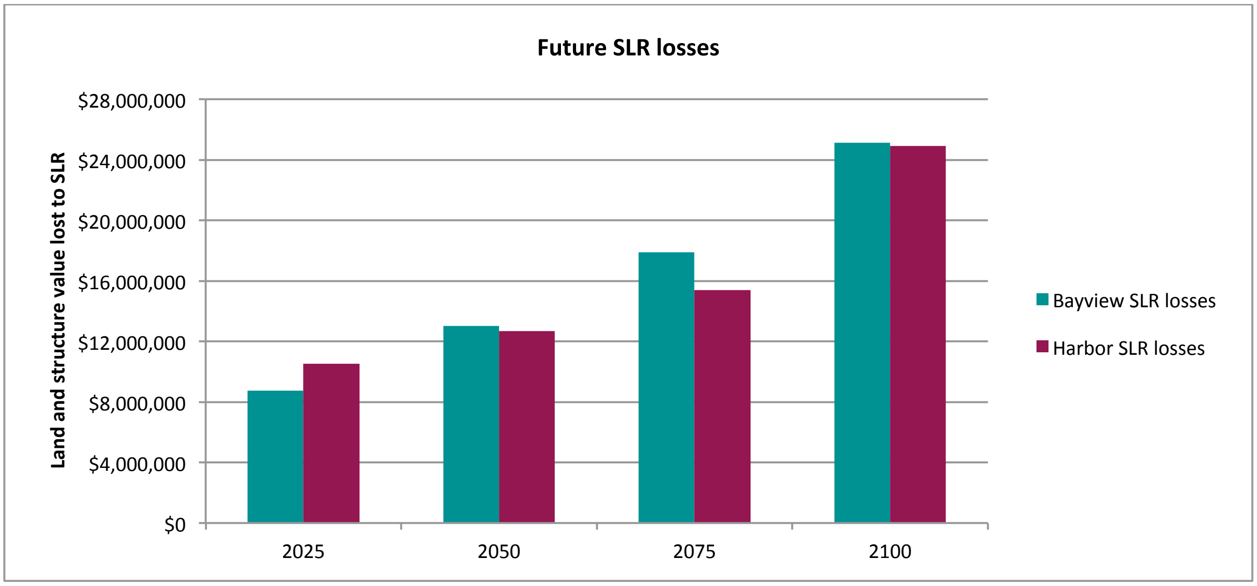


Sea level rise is added to the baseline water level data set of storm events. The XLSTAT program is used to fit the data with a three-parameter Weinbull distribution, as this type of probability distribution was found to best fit the original storm event data set. This gives the probability of each water level height for flood events in 2025, 2050, 2075, and 2100. The baseline water level for floods causing damage is 1.4 meters NAVD88, in 2025 it is 1.5, in 2050 it is 1.65, in 2075 it is 1.8, and in 2100 it is 1.95 meters NAVD88. This is because sea level is rising and the losses to sea level rise will increase, thereby raising the water level from which storm damages will occur. In the future, what is currently a 1-in-100 year flood event, or a flood event that has 1% annual probability of occurring, will become more frequent do to the influence of sea level rise.

4. Future sea level rise losses and storm damages

Impact costs are incurred due to inundation of land and structures from sea level rise and structural and content damage from storm surge. All costs are calculated in the absence of flood protection, or in a business as usual scenario. Using the IPCC RCP6.0 sea level rise scenario, direct losses are calculated for inundated land and structures and structures and contents damaged by storms. Storm tide water levels used to calculate damage costs are based on historical observations, and are considered in addition to the sea level rise projections up to 2100. These damage costs can serve as a baseline reference from which the costs and benefits of different adaptation policy or actions can be evaluated in later studies. Although the idea that flood protection will not be employed is not entirely realistic, as evidenced by homeowners in the case study neighborhoods who have in some cases raised their homes after big storms, it does however serve as a baseline showing the costs of inaction from which adaptation options can later be evaluated.

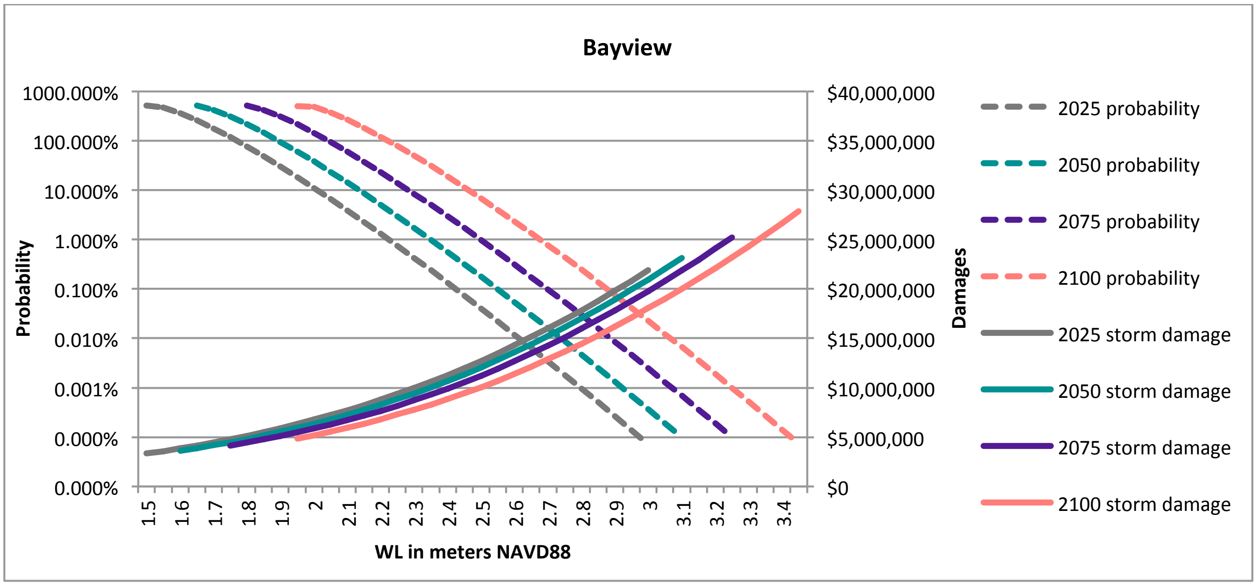
Figure 29 Sea level rise losses for 2025, 2050, 2075, and 2100. Land and structures lost to sea level rise, as reported in the first essay, are shown here. Storm damages are additional to the sea level rise losses in each future time period.

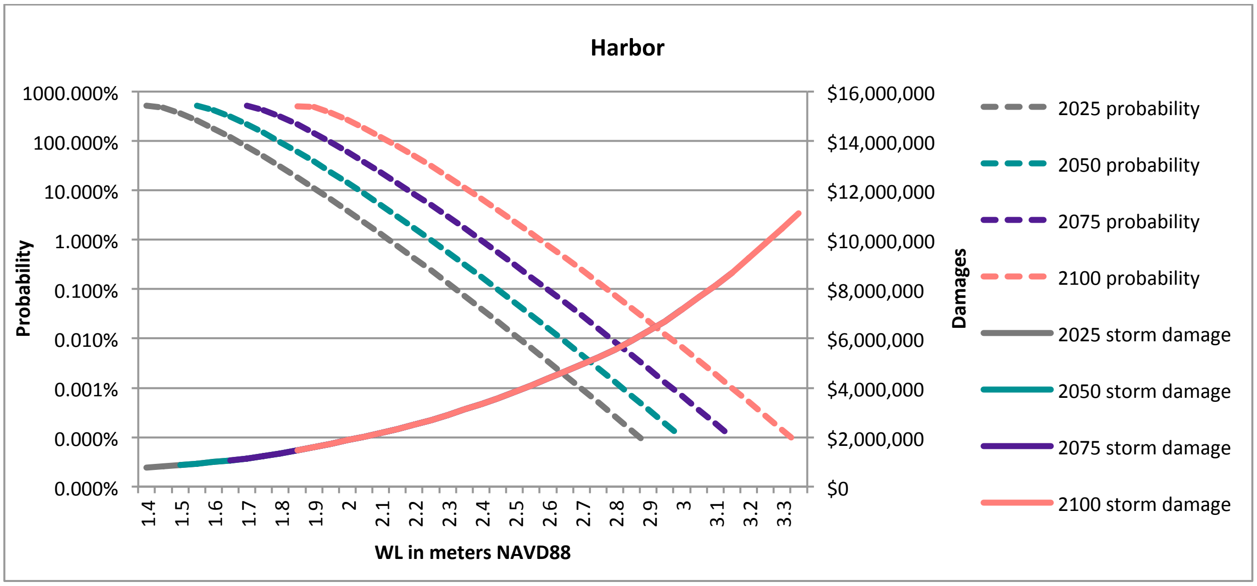


Results are presented in 5-centimeter storm tide height intervals. The future years (2025, 2050, 2075, and 2100) correspond with increases in water level height under sea level rise, in addition to the baseline storm tide water level. Sea level rise losses are discussed in detail in the first essay. The results are the same here. It is necessary to consider them when projecting future costs of storm tide as care must be taken to exclude structures lost to sea level rise from consideration of structure damage from storm flooding. Sea level rise losses and storm damages cannot be summed because sea level rise is a permanent loss, whereas storm damages can be incurred more than one time. For example, in Bayview, sea level rise losses in 2050 will be $13 million. Any time a storm tide of 2.25 meters NAVD88 occurs, with a 5% probability of occurring in 2050, the potentially damages are about $7.9 million every time that water level is reached.

In both case study areas, storm damages increase with storm tide height. Higher water levels equal higher damage costs. In Bayview, storm damages increase with both storm tide water level height and future sea level rise. In Harbor, storm tide damages do not change much as sea level rises, and increase less drastically with storm tide height. This is because the value of structures at risk to sea level rise in Harbor are low, so almost no structures are lost to sea level rise, and instead are still vulnerable to storm tide damages.

Figure 30 Probability of future storm tide damages with sea level rise in 2025, 2050, 2075, and 2100. The graphs show the yearly probability of a flood event occurring and the potential damages for Bayview (top) and Harbor (bottom) over time.

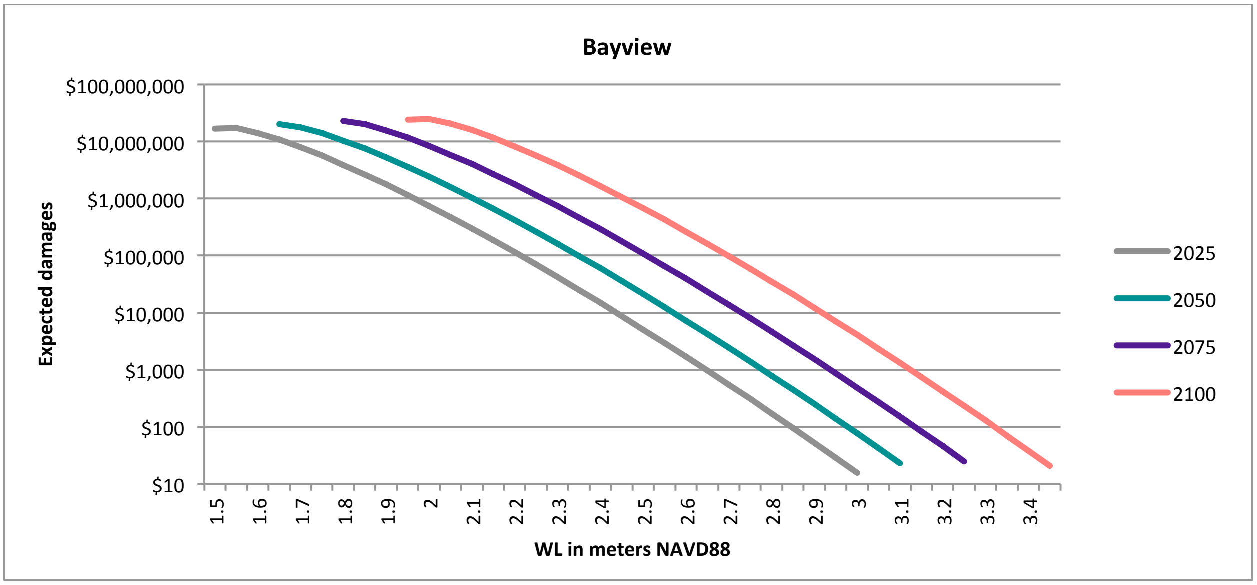


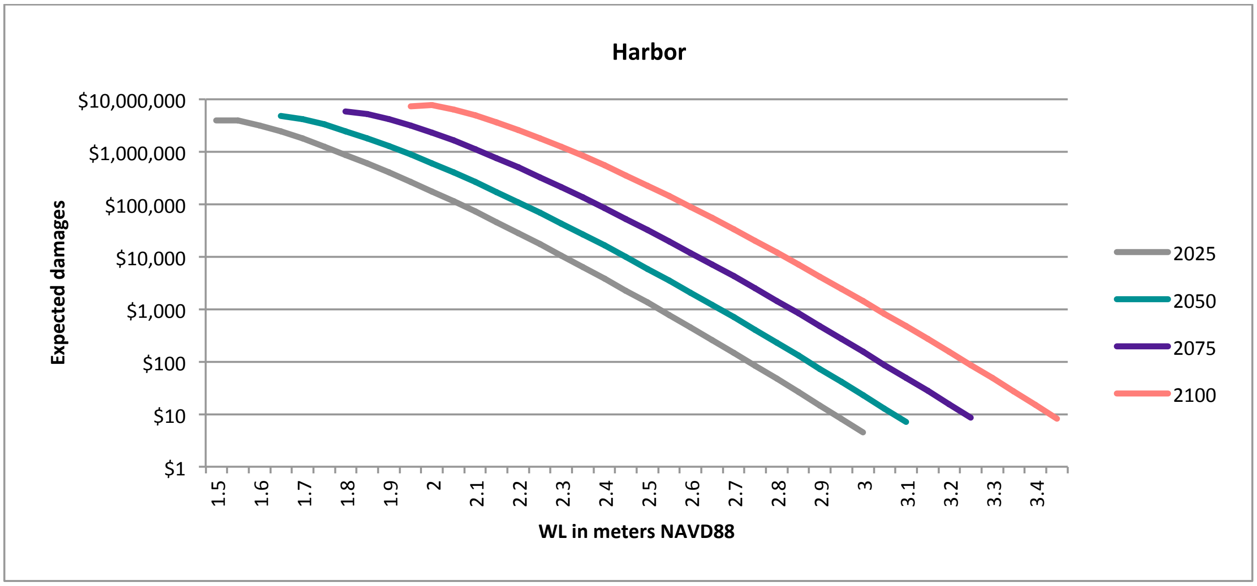


4.1. Expected damages

Expected damages are storm-flooding damages anticipated each year. They are calculated based on the probability of a flood event occurring and the associated damages. In both Bayview and Harbor, the expected damages decrease with increasing water levels. Although the damages increase as storm tide levels increase, the probabilities of those higher water levels are very low and decreasing, leading to an overall decreasing trend of expected damages with increasing storm tide levels in 2025, 2050, 2075, and 2100.

Figure 31 Expected storm tide damages with sea level rise. Expected damages for Bayview (top) and Harbor (bottom) are shown for storm flooding with sea level rise in 2025, 2050, 2075, and 2100.





5. Discussion

With sea level rise, the probability distribution of storm tide height shifts to the right, and the probability and frequency of higher-level storm tides increase. Sea level rise losses and storm flooding damages will be incurred. The economic loss of land and structures can occur only one time, while structures and content damages can be incurred repeatedly. Both sea level rise and storm tides have significant economic costs that will continue to increase in the future under current conditions. This assessment shows that the costs of inaction are significant. Differences in the direct damage estimates in the two case study areas are due to the number and values of properties included in the case study areas, land use (residential versus non-residential), and the topography and elevation.

Storm damages are higher in the near term in Bayview. This is likely because the high value properties on the coastline have not yet been lost to sea level rise. Once the value of these properties has been lost to SLR, the value at risk to future storms is lower. Additionally, as sea level rise inundates the coast, the further inland properties tend to have a higher elevation, so damages from storms will be lower. Harbor damages do not change much as sea level rise increases because not many structures are lost to sea level rise.

Regarding the storm data for Harbor, the storm damage for a given water level does not change much between years. This is because the sea level rise losses are low. The sea level rise losses are mostly land losses, not many structure losses, so storm damage does not vary significantly.

6. Conclusions

This essay to combines the sea level loss estimation methodology developed in the first essay with the storm tide water levels from the second essay to estimate future sea level rise losses and storm tide damages in the two Milford, Connecticut case study areas. Depth-damage functions are used to estimate the values of both land and structures lost to sea level rise and direct damages to structures and their contents from storm tide flooding. This methodology allows for a consistent assessment of sea level rise and storm losses together, using the same data set and same economic damage functions. These functions take advantage of the detailed, local level data on water level, elevation, land use, and structure characteristics and value.

Future studies on managing coastal communities and adapting to sea level rise and storm surge can take advantage of this methodology and use the results to geographically identify which land and structures are at risk, where they are located, and at what water level and how often they will be flooded. This methodology is easily transferable to other coastal communities where high-resolution data is available. As property data is derived from GIS, the results are easily transferable back to that format. High resolution cost data can be used to consider the costs and benefits of adapting to higher water levels at the project scale.

References

Abraham, J, and P Hendershott. 1993. “Patterns and Determinants of Metropolitan House Prices, 1977 to 1991.” In *Real Estate and the Credit Crunch*, edited by LE Browne and ES Rosengren, 18–42. Boston: Federal Reserve Bank of Boston.

Adger, W. Neil, Nigel W Arnell and Emma L Thompkins. 2004."Successful adaptation to climate change across scales." *Global Environmental Change* 15: 77-86.

Baede, A.P.M., ed. 2007. “Annex I Glossary.” In *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmantal Panel on Climate Change*. Cambridge University Press.

Boettle, M., J. P. Kropp, L. Reiber, O. Roithmeier, D. Rybski, and C. Walther. 2011. “About the Influence of Elevation Model Quality and Small-Scale Damage Functions on Flood Damage Estimation.” *Nat. Hazards Earth Syst. Sci.* 11 (12): 3327–34.

Bosello, Francesco, Carlo Carraro and Enrica De Cian. 2009. "An analysis of adaptation as a response to climate change." Copenhagen Concensus Center.

Bowditch, Nathaniel. 2002. “Chapter 9 Tides and Tidal Currents.” In *The American Practical Navigator*, 129–50. Paradise Cay Publications.

Burkett, V.R., and M.A. Davidson. 2012. *Coastal Impacts, Adaptation, and Vulnerabilities: A Technical Input to the 2013 National Climate Assessment*. Cooperative Report to the 2013 National Climate Assessment.

Darwin, Roy F., and Richard S. J. Tol. 2001. “Estimates of the Economic Effects of Sea Level Rise.” *Environmental and Resource Economics* 19 (2): 113–29.

Dawson, W.R. 2003. *Economic Guidance Memorandum 04-01, Generic Depth-Damage Relationships for Residential Structures with Basements*. Memorandum. U.S. Army Corps of Engineers.

De Moel, H., and J. Aerts. 2011. “Effect of Uncertainty in Land Use, Damage Models and Inundation Depth on Flood Damage Estimates.” *Natural Hazards* 58 (1): 407–25.

Department of Homeland Security, and FEMA. 2013. *Multi-Hazard Loss Estimation Methodology Flood Model Hazus®-MH MR5 Technical Manual*. Washington, D.C. http://www.fema.gov/media-library-data/20130726-1748-25045-4777/hazusmr5_fl_tm.pdf.

Gornitz, Vivien, Steve Hale, Kate Larsen, Naomi Levine, Cynthia Rosenzweig, and Lauren Sacks. 2004. *Bracing for Climate Change in the Constitution State*. Environmental Defense.

Hallegatte, Stéphane, Fanny Henriet, and Jan Corfee-Morlot. 2011. “The Economics of Climate Change Impacts and Policy Benefits at City Scale: A Conceptual Framework.” *Climatic Change* 104 (1): 51–87.

Hallegatte, Stéphane, Nicola Ranger, Olivier Mestre, Patrice Dumas, Jan Corfee-morlot, Celine Herweijer, and Robert Muir Wood. 2011. “Assessing Climate Change Impacts, Sea Level Rise and Storm Surge Risk in Port Cities: A Case Study on Copenhagen.” *Climatic Change* 104 (1): 113–37. doi:http://dx.doi.org/10.1007/s10584-010-9978-3.

Hallegatte, Stéphane, Nicola Ranger, Olivier Mestre, Patrice Dumas, Jan Corfee-Morlot, Celine Herweijer, and Robert Muir Wood. 2010. “Assessing Climate Change Impacts, Sea Level Rise and Storm Surge Risk in Port Cities: A Case Study on Copenhagen.” *Climatic Change* 104 (1): 113–37.

Huizinga, H.J. 2007. *Flood Damage Functions for EU Member States*. HKV Consultants for JRC-Institute for Environment and Sustainability.

IPCC. 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by M. L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC. 2013. “Sea Level Change.” In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by JA Church, PU Clark, A Cazenave, JM Gregory, S Jevrejeva, A Levermann, MA Merrifield, et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Jabeen, Huraera, Johnson Cassidy, and Adriana Allen. 2010. “Built-in Resilience: Learning from Grassroots Coping Strategies for Climate Variability.” *Environment and Urbanization* 22 (2): 415–31.

Johnson, J.F. 2000. *Economic Guidance Memorandum 01-03, Generic Depth-Damage Relationships*. Memorandum. U.S. Army Corps of Engineers. http://planning.usace.army.mil/toolbox/library/EGMs/egm01-03.pdf.

Kiefer, J.C., and J.S. Willett. 1996. *Analysis of Nonresidential Content Value and Depth-Damage Data for Flood Damage Reduction Studies*. IWR Report 96-R-12. U.S. Army Corps of Engineers.

Knutson, Thomas R., John L. McBride, Johnny Chan, Kerry Emanuel, Greg Holland, Chris Landsea, Isaac Held, James P. Kossin, A. K. Srivastava, and Masato Sugi. 2010. “Tropical Cyclones and Climate Change.” *Nature Geoscience* 3 (3): 157–63.

Leichenko, Robin, and Adelle Thomas. 2012. “Coastal Cities and Regions in a Changing Climate: Economic Impacts, Risks and Vulnerabilities.” *Geography Compas* 6 (6): 327–39.

Lichter, Michal, and Daniel Felsenstein. 2012. “Assessing the Costs of Sea-Level Rise and Extreme Flooding at the Local Level: A GIS-Based Approach.” *Ocean & Coastal Management* 59 (April): 47–62.

Lin, Ning, Kerry Emanuel, Michael Oppenheimer, and Erik Vanmarcke. 2012. “Physically Based Assessment of Hurricane Surge Threat under Climate Change.” *Nature Climate Change* 2 (6): 462–67.

McGranahan, G., D. Balk, and B. Anderson. 2007. “The Rising Tide: Assessing the Risks of Climate Change and Human Settlements in Low Elevation Coastal Zones.” *Environment and Urbanization* 19 (1): 17–37.

Merz, B., H. Kreibich, R. Schwarze, and A. Thieken. 2010. “Review Article ‘Assessment of Economic Flood Damage.’” *Nat. Hazards Earth Syst. Sci.* 10 (8): 1697–1724. doi:10.5194/nhess-10-1697-2010.

Michael, Jeffrey A. 2007. “Episodic Flooding and the Cost of Sea-Level Rise.” *Ecological Economics* 63 (1): 149–59.

Neumann, James E., Daniel E. Hudgens, John Herter, and Jeremy Martinich. 2010. “Assessing Sea-Level Rise Impacts: A GIS-Based Framework and Application to Coastal New Jersey.” *Coastal Management* 38 (4): 433–55.

Nicholls, Robert J., and Anny Cazenave. 2010. “Sea-Level Rise and Its Impact on Coastal Zones.” *Science* 328 (5985): 1517–20.

Nicholls, Robert J., P.P. Wong, V. Burkett, C.D. Woodroffe, and J. Hay. 2008. “Climate Change and Coastal Vulnerability Assessment: Scenarios for Integrated Assessment.” *Sustainability Science* 3 (1): 89–102.

Nordhaus, William. 2007. “Critical Assumptions in the Stern Review on Climate Change.” *Science* 317: 201–2.

Parsons, George R., and Michael Powell. 2001. “Measuring the Cost of Beach Retreat.” *Coastal Management* 29: 91–103.

Peltier, W.R. 2001. “Chapter 4 Global Glacial Isostatic Adjustment and Modern Instrumental Records of Relative Sea Level History.” In *International Geophysics*, edited by Michael S. Kearney and Stephen P. Leatherman Bruce C. Douglas, Volume 75:65–95. Academic Press.

Ross, D.A. 1995. *Introduction to Oceanography*. New York, NY: HarperCollins.

Sallenger, Asbury H., Kara S. Doran, and Peter A. Howd. 2012. "Hotspot of Accelerated Sea-Level Rise on the Atlantic Coast of North America." *Nature Climate Change* 2 (12): 884–88.

Shelton, John P. 1968. "The Cost of Renting versus Owning a Home." *Land Economics* 44 (1): 59.

Smith, DI. 1994. "Flood Damage Estimation - A Review of Urban Stage-Damage Curves and Loss Functions." *Water SA* 20 (3): 231–38.

Solomon, S, D Qin, M Manning, Z Chen, M Marquis, K.B Averyt, M Tignor, and H.L Miller, eds. 2007. "5.5 Changes in Sea Level." In *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Stern, N. 2007. *The Economics of Climate Change: The Stern Review*. Cambridge, UK: Cambridge University Press.

Stern, N. 2009. *The Global Deal: Climate Change and the Creation of a New Era of Progress and Prosperity*. New York, USA: Public Affairs.

Sterr, Horst. 2008. "Assessment of Vulnerability and Adaptation to Sea-Level Rise for the Coastal Zone of Germany." *Journal of Coastal Research* 242 (March): 380–93. doi:10.2112/07A-0011.1.

Sumich, J.L. 1996. *An Introduction to the Biology of Marine Life*. sixth edition. Dubuque, IA.

The Natural Resources Agency. 2012. *Central Valley Flood Protection Plan, Attachment 8F: Flood Damage Analysis*. STATE OF CALIFORNIA, THE NATURAL RESOURCES AGENCY, DEPARTMENT OF WATER RESOURCES.

Thieler, E. Robert. 2000. *National Assessment of Coastal Vulnerability to Future Sea Level Rise*. USGS.

Thurman, H.V. *Introductory Oceanography*. seventh edition. New York, NY: Macmillan.

Vuuren, Detlef P., Jae Edmonds, Mikiko Kainuma, Keywan Riahi, Allison Thomson, Kathy Hibbard, George C. Hurtt, et al. 2011. "The Representative Concentration Pathways: An Overview." *Climatic Change* 109 (1-2): 5–31.

Watkiss, P., F. Bosello, B. Buchner, M. Catenacci, A. Goria, Onno Kuik, and Etem Karakaya. 2007. *Climate Change: The Cost of Inaction and the Cost of Adaptation*. EEA Technical report No 13/2007. European Environment Agency.

White, Gilbert. 1945. "Human Adjustments to Floods." *University of Chicago, Dept. of Geography, Research Paper No. 29*.

White, Gilbert. 1964. "Choice of Adjustments to Floods." *University of Chicago, Dept. of Geography, Research Paper No. 93*.

White, Robert E. 2012. *Eldridge Tide and Pilot Book 2013*. Eldridge Tide & Pilot Book.

Yohe, G, J Neumann, and P Marshall. 1999. "The Economic Damage Induced by Sea Level Rise in the United States." In *The Impact of Climate Change on the United States Economy*, edited by R. Mendelsohn and J Neumann. Cambridge University Press.

Yohe, G. 1989. *The Cost of Not Holding Back the Sea: Phase 1 Economic Vulnerability. In: The Potential Effects of Global Climate Change on the United States.* Report to Congress. Appendix B: Sea Level Rise. EPA 230-05-89-052. Washington, D.C.: U.S. Environmental Protection Agency.

Yohe, Gary, James Neumann, and Holly Ameden. 1995. "Assessing the Economic Cost of Greenhouse-Induced Sea Level Rise: Methods and Application in Support of a National Survey." *Journal of Environmental Economics and Management* 29 (3): S78–S97.

Yohe, Gary, James Neumann, Patrick Marshall, and Holly Ameden. 1996. "The Economic Cost of Greenhouse-Induced Sea-Level Rise for Developed Property in the United States." *Climatic Change* 32 (4): 387–410.

Yohe, Gary W., and Michael E. Schlesinger. 1998. "Sea-Level Change: The Expected Economic Cost of Protection or Abandonment in the United States." *Climatic Change* 38 (4): 447–72.