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COASTAL WETLANDS AND FLOOD DAMAGE REDUCTION

Using Risk Industry-based Models to Assess Natural Defenses in the Northeastern USA

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EXECUTIVE SUMMARY

We quantify the economic benefits of coastal wetlands in reducing property damage from storms and flooding in the northeastern United States (USA). In 2012, Hurricane Sandy hit the northeastern coast of the USA causing devastating flooding and becoming the second costliest hurricane in USA history. As the likelihood and costs of hurricanes like Sandy continue to increase, there is a need for a more effective suite of strategies for risk reduction. There is great interest in the role of coastal wetlands and reefs as natural defenses in reducing some of this risk especially where these ecosystems are being degraded or lost. While there is substantial evidence for the physical ability of wetlands to attenuate waves there have been fewer assessments of the economic costs and benefits of their role in reducing flood damage to properties. This has limited their consideration by public agencies and private industries.

Using risk industry-based flood models, we predict the increase in damages from Hurricane Sandy if wetlands had been lost. We estimate that coastal wetlands saved more than US$ 625 million in avoided flood damages from Hurricane Sandy across the northeastern USA. For census tracts with wetlands, there was on average a 10% reduction in property damages across the region. The damage reduction benefits varied by state and reached as high as 29% for Maryland. We also find that the benefits of wetland conservation accumulate upstream. Some townships with few wetlands within their boundaries nevertheless benefited from the cumulative surge reduction of wetlands downstream. Wetlands can also increase flood heights and damages to some properties by blocking the flow of water and causing it to pile up, which is similar to effects observed for artificial defenses such as seawalls or levees.

To examine the benefits of wetlands beyond an individual hurricane, we estimate the effects of salt marshes on annual flood losses to properties in Ocean County, New Jersey for 2000 storm events. Areas behind existing marshes are predicted to have an average of 20% less property losses than areas where marshes have been lost. These benefits of salt marsh conservation for damage reduction are much higher for properties at lower elevations.

Together, these studies illustrate the direct and indirect flood risk reduction benefits that coastal wetlands provide by reducing flood heights and also by decreasing exposure. We show that coastal wetlands can reduce property damage from storms and that these effects can be readily incorporated into the insurance industry's risk models. These results help inform (i) risk reduction and conservation management priorities and (ii) the development of incentives for the conservation and restoration of natural defenses.

In a nutshell,

- Risk industry-based tools are used to quantify the economic benefits of coastal wetlands for property damage reduction from hurricane-induced flooding in the northeastern USA.
- It is estimated that during Hurricane Sandy, temperate coastal wetlands saved more than $625 million in flood damages and hundreds of millions of dollars in New Jersey alone. Where they remain, wetlands reduced damages by more than 10% on average.
- In Ocean County, New Jersey, salt marsh conservation can significantly reduce average annual flood losses by more than 20%.

INTRODUCTION

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Coastal flooding causes a significant amount of economic damage globally (Swiss Re, 2015). The Atlantic coastline of the USA is an especially high-risk area for storm-induced flooding damage and this risk will continue to increase with climate change and increasing development (Hallegatte et al., 2013; Hauer et al., 2016). The damage from storms in the northern Atlantic like Hurricane Sandy is largely caused by storm surges and is further aggravated by rising sea levels (Blake et al., 2013; Woodruff et al., 2013). In addition, population growth and urban development on these coastlines have a two-fold effect in increasing this risk by increasing the value of assets within high risk areas and by damaging ecosystems (Valiela et al., 2009) that could act as natural defenses (Barbier et al., 2010; Hauser et al., 2015). Structural defense measures like shoreline armoring can be very costly (Jonkman et al., 2013) and often have adverse effects on coastal ecosystems (Martins et al., 2009; Gittman et al., 2016). Hence, there is growing interest in cost effective risk reduction measures that include natural and nature-based defenses and that simultaneously address habitat conservation needs (Cheong et al., 2013; Temmerman et al., 2013; National Research Council, 2014; Spalding et al., 2014; US Army Corps of Engineers, 2015a).

While the role of wetlands and reefs for risk reduction is increasingly being recognized, the quantitative assessment and implementation of natural defenses is not common practice (European Commission, 2013; Beck et al., 2015; US National Science and Technology Council, 2015). Flood risk models and assessments by insurance providers and other private businesses have a significant influence on risk reduction measures and development choices in coastal areas (Bagstad et al., 2007; Crichton, 2008; Aerts et al., 2014). However, there are few industry analyses of the protective capacity of these ecosystems and the benefits of conserving them (however, see Fischbach, 2010; Reguero et al., 2014).

There is strong evidence that reefs and wetlands help protect coastlines under everyday circumstances by reducing wave energy and raising elevations (Shepard et al., 2011; Ferrario et al., 2014; Narayan et al., 2016), but there is less understanding of their effects on surge or flood reduction during extreme events. Most of these studies are in mangrove wetlands (see McIvor et al., 2012a, 2012b). For instance, Krauss et al. (2009), using observations during Hurricanes Katrina (2004) and Wilma (2005), showed that intact mangrove wetlands can reduce surge heights by up to 9.4 cm/km inland. Using a numerical model Zhang et al. (2012) showed that mangrove wetlands are more effective at reducing surge heights for fast moving storms (~40 km/hr) and that surge reduction varies non-linearly with wetland size. Relative to mangroves, there is much less knowledge about the capacity or value of marshes and other temperate coastal wetlands for reducing flood heights and damages. Loder et al. (2009a) simulated an idealized salt marsh to show that flood heights are reduced by higher bottom friction from vegetation and greater wetland continuity. In a recent field study, Stark et al. (2015) measured surge attenuation rates from 5 cm/km to 70 cm/km in a large tidal marsh.

Crucially, there are few studies of the economic value of wetlands for reducing flood damage, which is hampering their integration into risk management policy and practice. Some mangrove restoration projects observe that restored mangroves contribute to damage reduction during tropical cyclones (Das and Vincent 2009; Barbier et al., 2013; Brody et al., 2013; SNAPP Coastal Defenses Working Group, 2014). While these are useful demonstrations of the potential of ecosystems to protect coastlines they often do not quantify the value of this protection. The most common approach for assessing the storm protection value of wetlands is the replacement cost method, which estimates the value of a wetland based on the cost of the equivalent artificial structure that would replace its function. However, the major flaw in this approach is that it typically assumes that project costs estimated in one location can be transferred to estimates of benefits across large areas such as all national wetlands (Barbier, 2012; Beck and Lange, 2015). It is increasingly possible and recommended to follow standard risk assessment approaches for estimating the flood reduction benefits of ecosystems (Beck and Lange, 2015; Sanchirico et al., 2015).

This study addresses these gaps by quantifying the economic value of temperate coastal wetlands for property damage reduction using an insurance industry-based flood risk model. We first estimate these benefits in terms of avoided property damages for a catastrophic storm event, Hurricane Sandy. We calculate the flood losses from Hurricane Sandy for two scenarios: a "Present" scenario that considers the present extent of coastal wetlands and a "Wetland Loss" scenario where all coastal wetlands are replaced by open water. We also investigate the annual avoided damage benefits of salt marshes for a wider set of storm events in Ocean County, New Jersey (NJ). Together, the two studies describe the immediate economic impact of coastal wetlands during Hurricane Sandy at the regional scale and provide insights into their wider effects in reducing annual flood losses at the local scale.

METHODS

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We examine the effects of coastal wetlands on flood damage to properties in two ways (Table 1): (i) regionally across the entire northeastern USA coastline for a single storm event, Hurricane Sandy, and; (ii) locally for Ocean County, NJ across several hundred storms. Both studies use a storm surge and flood model developed by Risk Management Solutions (RMS) to estimate flood extents and heights during hurricanes (http://www.rms.com/perils/flood). These are combined with economic data from RMS' in-house databases on property exposure and damage functions to estimate flood losses.

The RMS Flood Model and Loss Estimates

The RMS flood model (hereafter "flood model") is used to estimate flood extents and peak surge heights for specific historical events such as Hurricane Sandy. The model is used widely by businesses and agencies across the northeastern USA. The flood model is based on a state of the art hydrodynamic model that resolves the depth-averaged shallow water equations and calculates the propagation of storm surges from the coastal shelf on to land (Danish Hydraulic Institute, 2016a). It uses extensive datasets on wind fields, property values, bathymetry, elevation and land cover. The model extends from the offshore continental shelf up to inland elevations which are well above the highest possible extent of flooding by storm surge. The bathymetry for the model is obtained from the Danish Hydraulic Institute (DHI) C-MAP dataset (Danish Hydraulic Institute, 2016b) and the land elevation from the U.S. Geological Survey National Elevation Dataset.

The flood model accounts for storm surge dissipation due to land cover using a Manning's friction coefficient (or Manning's n). Land cover is obtained from the U.S. Geological Survey National Land Cover Dataset (Arcement Jr and Schneider, 1989; Multi-Resolution Land Characteristics Consortium (MRLC, 2011). The coastal herbaceous and woody wetlands are represented using friction coefficients of 0.04 and 0.1 respectively.

The peak surge heights are interpolated on to a variable resolution grid with a maximum resolution of 100m X 100m for the areas with the highest number of properties and a minimum resolution of 5km X 5km for the least densely populated areas. These flood heights are combined with proprietary data on private property exposure and damage curves to estimate the economic losses due to flooding. The depth-damage curves were calibrated with historic flood insurance claims and structure types. These curves describe the damage likely to a structure depending on the peak flood depth and the type, condition and age of the structure for all privately owned (i.e., insurable) properties in the region.

We note that wave reduction is not explicitly analyzed in these studies. Wave-induced damages are implicitly included in the damage curves for certain locations and are contingent on the surge heights at these locations.

Impact of Coastal Wetlands on Flood Damages to Properties During Hurricane Sandy

For the Hurricane Sandy study, the flood model is run using Hurricane Sandy hydro-meteorological conditions to simulate surge extents and heights across the northeastern USA Atlantic coastline (Table 1).

Hurricane Sandy made landfall as a post-tropical cyclone in New Jersey in the USA on October 29, 2012 after having crossed Jamaica, Cuba and the Bahamas. It was a fast-moving (~29 km/hr), extraordinarily large cyclone with a radius of maximum winds of about 1611 km (or 870 nautical miles) prior to landfall. It caused at least 72 direct deaths in the USA and an estimated $50 billion in flood damages. It was the second costliest cyclone in USA history. The fatalities and damage from Hurricane Sandy were spread out across the Atlantic coast of the USA and were mostly due to storm surge flooding. The highest storm surges and inundation occurred along the coasts of New Jersey, New York and Connecticut. In New Jersey, Monmouth and Ocean County faced the brunt of the damage (Blake et al., 2013; NASA, 2013).

For the Hurricane Sandy Study, the flood model is run for two scenarios: (i) a "Present" scenario with temperate coastal wetlands included as they exist today; and (ii) a "Wetland Loss" scenario where all coastal wetlands were re-classified as open water with a reduced friction coefficient of 0.02 with all other conditions unchanged. The impact of wetlands on flood damages is therefore entirely due to the physical impact of wetland cover on flood heights.

Table 1: Details of Hurricane Sandy and Ocean County Studies

Study	Purpose	Region	Storm Event(s)	Coastal Wetland Scenarios	Key Outputs
Hurricane Sandy Study	To estimate savings in property damage during Hurricane Sandy due to presence of coastal wetlands	All Sandy-impacted coastal areas of the northeastern USA	1 event: Hurricane Sandy	All coastal wetlands. Examination of damages with current wetlands ("Present") and if wetlands were lost and became open water ("Wetland Loss").	Flood heights and damages for model scenarios with and without coastal wetlands.
Ocean County Study	To compare variation in annual damages from many storms for properties where salt marshes have been conserved versus lost	Ocean County, New Jersey	2000 events: set of storms generated using historical storms between 1900-2011	Salt marshes only. Examination of loss costs to uniformly distributed properties either behind existing marshes ("with marsh") or where they have been lost ("no marsh").	Average annual flood heights and damages for properties that are either behind a marsh or where marshes have been lost.

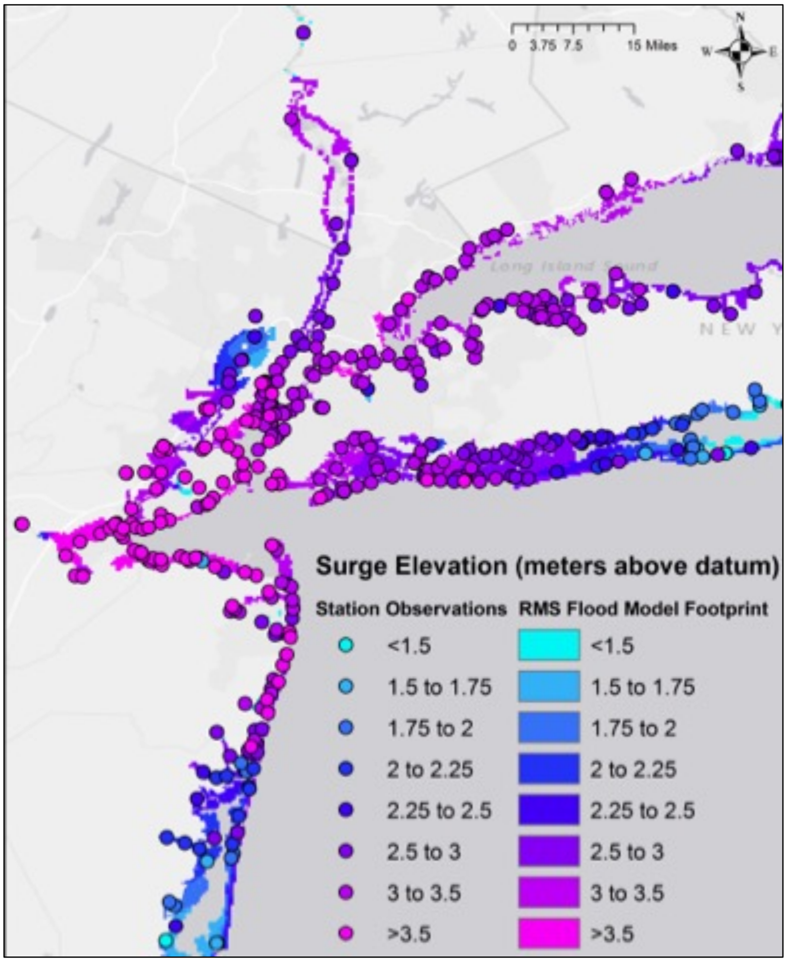

Figure 1: Flood model validation. Observed and predicted flood heights from Hurricane Sandy (here shown for parts of for New York and New Jersey). Station observations for the Sandy surge event were obtained from multiple sources (National Oceanic and Atmospheric Administration, 2012; US Geological Survey, 2012a, 2012b) and compared to the outputs from the RMS flood model.

For each scenario, the private property flood losses are estimated and the difference in losses is the risk reduction benefit of the wetlands. The model is validated for the "Present" scenario using tide gauge data and peak surge heights observed during the Hurricane Sandy surge event (Figure 1). All losses are estimated in terms of 2015 US$.

We examine some of the flood protection benefits of wetlands to public property. Model results for Hurricane Sandy flooding are combined with publicly available data on primary and secondary roads (US Census Bureau, 2016) to delineate all flooded roads within the Sandy-affected region. This is used to obtain the length of primary and secondary roads in each state that had reduced surge heights due to wetlands.

Impact of Salt Marshes on Annual Flood Damages to Properties in Ocean County

In Ocean County, NJ, we examine the estimated annual benefits of salt marshes for damage reduction across a wide range of storms. Ocean County is a heavily populated coastal area with extensive salt marsh. It is highly vulnerable to coastal storms. During Hurricane Sandy, some properties were flooded by more than 2 meters of water.

To estimate annual flood damages to properties, flood extents and heights are simulated for a set of 2000 storm events. These are a subset of storms specific to Ocean County. Each of the 2000 events has a frequency assigned to calibrate the occurrence of different intensity storms to the observed frequency of storms over the period 1900-2011. The flood model simulates surge extents and heights for each event using the land cover classifications in the national land cover database, and from these, average annual flood heights are obtained for every location within Ocean County.

To examine the potential effects of marsh conservation, we compare average annual flood losses for areas with extant salt marshes and areas where marshes have been lost to development. To identify the zone of influence of salt marshes we delineate upland areas behind salt marshes that were likely to benefit from flood reduction (Figure 2). Ocean County is ideal for this test, because it contains clear areas with present marshes and lost marshes in an alternating pattern (Figure 2). Watershed features for each salt marsh within the county are created following standard watershed generation procedures up to 5 meters in elevation to include areas that could have potentially been impacted by storm flooding.

To isolate the effect of the salt marshes we first assume a uniform grid of identical property types with the same hypothetical insurable value ($1,000,000) throughout the study region. At each location the expected annual loss is estimated using the modelled annual distribution of flood heights and this is expressed as an annual loss cost. The annual loss cost is calculated as the ratio of the annual loss to the insurable value and expressed per $1000 units. For example, an annual loss cost of 5 implies an expected annual loss of $5 per $1000, which translates to a $5000 annual loss for a property of $1,000,000 in value.

All properties are classified by elevation and the loss costs are then compared for areas with and without marshes. The variation in loss costs between the two categories indicates the impact of marshes on annual flood damages for each elevation class. We also assess the direct relationships of average annual loss costs with elevation and distance to coast for all these properties. Losses are estimated in terms of 2015 US$.

Figure 2: Salt marshes and their watersheds in Ocean County, New Jersey. Existing saltmarshes are in yellow. Red areas are the watersheds behind marshes up to 5 meters in elevation. Most of the low-elevation, coastal properties between these marshes are on land that historically had salt marshes. Flood losses were compared by elevation.

RESULTS

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Impact of Coastal Wetlands on Flood Damages to Properties During Hurricane Sandy

Temperate coastal wetlands are predicted to have reduced flood heights (Figure 3) and more than $625 million in flood damages across the Sandy-affected region (Table 2). The difference in losses between the two scenarios demonstrates the considerable role that coastal wetlands play in flood risk reduction across the region (Figure 4).

Wetland loss (i.e., conversion to open water) would have resulted in an average increase in flood heights across the region though this effect is highly variable. Wetlands are predicted to have reduced flood heights across more than 80% of the northeastern USA coastal floodplain (total = 3000 km^2) and in some locations by more than 1 meter. In 20% of the region (~600 km^2) wetlands had negligible effects or even increased flood heights, in some locations by up to 0.6 meters.

The reduction in flood damages by wetlands was a little over 1% of the total flood losses from Hurricane Sandy. The majority of the flood losses from Hurricane Sandy (~$46 billion) were along the heavily urbanized coastlines of New York and New Jersey in areas with few remaining wetlands. For census tracts with wetlands, there was on average 10% reduction in property damages.

Delaware and Maryland are predicted to have had the greatest relative savings in damages from wetlands across all census tracts during Hurricane Sandy of 10% and 29% respectively. New Jersey saw the highest absolute savings from coastal wetlands – almost $430 million in property damages, which represents 3% of the total losses in the state.

Many properties located at the upstream end of estuaries received cumulative benefits from downstream wetlands which reduced flood heights throughout the estuary. Indeed, some townships with few wetlands within their borders still saw significant damage reduction benefits from wetlands in adjacent townships (Figure 5).

Table 2: Differences in damages from Hurricane Sandy between "Present" and Wetland Loss" scenarios by state. All values rounded to the nearest $100,000, except for absolute difference for Maine, rounded off to the nearest $1000.

State	Present ($)	Wetland Loss ($)	Absolute Difference ($)	% Difference
Connecticut	2,180,600,000	2,181,000,000	400,000	0.02
Delaware	228,100,000	251,900,000	23,800,000	10.43
Massachusetts	1,452,300,000	1,458,600,000	6,300,000	0.43
Maryland	15,500,000	20,000,000	4,500,000	29.03
Maine	17,600,000	17,603,000	3,000	0.02
North Carolina	9,400,000	8,800,000	-615,000	-6.47
New Hampshire	29,600,000	30,500,000	900,000	3.04
New Jersey	14,014,600,000	14,443,300,000	428,700,000	3.06
New York	32,314,600,000	32,452,800,000	138,200,000	0.43
Pennsylvania	174,400,000	188,100,000	13,600,000	7.86
Rhode Island	72,100,000	72,400,000	300,000	0.42
Virginia	195,400,000	205,300,000	9,900,000	5.07

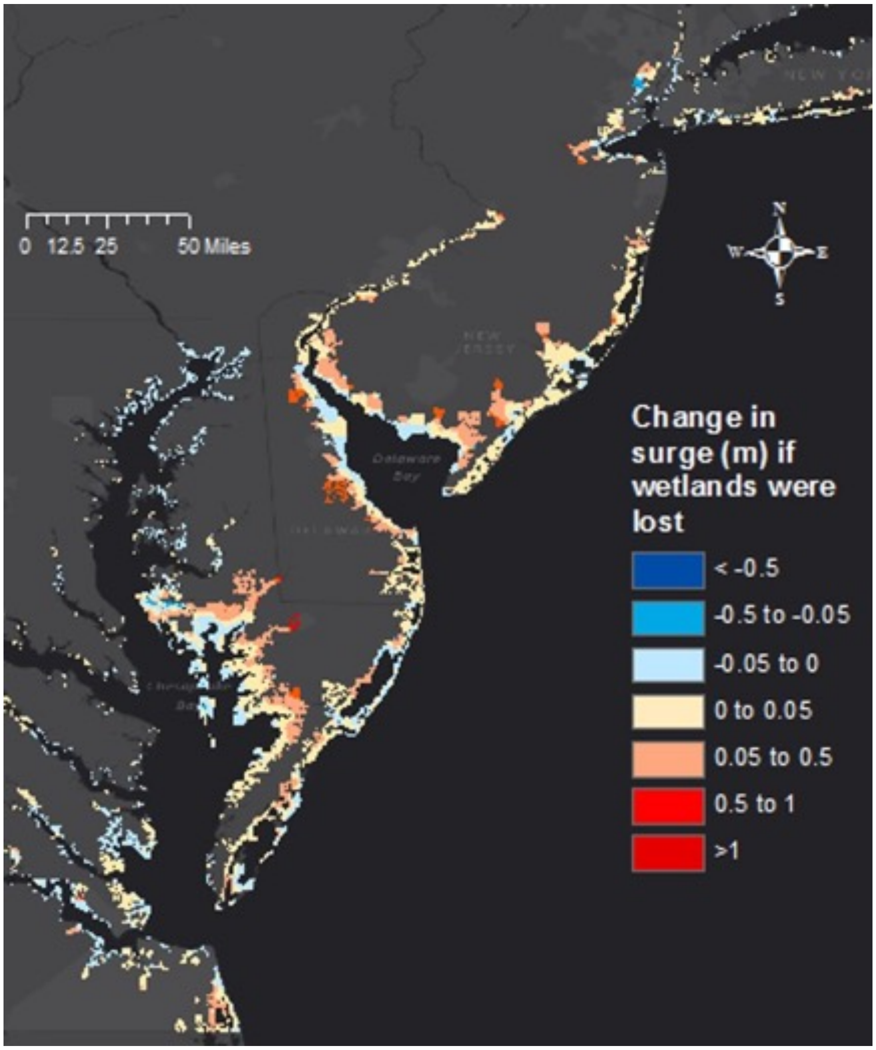

Figure 3: Wetland impacts on Hurricane Sandy surge. Change in Hurricane Sandy surge heights around the New Jersey and Chesapeake Bay regions if present coastal wetlands were lost.

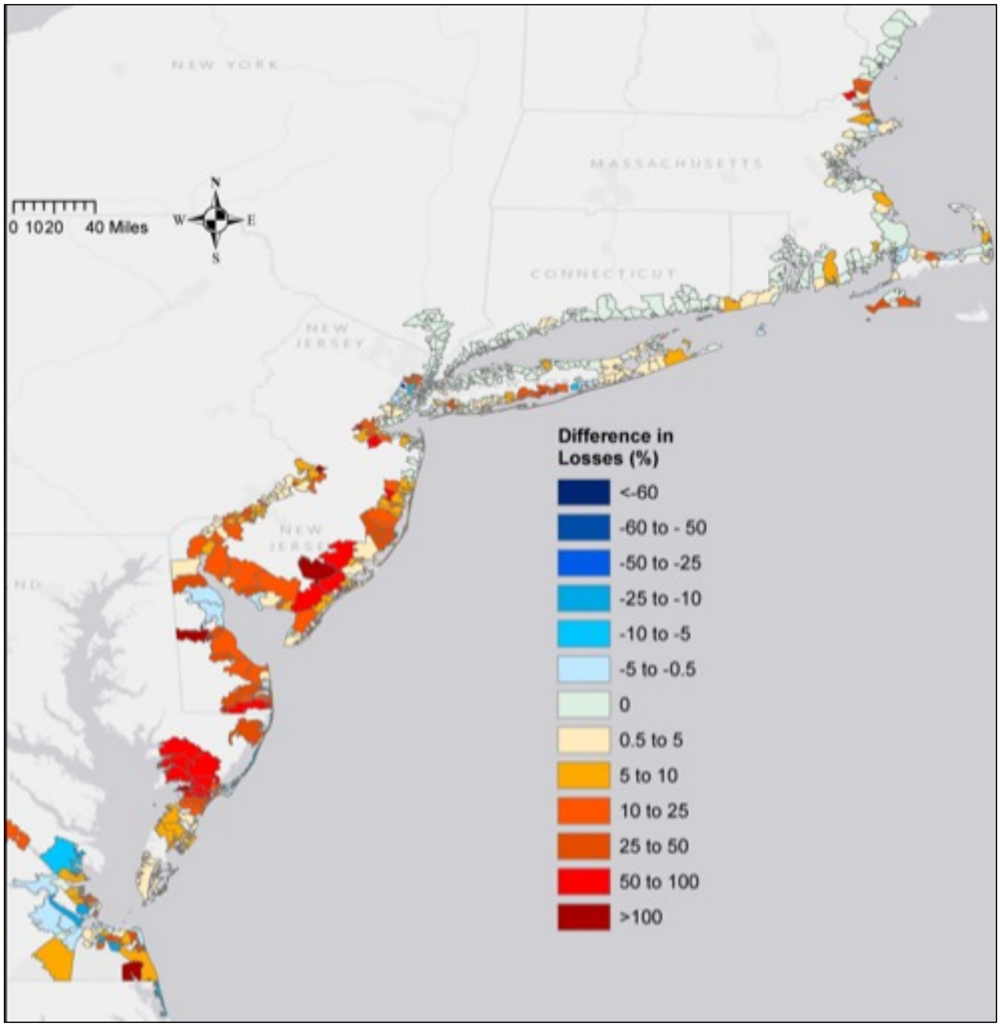

Figure 4: Wetland impacts on flood losses to properties. Percent changes in Hurricane Sandy flood losses between "Present" and "Wetland Loss" scenarios. The spatial units are census tracts.

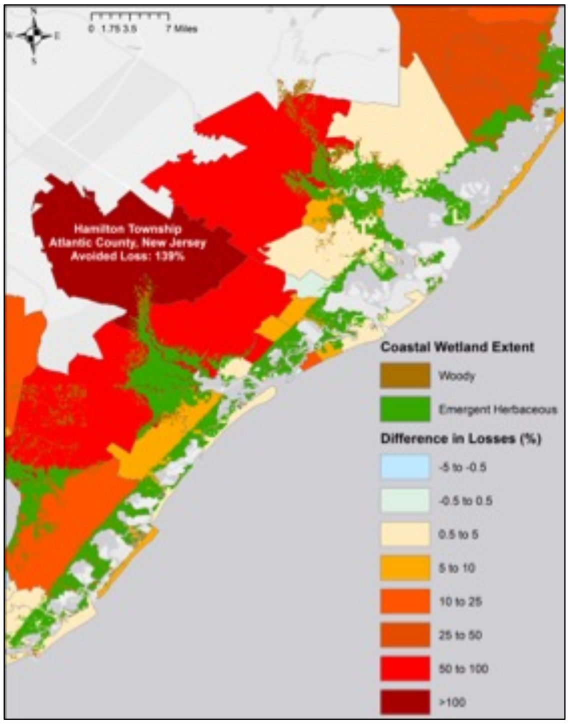

Figure 5: Cumulative wetland impacts on property losses. The effects of wetlands on flood damage reduction in Atlantic County, New Jersey. Hamilton Township contains very few wetlands, but there was significant loss reduction, which appears to arise from the cumulative effects of substantial wetlands further down the estuary.

Preliminary analyses of flooding on primary and secondary roads showed that wetlands also protected coastal roads from flooding during Hurricane Sandy (Table 3). On average, wetlands reduced flood heights by 0.06 meters for over 2000 kilometers of highways and major roads. Like other wetland effects these reductions were highly variable. For instance, in New Jersey wetlands reduced flood heights by up to 1.2 meters for some roads. Delaware and Maryland each had more than 400 kilometers of roads receiving protection benefits from wetlands.

Impact of Salt Marshes on Flood Damages in Ocean County

In Ocean County, elevation and marsh presence significantly reduced annual property losses. On average, properties located behind a marsh are predicted to save more than 20% in annual flood loss costs compared to properties where marshes have been lost (Figure 6). At the lowest elevations, properties built behind existing salt marshes have considerably lower annual loss costs (more than 50% lower at some elevations) compared to properties built on or behind areas where marshes have been lost. Not surprisingly, losses for all properties decrease rapidly as elevations increase, becoming negligible at elevations above 2 meters (Figure 7). Elevation was more important than distance from coast; the benefits of wetlands for annual loss costs did not vary significantly with distance from the coast.

Table 3 Length of primary and secondary roads in the Hurricane Sandy floodplain estimated to receive flood protection benefits from wetlands.

State	Length of Roads Protected (km)
Connecticut	30.26
Delaware	502.60
Massachusetts	94.63
Maryland	435.81
Maine	0.80
North Carolina	28.49
New Hampshire	40.07
New Jersey	333.13
New York	300.63
Pennsylvania	41.68
Rhode Island	17.06
Virginia	403.95
Total	***2228.94***

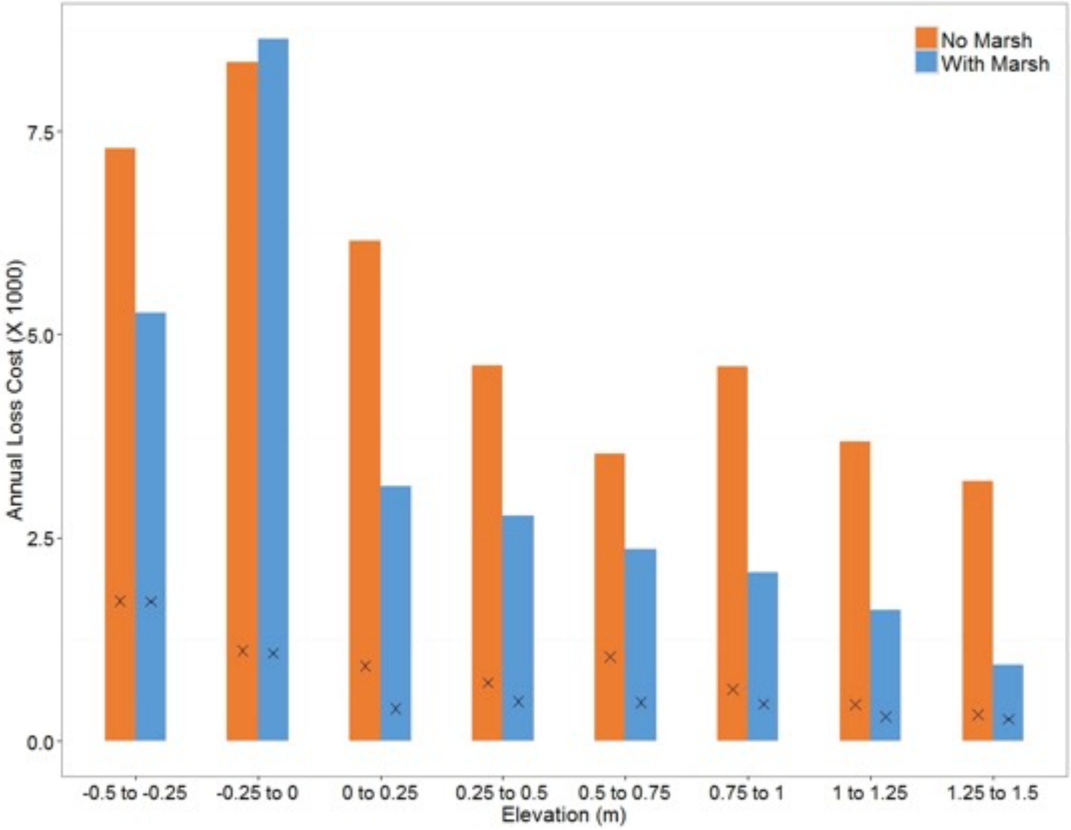

Figure 6: Effect of marsh presence on annual flood losses in Ocean County. Differences in Annual Loss Costs for properties 'With Marsh' (blue) and with 'No Marsh'(orange) for elevations up to 1.5 m above datum. Shaded bars show range of values. 'X's show average values. Elevations are all with respect to the North American Vertical Datum of 1988 (NAVD 88).

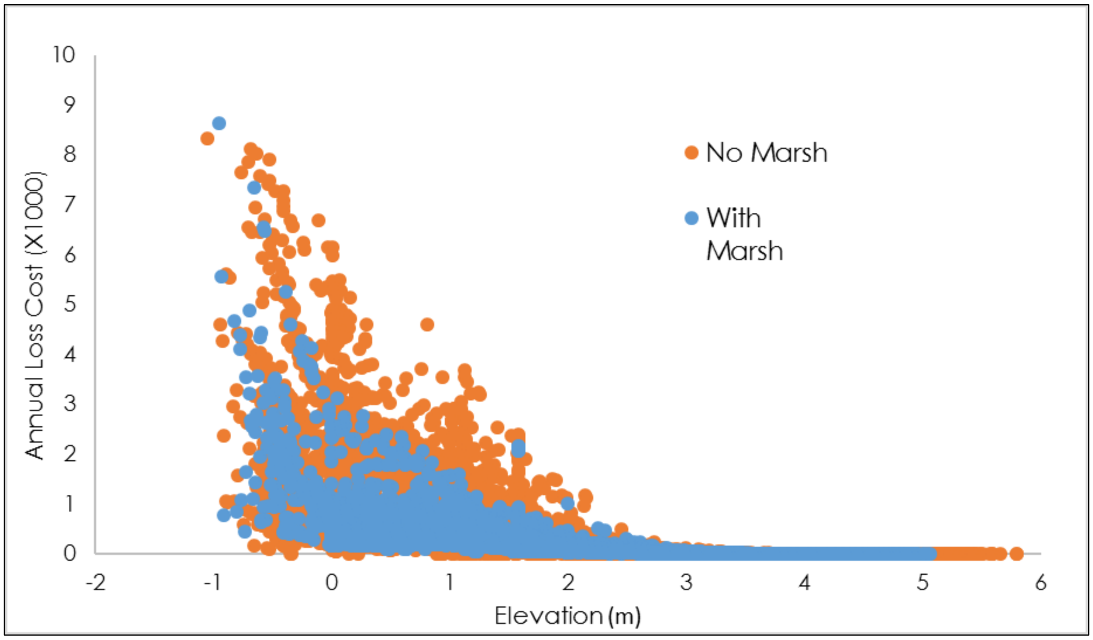

Figure 7: Distribution of annual loss costs by elevation in Ocean County. All properties are classified by whether they are behind an existing marsh ('With Marsh') or not ('No Marsh'). Elevations are all with respect to the North American Vertical Datum of 1988 (NAVD 88).

DISCUSSION

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Using industry-based risk models, we estimate that existing coastal wetlands saved hundreds of millions of dollars in property damages across the northeastern USA during Hurricane Sandy and, that marsh presence can reduce annual flood losses by more than 20%. For Hurricane Sandy, the coastal wetlands remaining in the northeastern USA (172,000 ha) saved more than $ 625 million in flood damages. This represents approximately 1% of the total flood damages from Sandy. However, if we consider only the census tracts (e.g., townships) with wetlands, their reduction in property damages was estimated to be more than 10% on average.

The Hurricane Sandy study shows the predicted role of wetlands in catastrophic events. It is also true that the impacts of any one event depend a great deal on the distribution and extent of surge, wetlands, assets and other factors. The Ocean County study estimates the annual benefits of conserving marshes for flood risk reduction. This study looks at many storms and controls for the distribution of exposure to focus on the role of wetlands in annual loss costs. Together, these high resolution analyses help fill an important gap in our understanding of the role of temperate coastal wetlands in flood damage reduction. They can also inform public and private incentives that support wetland conservation and restoration to cost effectively enhance the protection of people and property.

In our flood model (like most other flood models) wetland presence is represented using a static friction (Manning's) coefficient which may not fully resolve the role of wetlands in surge and damage reduction. Wetlands reduce surge heights by impeding the flow of water (Resio and Westerink, 2008). Wetland vegetation provides frictional resistance to the flow of water and changes in this friction due to wetland loss can significantly impact flood heights and extents. A recent assessment of surge attenuation within mangrove wetlands found that using a static friction coefficient could under-estimate vegetation effects in reducing flood heights because it under-represents the amount of vegetation submerged in the water column over the duration of the storm (Zhao and Chen, 2016). Lost wetlands may be replaced by open water (Kearney and Rogers, 2002; Kirwan and Megonigal, 2013) or they may be replaced by agriculture, urbanization, or other anthropogenic land-uses (Kennish, 2001). In the latter scenario, the change in land-use may have less impact on frictional resistance to flooding, but it will increase overall asset exposure and risk.

These results for the northeastern USA show that coastal wetlands have significant benefits even though their distribution has been heavily impacted. Some studies such as Barbier et al. (2008) note that the protection benefits of coastal wetlands are non-linear with regard to wetland width; most of the protection is provided within the first several hundred meters. Our results are consistent with this finding and further show that the location of wetlands relative to the coastline and exposed properties is equally crucial in determining their protective value. While some coastal protection benefits from wetlands may be achieved over relatively small areas, other ecosystem services such as fish production, nutrient cycling, and carbon sequestration often require larger expanses of wetlands.

Wetland benefits can be cumulative. Some areas at the upstream end of estuaries like Hamilton township (Figure 5) benefited from the cumulative surge reduction impact of several kilometers of downstream wetlands. These results highlight the importance of identifying and accounting for these cumulative benefits which are not always apparent when doing simple correlations (e.g., by census tract) of wetland area and surge protection benefits. These difficulties in spatially quantifying wetland benefits may underlie some of the debate on the efficacy of natural defenses in flood risk reduction (Feagin et al., 2015).

In most locations wetlands reduced flooding but in some places they increased predicted surge heights and damages. Similar to artificial defenses, these effects are often related to the modification of flow patterns around the wetland, including a damming or blocking effect (Loder et al., 2009b). For example, seawalls can aggravate erosion nearby and poorly-designed levees can aggravate flood damages and loss of life (Kates et al., 2006). In Chesapeake Bay surge heights increased in front of wetlands and decreased behind them (Figure 8). As with the design of engineered defenses, understanding exactly how and where wetlands will affect flooding is crucial to ultimately integrating them into coastal risk management practice.

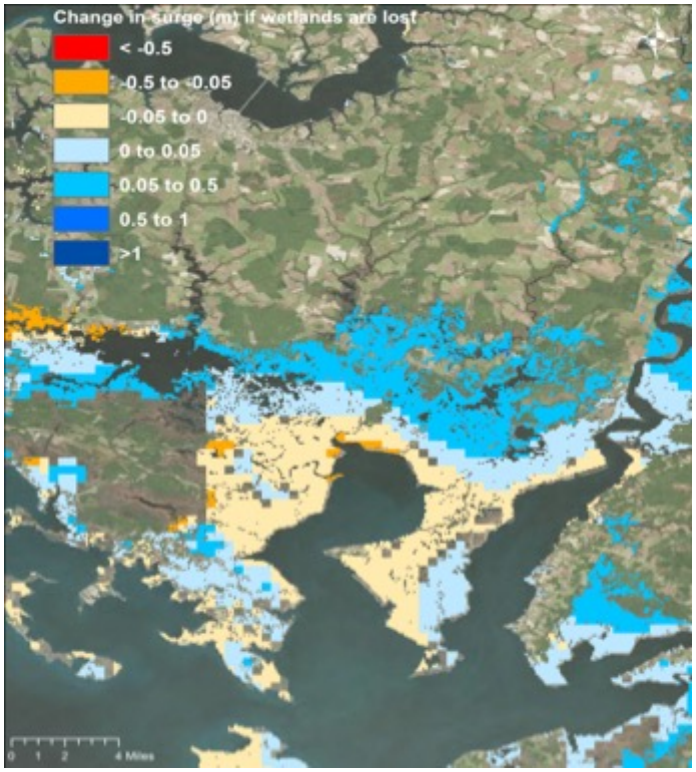

***Figure* 8: Wetlands can increase surge heights.** A comparison of surge heights within wetlands for “Present” and “Wetland Loss” scenarios in Chesapeake Bay. Here, flood waters ‘pile up’ in the wetlands in front and are reduced behind them. Areas in orange experienced higher surge and areas in blue had lower surge heights.

The Ocean County study illustrates the two-fold benefits of marshes for coastal defense. First, where marshes are conserved then properties are not built in the lowest most exposed (high risk) areas. Second, when marshes are left in place flood reduction benefits are preserved for upland properties. Across the northeastern USA, development over wetlands place significant critical infrastructure such as power plants and transportation terminals at great risk. Over the past century parts of New Jersey such as Barnegat Bay have lost more than 25% of their salt marshes to infilling and development. The New Jersey Coastal Wetlands law of 1970 has limited the loss of salt marshes since then (Lathrop Jr and Bognar, 2001). The results of our studies quantify the benefits of conserving and restoring these wetlands. Local land managers and other stakeholders have identified sea-level rise and pollution as major threats to these wetlands and coastal development as the main barrier to their migration (Leichenko et al., 2013).

The Ocean County study uses expert analyses and GIS tools to identify wetland watersheds. These studies are however difficult because there is often surprisingly limited spatial data on past marsh distribution. We believe that there should be more studies like in Ocean County that examine the effects of past marsh loss. There are also more complex changes that could be considered in future modeling efforts which could include the damages from storms to the wetlands directly and thus their future protection benefits (Kirwan et al., 2016).

Our study underestimates the wave reduction capacity of wetlands. Wave reduction is indirectly estimated only as a consequence of a reduction in surge heights. Fuller and more explicit evaluations of this effect are needed to accurately reflect the full range of benefits from these wetlands. We also do not account for other risk reduction benefits from wetlands such as the long-term stabilization of shorelines and increases in near-shore elevations (Gedan et al., 2011).

Our analyses chiefly consider the protection of private assets; the benefits of wetlands would increase if the protection of public assets was added. We provide a preliminary assessment of the length of roads protected by wetlands during Hurricane Sandy (Table 3). Over 2000 km of highways and major roads across the Sandy-affected region saw a reduction in surge heights due to coastal wetlands. In New Jersey wetlands reduced flood heights by more than 1 meter on some roads. Such large reductions in surge heights can have a significant effect on flood damages especially at high flow velocities (Teo et al., 2012).

Wetland benefits could be better incorporated in the decision-making processes of risk managers. Wetlands were already considered in the RMS flood model, but the effects were not easily discernible from the many other factors that influence surge and flood risk. Previously, decision makers and users of these models have not asked for these effects to be separated and explored. Since Hurricane Katrina in 2005 in the USA, risk modelers in the insurance industry have focused on improving the accuracy and precision of their models to better understand drivers of flood risk and increasingly account for artificial defenses such as levees and seawalls (Kuehner-Hebert, 2015; Reynolds, 2015). Unlike artificial defenses, which many model users (public and private) request to be explicitly modelled and valued, it is not yet common for wetland management scenarios to be assessed by industry flood risk modelers. Wetlands are probably already included as land-cover estimates within many industry flood models. Our study illustrates the ability of the industry to explicitly measure the long-term benefits of wetland presence for flood risk reduction across a large region at high resolution.

These results identify where and why there should be more incentives for wetland conservation and restoration for risk reduction. Indeed, there is increasing interest in the USA and elsewhere for exploring the use of coastal wetlands and other nature–based solutions for risk reduction in policy and practice. For example, the Department of Transportation in the USA is conducting pilot studies in three Sandy-affected states (New

Jersey, Maine and New Hampshire) to explore the potential for nature-based solutions to protect coastal roads from sea-level rise and storm surges (US Department of Transportation, 2016). The European Union has identified nature-based solutions for disaster risk reduction and climate change adaptation as a research priority (European Commission, 2016). Federal and state government agencies in the USA increasingly support the examination of coastal wetlands for risk management of public and private coastal assets (Association of State Floodplain Managers, 2003; US Environment Protection Agency, 2012). The Federal Emergency Management Agency (FEMA) in its latest Executive Order Guidelines requires that any risk reduction measure should minimize its adverse impact on the rest of the floodplain and use nature-based approaches where they provide the intended level of protection (Federal Emergency Management Agency, 2015).

CONCLUSIONS

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These results show that wetlands provide direct, quantifiable reductions in flood risk for individual extreme events and average annual flood losses, and that these benefits can be readily included and advanced in risk industry-based tools. We highlight the significant benefits of coastal wetlands, which should be considered by public and private risk managers. This work also supports the development of better public and private incentives for wetland conservation and restoration for coastal risk reduction. These results illustrate the importance, especially for development agencies and land-use planners, of the risks of building over wetlands in the lowest elevation exposed areas. Finally, these results provide impetus for improving consideration and integration of natural defenses within coastal engineering and risk management practice.

Identifying where coastal ecosystems can provide risk reduction is essential for facilitating decisions on county- and state-wide coastal management, insurance and conservation. These quantitative analyses can support decision-making tools for the prioritization of nature-based solutions for risk reduction and conservation (Guannel et al., 2015; The Nature Conservancy, 2016). Information on where and how coastal wetlands and other ecosystems work to reduce risk can inform state-wide coastal resiliency strategies, such as the Living Shorelines resilience strategies in Maryland (National Oceanic and Atmospheric Administration, 2015). Our work to quantify the risk reduction benefits of these ecosystems also informs the use of financial mechanisms like resilience and catastrophe bonds (Vajjhala and Rhodes, 2015) to fund conservation and restoration projects.

Finally, there is growing interest among national government agencies in wetland restoration targeted at building resilience (US Army Corps of Engineers, 2015b; US National Fish and Wildlife Service, 2015). In addition to quantitative studies on risk reduction, we believe it is essential to develop a better understanding of effective restoration techniques and projects that will help sustain these ecosystems and enhance their capacity to cope with natural disasters while continuing to provide multiple services.

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