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Probabilistic life cycle analysis model for evaluating electric power infrastructure risk mitigation investments

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Abstract One effect of climate change may be increased hurricane frequency or intensity due to changes in atmospheric and geoclimatic factors. It has been hypothesized that wetland restoration and infrastructure hardening measures may improve infrastructure resilience to increased hurricane frequency and intensity. This paper describes a parametric decision model used to assess the tradeoffs between wetland restoration and infrastructure hardening for electric power networks. We employ a hybrid economic input–output life-cycle analysis (EIO-LCA) model to capture: construction costs and life-cycle emissions for transitioning from the current electric power network configuration to a hardened network configuration; construction costs and life-cycle emissions associated with wetland restoration; and the intrinsic value of wetland restoration. Uncertainty is accounted for probabilistically through a Monte Carlo hurricane simulation model and parametric sensitivity analysis for the number of hurricanes expected to impact the project area during the project cycle

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and the rate of wetland storm surge attenuation. Our analysis robustly indicates that wetland restoration and undergrounding of electric power network infrastructure is not preferred to the "do-nothing" option of keeping all power lines overhead without wetland protection. However, we suggest a few items for future investigation. For example, our results suggest that, for the small case study developed, synergistic benefits of simultaneously hardening infrastructure and restoring wetlands may be limited, although research using a larger test bed while integrating additional costs may find an enhanced value of wetland restoration for disaster loss mitigation.

1 Introduction

Recently, climate change has been associated with potential increases in hurricane frequency or intensity (Emanuel 2005). Increases in population density in coastal areas have also been forecasted (Nicholls and Small 2002; Small and Nicholls 2003), thus increasing the urgency of mitigating potential adverse outcomes associated with hurricane events. These observations have led risk managers to consider the effects of increased hurricane frequency and intensity on networks of lifeline infrastructure that support our societies (U.S. Congress Office of Technology Assessment 1990). Examples of lifeline infrastructure networks include electric power networks, drinking water and wastewater networks, transportation networks, and oil and gas pipeline networks. Hurricane Katrina has further focused attention in the USA on the potential adverse impacts of increased hurricane frequency and intensity (Day et al. 2007), and attendant risk mitigation decisions are currently being re-evaluated (Bigger et al. 2009; U.S. Army Corps of Engineers 2004). It has been hypothesized that coastal wetland restoration may be a cost-effective approach to mitigating the impacts of future hurricanes (Wamsley et al. 2009, 2010).

The objective of the analysis presented in this paper is to demonstrate a methodology for evaluating potential risk mitigation synergies between coastal wetland restoration and infrastructure protection, focusing on electric power network hardening. We evaluate the life cycle costs associated with electric power network hardening and wetland restoration for a model city case study for three scenarios: undergrounding all electric power equipment; undergrounding only electric power equipment in the commercial zone; and making no changes to the existing network configuration. For each of these scenarios, we evaluate life cycle costs with and without wetlands, and including and not including indirect economic and environmental costs. Our results suggest that for our case study city, wetland restoration and infrastructure hardening are not the preferred options. This result has important implications for coastal adaption planning. Natural ecosystem restoration may be difficult to justify as an approach for coastal adaptation without separately considering the valuation of biodiversity, ecological services, and carbon sequestration. While these issues pose difficult valuation problems, the more directly quantifiable benefits of wetland restoration may not offset the significant cost of restoring or building wetlands in many locations.

2 EIO-LCA disaster mitigation framework

Risk mitigation decisions are currently evaluated using several tools, including but not limited to: benefit–cost analysis (BCA) (Arrow et al. 1996), life-cycle cost analysis (LCA) (Chang and Shinozuka 1996), and probabilistic decision analysis (Keeney 1982). BCA involves maximizing the ratio of benefits expected from a decision to the expected costs incurred by taking a decision. The assumption is that maximizing this ratio maximizes public welfare. LCA extends BCA by accounting for the costs incurred over the life cycle of a project undertaken as a result of a specific decision. Probabilistic decision analysis involves parameterizing the decision choices and probability of potential adverse outcomes to be mitigated such that the uncertainty associated with the occurrence of an adverse event is quantitatively evaluated in the decision framework and the decisions are based on maximizing expected utility. Risk mitigation decisions can be evaluated using a combination of each of these tools. One recent disaster risk mitigation methodology proposed combining each of these tools is the extended life cycle cost analysis framework (ELCA) (Chang 2003).

ELCA extends traditional approaches to BCA by incorporating societal costs and benefits over a risk mitigation project's planned life with the benefits and costs expected to accrue to the relevant lifeline agency over a project's planned life. The computation of societal and lifeline agency costs and benefits is facilitated by a transparent framework accounting for four types of costs and benefits (Chang 2003): planned costs undertaken by the lifeline agency; costs imposed on society by the lifeline agency's actions; expected unplanned costs undertaken by the lifeline agency; and, expected unplanned costs imposed on society through lifeline service disruption and restoration.

In the present paper, we extend the ELCA by incorporating supply-chain environmental impacts and other societal impacts associated with disaster risk mitigation projects. To incorporate these environmental and societal impacts, the economic input–output life-cycle assessment (EIO-LCA) framework (Hendrickson et al. 2006) is employed. We describe this new framework below in the section titled "EIO-LCA Disaster Mitigation Framework". We then apply the extended ELCA to a hypothetical case study with three decision scenarios evaluating wetland restoration and electric power network hardening to mitigate electric power infrastructure risk in the event of increased hurricane frequency and intensity.

2.1 Extended ELCA framework

Chang and Shinozuka (1996) and Chang (2003) have extended the practice of project life-cycle cost analysis to disaster loss estimation methodology. We adapt this framework for our purposes and present the details of its characterization here. As described above, this framework consists of four parts:

$$C = C_1 + C_2 + C_3 + C_4 \quad (1)$$

where: C_1 = planned costs undertaken by the lifeline agency; C_2 = costs imposed on society by the lifeline agency's actions; C_3 = expected unplanned costs undertaken by the lifeline agency; and, C_4 = expected unplanned costs imposed on society through lifeline service disruption and restoration.

The planned costs undertaken by the lifeline agency, C_1, are the sum of direct costs to the utility of performing routine maintenance on the infrastructure network and the costs to the utility of performing mitigation investments (with their associated maintenance costs). The maintenance and mitigation investments required depend on the nature of the network and the anticipated natural disaster. More specifically, the maintenance costs, C_m, are calculated as the sum of the maintenance cost m for system element i, multiplied by a discount factor for year t, $z(t)$, for all system elements over the planned project life.

$$C_m = \sum_t \sum_i m_i (x_i, t) \cdot z(t) \tag{2}$$

The mitigation investment costs, C_{mit}, are calculated as the sum of the mitigation investment cost e for system element i, multiplied by the discount factor for year t for all system elements over the planned project life.

$$C_{mit} = \sum_t \sum_i e_i (x_i, t) \cdot z(t) \tag{3}$$

Both of these costs depend on properties of the system elements including their age, materials, and tasks required.

The costs imposed on society as a result of the lifeline utility's mitigation decisions, C_2, are the sum of the benefits associated with disaster mitigation activities (e.g., increased employment and improved operational efficiency) and the environmental impacts associated with the activities required by the mitigation decisions. Chang and Shinozuka (1996) and Chang (2003) included only the economic portion of these costs and benefits. Here we extend this to incorporate the life-cycle environmental costs of agency decisions.

To compute costs and benefits, we employ the EIO-LCA approach. In short, EIO-LCA adapts the Leontief input–output economic model to estimate the environmental emissions associated with a product or service over its lifetime (Hendrickson et al. 2006). Because the overall economic activity associated with a product or service over its lifetime is more inclusive than the revenue associated with its purchase, we can take advantage of this feature of the EIO-LCA model to compute the environmental costs and economic benefits attributable to the lifeline agency's mitigation decisions. We propose that the benefits, beyond risk mitigation, of the lifeline agency's decision are the additional economic output associated with maintenance and mitigation activities above the direct costs to the lifeline agency, EO_m and EO_{mit}, respectively. In the event that wetland restoration is chosen, additional economic benefits accrue due to the economic value of the ecosystem services of the restored wetland area, EV_{wet}. The costs imposed on society include the environmental costs and service disruptions associated with the maintenance and mitigation investments. In this paper, we ignore the costs of the service disruptions due to maintenance and mitigation investments, including only the environmental costs, R_m and R_{mit}, of the maintenance and mitigation investments, respectively.

$$C_2 = \sum_t \left[(EO_m + EO_{mit} + EV_{wet}) - (R_m + R_{mit}) \right]_t \cdot z(t) \tag{4}$$

For the mathematical details of the EIO-LCA model, the reader is referred to Hendrickson et al. (2006).

The expected lifeline utility costs in the event of a natural disaster, C_3, are the sum of the expected repair costs associated with system element failures caused by the natural disaster, C_r, and the revenue loss attributable to the attendant service disruptions, C_v.

$$C_3 = C_r + C_v \tag{5}$$

As with C_m and C_e, the repair costs of a system element failure depend on the element properties, age of the system element, and tasks required to perform the repair. Chang (2003) characterizes the expected repair costs of system element i over the project life as the sum of the product of the expected failure probability in event of a natural disaster, F_i, and its unit repair cost r_i for each system element over the life of the project. The expected failure probability due to natural disasters over the planned life of the project is computed by integrating the product of the system element's fragility curve, P_F, and the hazard curve for natural disasters, $p(h)$, over the range of possible disaster intensities, h. The hazard curve gives the probability of a hazard of intensity h occurring, and the fragility curve gives the probability of element failure as a function of h, system element age, and system element type.

$$C_r = \sum_t \sum_i [F_i(x_i, t) \cdot r_i] \cdot z(t)$$

$$F_i(x_i, t) = \int_h P_F(x_i, t, h) \cdot p(h)\, dh \qquad (6)$$

The revenue loss attributable to attendant service disruptions, C_v, is the sum of the product of the expected annual unmet demand, V_t, and unit price, p, of the service provided over life of the project. The unmet demand is a function of the time to service restoration, τ, the percent initial unmet demand, ω, the normal demand volume, D, the hazard curve for natural disaster intensity, and decision-making factors related to system repairs, w.

$$C_v = \sum_t V_t \cdot p \cdot z(t)$$

$$V_t = \int_h \tau(w, h) \cdot \omega(h) \cdot D \cdot p(h)\, dh \qquad (7)$$

Finally, the expected costs imposed on society in the event of a natural disaster, C_4, are the sum of the losses in economic activity that occur from utility outage and cascading business losses directly caused by utility outages. As with the costs imposed on society due to routine maintenance and initial mitigation investments, C_4 may be divided into the economic output and environmental costs. We include the economic output, EO_r, caused by the repairs C_r, the economic output lost, EO_l, due to direct business losses, C_B, and the lost economic output, EO_{ul}, associated with decreased utility revenues, C_v. We also account for the environmental costs associated with repairs, R_r, and the reduction in environmental costs due to direct business losses, R_l, and service interruptions, R_{ul}.

$$C_4 = \sum_t \left[\{EO_r(C_r) - EO_l(C_B) - EO_{ul}(C_v)\} - \{R_r - R_l - R_{ul}\}\right]_t \cdot z(t) \qquad (8)$$

While we have defined the repair costs and the lost lifeline utility revenues above, the direct economic losses of business interruption are a function of the time to service restoration, τ, the initial economic loss attributable to the natural disaster, ε, the post-event percent unmet demand ω in area a due to an event of intensity h, the normal economic activity Q in area a, the probability of a disaster with intensity h, and business resiliency to lifeline outage ρ.

$$C_B = \sum_t E_t \cdot z(t)$$

$$E_t = \int_h \tau(w,h) \cdot \varepsilon\left[\omega_a(h), Q_a, \rho\right] \cdot p(h)\, dh \tag{9}$$

As a simplifying assumption, we use empirical estimates of direct business losses due to power outages reported by LaCommare and Eto (2006), as discussed below, in lieu of formal studies of economic resilience to power outages.

3 Case study illustration

3.1 Case study city

In order to illustrate the method, we utilize as a case study example a synthetic small city assumed to be located in a hurricane-prone coastal area. This synthetic city is then subjected to simulated hurricanes. Infrastructure damage is, in turn, simulated probabilistically based on fragility curves and assumptions presented in the literature. We examine two causes of failure: wind-induced damage of utility poles and surge-induced damage of buried electrical lines. The costs associated

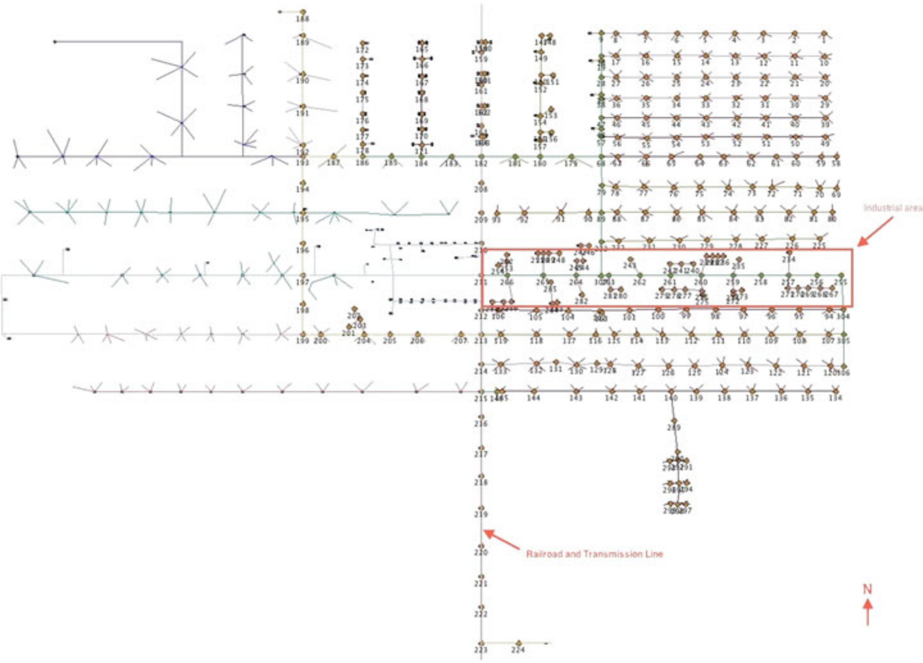


Fig. 1 Micropolis electric power network configuration

with damage, repair, and outage of various electric power network components are presented in subsequent sections. In addition, we discuss the environmental impact and indirect economic cost assumptions for each infrastructure component. We focus on mitigating risk to the electric power system of this city with wetland restoration and infrastructure hardening being the two options available. We define the project area as a small North Carolina coastal city straddling Category 3 and Category 5 hurricane storm surge zones, with the city extending approximately 1 mile inland and ½ mile along the coast. The prototype for this city is a model city called "Micropolis," developed at Texas A&M University as one of two model cities to be used as testbeds for infrastructure risk research and planning (Brumbelow et al. 2007). Micropolis has approximately 5,000 residents in a historically rural region, and details are provided for each building in the city as well as the power and water systems for the city. The number of electric power customers (residential, industrial, and commercial) is specified, as is the customer electricity demand and configuration of the electric power network. Micropolis has 434 residential customers, 15 industrial customers, and nine commercial or other customers in the project area served by approximately 9.7 circuit-miles of overhead electric power distribution line. Micropolis' electric power network configuration is shown in Fig. 1.

3.2 Hurricane simulation model

We developed a statistical model that best describes the relationship between climate variability and North Atlantic tropical cyclone (TC) counts (Sabbatelli and Mann 2007) in the U.S. through the use of count regression analysis and data mining techniques. In our modeling implementation we used 17 climate variables, with their quarterly and annual averages for 73 total covariates and tropical cyclone counts in the U.S. from 1948–2004.

We implemented three distinct approaches and compared their results to choose the model with the most superior fit and predictive accuracy. The first two approaches involved constructing regression trees to identify the most important variables prior to fitting a Poisson Generalized Linear Model (P-GLM) on the reduced data set consisting of the most important variables. The third approach consisted of fitting a P-GLM without any previous data mining implementations.

Our fit and prediction results indicate that fitting regression trees prior to fitting a P-GLM leads to better fit results and predictive accuracy. The statistics of our final best model that was developed through this procedure is summarized in Table 1.

Our prediction errors, shown in the first column of Table 1, are calculated based on 50 random hold-out cross validation tests. In each of 50 independent iterations, 10% of the data is randomly held out to create a validation set. The model is then built on the remaining subset of the data, the training set, and the predictions are tested against the validation set. The MSE (Mean Squared Error) and MAE (Mean

Table 1 Mean squared error (MSE) and mean absolute error (MAE) for the hurricane count model for both the fitting data set and 50 repeated, random hold-out validation tests

Model prediction error		Model fitting error		Null model prediction error	
MSE	MAE	MSE	MAE	MSE	MAE
4.523	1.0523	5.747	1.873	10.377	2.660

The null model is an intercept-only model based on the historic mean

Absolute Deviation) in the first columns represent the difference between the actual TC counts and the cou nts predicted by the P-GLM model, averaged over the 50 repeated validation tests. The fit errors are the difference between the fitted values from our model and the observed number of TC counts. The last columns shows the errors calculated when model is replaced by the mean observed TC counts (10.4). As can be seen in Table 1, the errors are much larger in this case. Overall the results suggest that our model can be used to reconstruct the past history of TC counts as well of making future predictions with reasonable predictive accuracy.

Equation 10 reports the model. Our model suggests that TC counts in the U.S. are positively associated with annual global land and ocean temperature anomaly (CRU) and negatively correlated with annual Sea Level Pressure (SLP) anomaly and annual El-Nino Southern Oscillation (ENSO) anomaly, with the temperature-related covariate (CRU) having a bigger impact on tropical cyclone counts than the other two covariates.

$$\ln\left(TC_{count}\right) = 409 + 0.928\,(CRU) - 0.401\,(SLP) - 0.138\,(ENSO) \tag{10}$$

In this analysis, we use a joint distribution based on historical records for CRU, SLP, and ENSO to simulate the number of tropical cyclones impacting the project area over the 50-year life cycle. We then downscale from these tropical cyclone counts to the number of hurricanes that would impact our project area in three steps. First, we multiply the number of predicted TC counts by the ratio of (1) hurricanes counts to (2) the count of all tropical cyclones in the historical record. Second, we multiply this number of hurricanes in the North Atlantic by the proportion of hurricanes in North Carolina to North Atlantic hurricanes. Finally, we assume that hurricanes making landfall within 100 nautical miles of the project area impose costs on the infrastructure in Micropolis. This procedure is summarized in Eq. 11.

$$\mathrm{H}_{proj} = TC_{counts} \cdot \left[\frac{\mathrm{H}_{N.Atl.}}{TC_{counts}}\right] \cdot \left[\frac{\mathrm{H}_{N.C.}}{\mathrm{H}_{N.Atl.}}\right] \cdot \left[\frac{100nm}{261.6nm\ \text{(N.C. coastline)}}\right] \tag{11}$$

3.3 Coastal wetland restoration

As discussed above, it has been hypothesized that wetland restoration and infrastructure hardening measures may improve infrastructure resilience to increased hurricane frequency and intensity. Infrastructure hardening increases resilience by decreasing the likelihood of failure for a given wind load or surge depth. Wetland restoration acts to decrease surge depths. Here, we briefly present our assumptions about wetland restoration techniques and the effects of wetlands on storm surge attenuation for the simulation.

Wetland restoration projects generally fall into three classes: wetland creation from dredged materials; manipulation of sediment flow; and, conversion of open waters to wetlands (Turner and Streever 2006). In these three classes, eight approaches are discussed in detail by Turner and Streever (2006): crevasse splays, former agricultural impoundment conversion, backfilling, managing spoil banks, bay bottom terracing, dredged material wetlands, excavated wetlands, and thin-layer placement. For more details on each technique, the reader is referred to Turner and Streever (2006). The costs of each approach are highly variable, ranging from \$0 to \$44,000 per hectare; moreover, the implementation of each approach is highly dependent on prior experience, landscape attributes, and wetland ecosystem resources, services, and inhabitants. For the purpose of our case study, we assume that wetlands may be constructed in open ocean using dredged material wetlands, and assume the highest value presented by Turner and Streever (2006) for the cost of wetland restoration as the cost of wetland restoration in our model, $44,000.

Wetland ecosystems provide several economic benefits due to their intrinsic natural processes and services. The valuation of these services is difficult, however, and methodology for their inclusion in wetland restoration decision analyses is not straightforward. Two difficult aspects of assessing decisions considering potential synergies between wetland restoration and coastal infrastructure hardening are estimating the economic value of an acre of wetlands and, separately, estimating the amount of carbon sequestered by the wetlands. The carbon sequestration potential of wetland ecosystems is very difficult to establish. While Bridgham et al. (2006) estimate that North American wetlands are a small to moderate carbon sink (49 Tg C/year), the uncertainty in this estimate is greater than 100%. We assume that our restored wetlands will most resemble tidal marsh, swamp, or coastal floodplains. Bridgham et al. (2006) and Chmura et al. (2003) estimate that the rate of carbon sequestration in these wetland categories is 7.3×10^{-4} $MtCO_2E$/ha (2.56 $MtCO_2E$/year for our project area). In addition, methane emissions from North American wetlands may offset the benefits of wetland concentration. Consequently, Bridgham et al. (2006) suggest that, with the exception of estuarine wetlands, carbon sequestration potential should not be considered in wetland restoration decisions. Due to this uncertainty, we do not consider carbon sequestration potential of wetland ecosystems in this analysis. We do use empirical estimates of the economic value of tidal marsh, coastal floodplains, and other wetlands from Costanza et al. (1989) and Costanza et al. (1997) as the economic value of the restored wetlands' ecosystem services in our analysis. These empirical estimates include the value of various wetland ecosystem services and processes, as well as supported economic activities, as intrinsic to the wetlands. From these estimates, we assume that the value of our restored wetlands lies in the range between $6,000–$30,000 USD/ha.

Several investigators have recently studied the effect of wetlands on storm surge attenuation rates (U.S. Army Corps of Engineers 1963; Loder et al. 2009; Resio and Westerink 2008; Wamsley et al. 2009, 2010). However, the amount of storm surge attenuation attributable to surge flow over wetlands remains uncertain. The principal challenge to quantification of storm surge attenuation is quantification of the increased drag on storm surge due to bottom friction of wetlands. This challenge is further complicated by the spatial heterogeneity of storm surge profiles over wetlands and the spatial variability of drag caused by wetland composition. For these reasons, empirical rules of thumb have been employed to incorporate storm surge attenuation into approaches to wetland restoration and valuation. These empirical rules of thumb range from 1 m (height) surge attenuation per 4 km wetlands restored to 1 m surge attenuation per 60 km wetlands restored. The U.S. Army Corps of Engineers (1963) estimate, quoted by Resio and Westerink (2008), is 1 m surge attenuation per 14.5 km wetland restored.

Although we use a simple linear relationship for storm surge attenuation over wetlands, this rule of thumb is known to have several weaknesses as indicated by recent studies. For example, Loder et al. (2009) find that marsh elevation and bottom friction contribute to storm surge attenuation, while marsh continuity may amplify storm surge. These findings are consistent with the general findings of Wamsley et al. 2009: storm surge attenuation is nonlinearly dependent on landscape characteristics (e.g., bathymetry, wetland attributes, presence of structures, etc.) and storm characteristics (e.g., storm speed, size, track, and intensity). The nature of storm surge attenuation over wetlands is also discussed in a concurrent paper in the present special issue of *Climatic Change* (Gedan et al. 2010). Gedan et al. (2010) indicate that nonlinearities may emerge in wetlands' abilities to attenuate hurricane storm surge due to biological and physical characteristics of the wetlands, including differences in the identity, phenology, and morphology of the species comprising the wetland system. Moreover, Gedan et al. (2010) also indicate that variation in storm characteristics and coastal geography may also overcome the attenuation effects attributable to the wetland system. These studies indicate that wetland storm surge attenuation is a complex function of vegetation, bathymetry, and topology. Approximation of this function as a linear trend does not accurately reflect these complex relationships and may, in turn, not accurately estimate risk reductions in coastal areas. Nonetheless, we summarize results from these studies using general ranges of attenuation rates, as this complexity is not the present focus of our paper.

Consequently, our model incorporates this uncertainty by employing a triangular distribution on the storm surge attenuation rate attributable to wetlands, with minimum and maximum values of 1 m:60 km [surge attenuated: wetlands restored] and 1 m:4 km, respectively. The mode of this triangular distribution is the U.S. Army Corps of Engineers empirical rule, 1 m:14.5 km. To incorporate the attenuation rate into our simulation analysis, we employ a simplified rule-based approach to determine the amount of storm surge height attenuation. First, we draw a rate from this triangular distribution. Next, the Saffir-Simpson storm category is determined by the simulated wind speed. The simulated non-attenuated storm surge amount is then the midpoint of the range of storm surge heights expected for the Saffir-Simpson category. Finally, we subtract the amount of storm surge reduction implied by the simulated attenuation rate from the midpoint of the Saffir-Simpson category surge to obtain the attenuated storm surge. It must be noted, however, that this simplified approach used in our simulation may not be valid for some events, as the relative level of surge reduction may diminish as the overall surge potential increases (Loder et al. 2009).

For our case study, our wetland restoration option involves the restoration of wetlands sufficient to attenuate storm surge height by 2 ft using dredged material wetlands (Turner and Streever 2006) under the assumption of the U.S. Army Corps empirical rule of thumb, ignoring uncertainty in the attenuation rate. This leads to restoring to wetlands to a distance of 2.5 miles out from the coast. Under these assumptions, the wetland area we have restored in our case study is 3500 ha, requiring an initial investment of $140,000,000.

4 Electric power network hardening

The electric power system for our case study city is shown in Fig. 1, while a descriptive overview is provided in Table 2. The as-is overhead network equipment is indicated by numbered poles, while existing underground equipment are designated by nodes with no numbers. A transmission line runs along the railroad in the middle of the city. The railroad also separates the city into the distinct hurricane storm surge zones listed above: Category 3 east of the railroad, Category 5 west of the railroad. In this

Table 2 Project area descriptive figures

Miles of circuit line	9.6 mi
Depth of micropolis area inland	1 mi
Project area	0.5 mi^2
Number of residential customers	434
Number of commercial, industrial, other customers	24
Hurricane category (surge zone)	3 (East of railroad) 5 (West of railroad)

analysis, we consider three scenarios: undergrounding all electric power equipment east of the railroad (Scenario 1); undergrounding only the electric power equipment in the commercial zone east of the railroad (Scenario 2); and making no changes to the existing network configuration (Scenario 3).

First, we discuss the fragility curve assumptions we employ in our model. The fragility curves for underground and overhead power network components are of critical importance for evaluating the impacts of hurricanes on electric power infrastructure. While overhead electric power network infrastructure is primarily impacted by the wind associated with hurricanes, underground infrastructure is primarily impacted by storm surge. As storm surge inundates inland areas, pad-mounted transformers, buried lines in unsealed conduits may be damaged, and underground equipment may be uncovered as the surge recedes. In our model we then used a connectivity-based approach for estimating the impacts of power system component failures on power supply to individual buildings. We assume that if a building is connected to the substation, it can receive power. A failure of a line, transformer, or pole is assumed to break the path on which that component resides. While this approach does not capture power load flow balance and short-term system dynamics, it is a reasonable first approximate for a low-voltage, radial-topology power distribution system such as the one used in our test case. For a high-voltage transmission system, a full power load flow model would likely be needed.

To estimate the fragility curves for underground and overhead power network components, we use data primarily from Han et al. (2009), and Brown (2009). Han et al. (2009) uses data from a large investor-owned utility (IOU) in the Gulf Coast region to estimate power outages from hurricanes and to estimate a fragility curve for wooden poles. The fragility curve for a distribution pole, as a function of wind speed, is found to be approximated by the cumulative distribution function (cdf) of a normal distribution with mean parameter 154 and shape parameter 27. These assumptions are presented in Table 3. Three cases for the project area are now evaluated, using probability and cost estimates for underground equipment failure from Xu and Brown (2008) and Brown (2009): (1) all existing equipment is overhead (no changes); (2) all equipment in the storm surge category 3 zone is placed underground; and, (3) only the electrical equipment in the commercial area in storm surge category 3 zone is placed underground. According to Xu and Brown (2008) and Brown (2009), reasonable estimates of the annual maintenance costs per circuit mile for an overhead system are \$4,500, including tree-trimming, and the annual maintenance costs per circuit-mile for underground equipment is \$4,000. The initial investment costs for undergrounding existing equipment is estimated as \$1.333 million per circuit-mile (Xu and Brown 2008; Brown 2009). This includes the cost of undergrounding non-electric equipment such as cable and telephone lines. No initial investment is included in this analysis for overhead circuitry because the system currently exists as an

Table 3 Cost and storm-condition reliability assumptions for undergrounding analysis

Initial investment for undergrounding existing overhead equipment	\$1,333,333/circuit-mile
Repair cost for overhead system component failure	\$4,000/component
Repair cost for underground system component failure	\$60,000/component
Cost of residential customer interruption hour	\$2.70/h
Cost of commercial customer interruption hour	\$886/h
Cost of industrial customer interruption hour	\$3,853/h
Economic output stimulated by \$1 million investment n in electric power network constructio	\$1,160,000
Economic output stimulated by \$1 million investment in electric power network maintenance	\$1,160,000
Greenhouse gas emissions produced by \$1 million investment in electric power network maintenance and construction	676 $MtCO_2E$
Greenhouse gas emissions produced by \$1 million general economic activity	503 $MtCO_2E$/\$1 million GDP-PPP
Monetary value of greenhouse gas emissions	16,000,000 \$/$MtCO_2E$
Probability of pole/span failure as function of windspeed, x (mph)	$p = \Phi\left(x \,\middle|\, \mu = 154, \sigma^2 = 27\right)$
Probability of underground equipment failure	0.13
Time to service restoration for overhead line failure	4 h
Time to service restoration for underground line failure	10 h
Time to service restoration for transformer failure	6.5 h
Average residential rate	\$0.11/kWh
Average commercial/industrial rate	\$0.16/kWh

overhead system. We can then estimate the amount of economic output stimulated by investing in underground power line construction using a multiplier obtained from the EIO-LCA model (The Green Design Institute 2009). We also estimate the equivalent greenhouse gas emissions from this amount of construction from the EIO-LCA model as 676 Mt CO_2 equivalent ($MtCO_2E$) emissions per \$1 million invested in electric power network construction (NAICS Sector 237130). The environmental impact and economic output stimulated by electricity production is slightly different, \$0.6 million and 9,160 $MtCO_2E$ per \$1 million of economic activity, also estimated using the EIO-LCA model. These later numbers are needed for estimating the reduction in environmental impacts due to lost electricity production when power systems fail after hurricanes. We consider only the contributions to global warming potential as environmental impacts, though other emissions would be associated with construction and power generation activities. To convert the environmental impacts to a monetary value, we assign the spot price for a 1 $MtCO_2E$ certified emission reduction (CER) on the European Climate Exchange (2009) as the economic value of 1 $MtCO_2E$. On 30 December 2009, the price of a CER in USD is \$16.00 per metric ton (\$16 million per Mt). Because of the possibility of cap and trade being adopted in the U.S., we assume the cost of 1 Mt CER is the economic value of 1 $MtCO_2E$. To estimate the private losses associated with interruptions due to system component failures, we assume the cost of an interruption-hour for residential, commercial, and industrial customers is \$2.70, \$886, and \$3,853, respectively (LaCommare and Eto 2006).

Finally, we must estimate the influence of reliability on costs. We assume that the repair cost for overhead system element failures is \$4,000 per failure, while the repair cost for underground system element failures is $60,000 per failure (Xu and Brown 2008). We ignore differences in non-storm reliability between overhead and underground systems as a first approximation. We estimate the hurricane failure probability of poles from Han et al. (2009). The failure probabilities of spans and pad-mounted transformers for underground and overhead equipment and the time to service restoration for overhead and underground system elements are approximated based on empirical rules of thumb (Xu and Brown 2008). The cost per customer interruption hour for residential and commercial customers is estimated from Florida Public Utilities Commission data (Xu and Brown 2008).

5 Results

5.1 Micropolis case study results

Here we present the results of our analysis for the three scenarios. For the purpose of this base case, the portion of Micropolis east of its railroad is classified as a hurricane storm surge category 3 zone, while the portion of Micropolis west of the railroad is a category 5 zone. Because we make no changes to west Micropolis, and the storm surge zone category for this area is much higher than the intensity of storms experienced in this area, surge-induced failures in this zone will not occur in our simulation model. Consequently, we neglect the cost of underground maintenance and failure in this zone. The scenarios proposed are illustrated as a decision tree in Fig. 2. Finally, our base case scenario assumes a time horizon of 50-years and a discount rate of 8% applied to all utility investments and imposed costs. We reserve discussion of the impact of choice of discount rate for a later section.

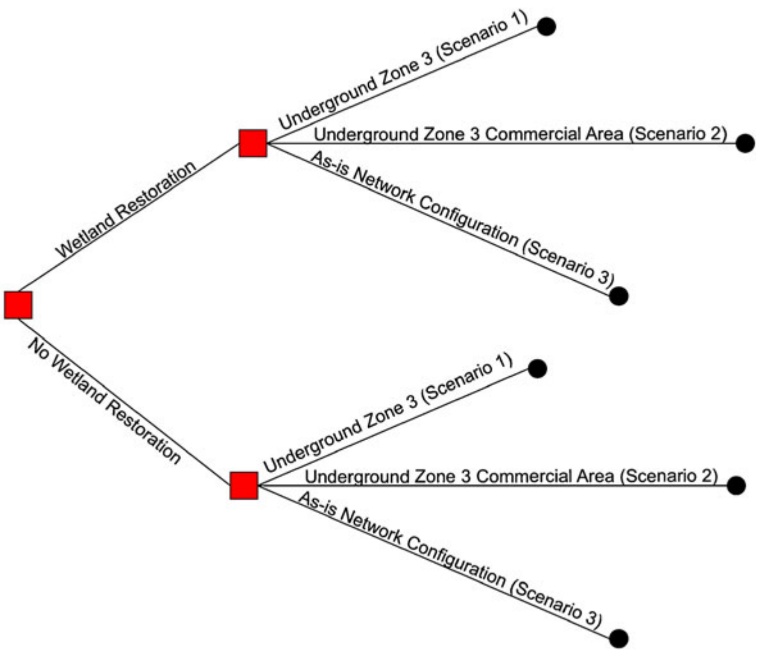


Fig. 2 Decision tree illustrating proposed scenarios for analysis with and without wetland restoration

5.1.1 Life cycle cost results, no environmental costs considered

The life cycle cost results for the base case with no wetlands restoration and no environmental costs included is shown in Table 4. Table 4 reports the costs of each option without considering environmental impacts over the project life cycle. This table suggests that Scenario 1 (S1), with no wetland restoration, has the highest project life cycle costs of any option. Although these costs are primarily the cost of the initial undergrounding investment, we see that Scenario 1 (the complete underground conversion) costs more than Scenario 3 (S3, the completely overhead case) in terms of expected private losses (e.g., business losses). This increased relative cost may be due to the large costs of downtime for an underground system component failure. Although the expected utility costs are less for Scenario 1, the initial mitigation investment excluded, these costs savings do not appear to justify the undergrounding investment. Similar observations may be made for Scenario 2 (S2, underground conversion of commercial zone only) relative to Scenario 3. While the utility expected costs are lower for Scenario 2 than Scenario 3, any advantage these savings might suggest is tempered by the large initial investment and increased private losses for Scenario 2 relative to Scenario 3.

Table 5 reports the costs among the options including wetland restoration. This table suggests that when wetland restoration is included in the life cycle cost analysis, the choice among options is similar to the decision excluding wetlands. The cost difference and allocation among the cost components is close to the results reported in Table 4, with the exception of the substantially higher cost of wetland restoration construction. Although including wetlands reduces the costs to private losses approximately 29%, thus reflecting a reduction in the failure rate of underground components, this synergistic cost reduction does not justify the investment in disaster mitigation by undergrounding and wetland restoration.

While Tables 4 and 5 report average costs, these tables do not indicate the amount of variability in the simulation cost estimates. Figure 3 reports the empirical cumulative density function for the absolute value of the life cycle project losses. In this figure, expected life cycle losses are the sum of the expected utility costs and the

Table 4 Average costs for 50-year life cycle of three hardening scenarios, excluding wetland restoration and induced economic output and environmental costs (Million USD, 8% discount rate)

	Scenario 1, no wetlands	Scenario 2, no wetlands	Scenario 3, no wetlands
Maintenance costs	$(0.490)	$(0.527)	$(0.534)
Mitigation investment	$(8.744)	$(1.355)	N/A
Planned utility costs, C1	$(9.234)	$(1.882)	$(0.534)
Planned costs imposed on society, C2	$–	$–	$–
Cost of repairs	$(0.0145)	$(0.0215)	$(0.0157)
Lost revenue due to Disaster	$(0.00587)	$(0.0326)	$(0.0307)
Expected Utility Costs, C3	$(0.0203)	$(0.0542)	$(0.0464)
Expected Private Losses	$(0.0396)	$(0.0332)	$(0.00606)
Disaster costs imposed on society, C4	$(0.0396)	$(0.0332)	$(0.00606)
Total life cycle costs	$(9.294)	$(1.969)	$(0.586)
Average number of hurricanes in 50-year project life cycle	3.44	3.51	3.41

Costs are averaged over the $N = 1{,}000$ simulations of the 50-year life cycle

Table 5 Average costs for 50-year life cycle of three hardening scenarios, including wetland restoration while excluding induced economic output and environmental costs (Million USD, 8% discount rate)

	Scenario 1, with wetlands	Scenario 2, with wetlands	Scenario 3, with wetlands
Maintenance costs	$(0.490)	$(0.527)	$(0.534)
Mitigation investment	$(138)	$(131)	$(130)
Planned utility costs, C1	$(139)	$(132)	$(130)
Economic value of wetland ecosystem services	$467	$467	$467
Planned costs imposed on society, C2	$467	$467	$467
Cost of repairs	$(0.0145)	$(0.0206)	$(0.0157)
Lost revenue due to disaster	$(0.00587)	$(0.0282)	$(0.0329)
Expected utility costs, C3	$(0.0203)	$(0.0488)	$(0.0486)
Expected private losses	$(0.0396)	$(0.0280)	$(0.00648)
Disaster costs imposed on society, C4	$(0.0396)	$(0.0280)	$(0.00648)
Total life cycle costs	$328	$335	$336
Average number of hurricanes	3.44	3.51	3.41

disaster costs imposed on society (e.g., C3 + C4). Although Fig. 3 does not include environmental costs or induced economic activity, Fig. 3 gives a more illustrative picture of the variability in lifecycle costs associated with each scenario.

Figure 3 shows that, while wetland restoration does not induce large life cycle loss differences under any scenario, Scenario 1's cost curve is shifted to the left of the curves for Scenarios 2 and 3. Thus, the larger average cost of Scenario 3 reported in Tables 4 and 5 may be due to the larger tail of Scenario 1's distribution relative to Scenarios 2 and 3. Indeed, Fig. 4 seems to contradict the results reported in Tables 4

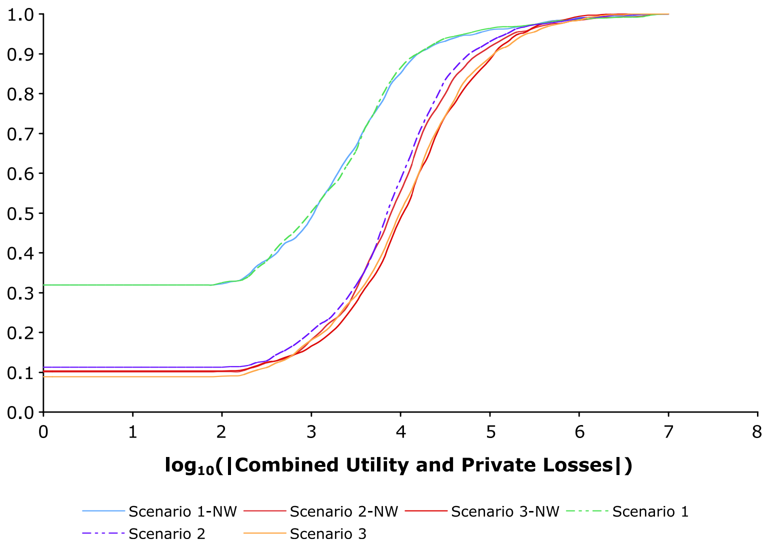


Fig. 3 Empirical CDFs for 1,000 simulations of the 50-year life cycle losses (C3+C4) under each scenario

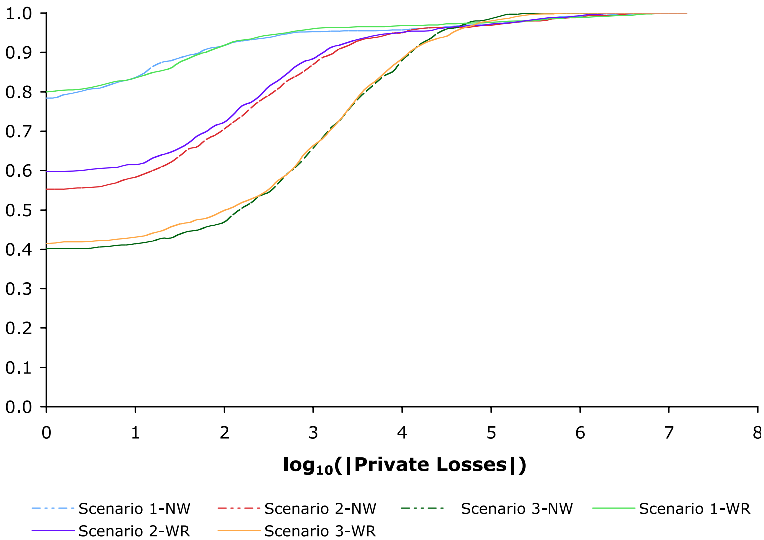


Fig. 4 Empirical CDFs for 1,000 simulations of the 50-year life cycle private losses (C4) under each scenario

and 5, especially for private losses (C4). Figure 4 reports the cost curves for private losses under each scenario, excluding induced economic output and environmental costs. Figure 4 suggests two observations. First, in the event of a disaster, most costs will be borne by Micropolis' power utility. Second, although the average private loss is largest under Scenario 1, Scenario 1 has the largest probability that no private losses will be incurred when compared to Scenarios 2 and 3 (70–80% vs. 55% and 40%, respectively).

5.1.2 Life cycle costs, induced economic and environmental costs included

In, Table 6 we report the results of our base-case analysis including environmental costs, but excluding the economic value of wetlands' ecosystem services. These results include economic activity and greenhouse gas emissions induced (or averted) by maintenance and mitigation activities, repair costs, revenue losses, and private losses.

Generally, the case study results including environmental costs reinforce the observations made from the life cycle analyses excluding environmental costs. This may be attributable primarily to the price of carbon emission reductions relative to the amount of carbon emitted by general economic activity. First, consider private losses under each scenario. While private losses remain greater in Scenarios 1 and 2 relative to Scenario 3, the carbon emissions averted by private losses is only 503 MtCO2E per \$1 million private losses in terms of $MtCO_2E$/\$GDP-PPP. On the other hand, the amount of carbon emitted by electricity production is nearly 20 times greater than the amount of carbon emitted by general economic production (9,160 $MtCO_2E$ from electricity generation:503 $MtCO_2E$ from economic activity). Because the private losses are greater in the full undergrounding case, and electric power production forces much more greenhouse gas production than general economic production, the favorability of the status quo is enhanced by the inclusion of environmental costs.

Table 6 Average costs for 50-year life cycle of three hardening scenarios, including wetland restoration, and induced economic output and environmental costs (Million USD, 8% discount rate)

	Scenario 1, with wetlands	Scenario 2, with wetlands	Scenario 3, with wetlands
Maintenance costs	$(0.490)	$(0.527)	$(0.534)
Mitigation investment	$(138)	$(131)	$(130)
Planned utility costs, C1	$(139)	$(132)	$(130)
Economic output induced by maintenance	$0.569	$0.611	$0.619
Economic output induced by mitigation	$160	$151	$150
Environmental costs of maintenance	$(5,305)	$(5,703)	$(5,776)
Environmental costs of mitigation	$(1,496,000)	$(1,416,000)	$(1,402,000)
Economic value of wetland ecosystem services	$467	$467	$467
Wetland carbon sequestration	$504	$504	$504
Planned costs imposed on society, C2	$(1,500,000)	$(1,421,000)	$(1,406,000)
Cost of repairs	$(0.0145)	$(0.0206)	$(0.0157)
Revenue loss due to disaster	$(0.00587)	$(0.0281)	$(0.0329)
Expected utility costs, C3	$(0.0203)	$(0.0488)	$(0.0486)
Economic output induced by repairs	$0.0168	$0.0239	$0.0182
Lost economic output induced by revenue loss	$(0.00939)	$(0.0451)	$(0.0526)
Direct private losses	$(0.0396)	$(0.0280)	$(0.00647)
Environmental costs of repairs	$(157)	$(223)	$(170)
Environmental costs averted by revenue loss	$860	$4,129	$4,821
Environmental costs averted by private losses	$0.000319	$0.000225	$0.000052
Disaster costs imposed on society, C4	$703	$3,906	$4,652
Total life cycle costs	$(1,500,000)	$(1,418,000)	$(1,402,000)
Average number of hurricanes in project cycle	3.44	3.51	3.41

In future applications of this methodology, more case-specific cost assumptions must be made in lieu of our demonstrative assumptions. Important considerations include construction of a hybrid EIO-LCA model for the specific construction processes involved and the local economy impacted, wetland valuation methods specific to the wetland habitat to be restored, and more realistic surge attenuation modeling employing SLOSH or ADCIRC (e.g., Loder et al. 2009; Resio and Westerink 2008; Wamsley et al. 2009, 2010).

5.2 Sensitivity analysis

We evaluate the sensitivity of our results to: 1.) The number of hurricanes expected to impact the project area over the 50-year life of the project; 2.) The rate of storm surge attenuation observed over marsh wetlands; and, 3.) The separation between social and private decision makers represented by the choice of different social and private time discounting rates. We choose these parameters for sensitivity analysis because we expect that overall costs are most influenced by the total number of hurricanes making landfall in the project area, while the potential synergies between wetland restoration and electric power network hardening would be most influenced by the rate of storm surge attenuation observed. Furthermore, the choice of a time discount rate is quite controversial, and we would like to understand more about how the dichotomy among decision maker classification might influence our results.

5.2.1 Sensitivity to number of hurricanes impacting project area

First, Fig. 5 reports the average life cycle costs, excluding environmental and economic impacts, for the three scenarios including wetland restoration under different assumptions about the number of hurricanes expected to influence the project area. Figure 5 assumes a wetland storm surge attenuation rate of 1 m:14.5 km, and an 8% discount rate. Although North Carolina may be reasonably expected to receive an average of 3–5 hurricanes in a 50-year planning horizon, we show results for a range of 3–15 hurricanes over a 50-year planning horizon for extension to other local cases. These results reflect the intuitive idea that the life cycle costs increase as the number of hurricanes increases. The top panel of Fig. 5 illustrates that under Scenarios 1 and 2, utility costs are less than the costs imposed on society through private losses, while for Scenario 3, private losses are always less than utility costs. In addition, Fig. 5 suggests that private losses under Scenario 3 are most sensitive to increases in the number of hurricanes. The bottom panel of Fig. 5 reports the probability that no loss is incurred over the 50-year project life cycle. Although the probability that no loss is incurred decreases substantially for each scenario as the number of hurricanes increases, the probability that no private loss is incurred remains much higher under Scenario 1 than the other Scenarios proposed. For Scenario 1, the probability that no private losses are sustained remains higher than 0.5 until the number of expected hurricanes over the 50-year project life cycle increases beyond 10.

5.2.2 Sensitivity to wetland storm surge attenuation rate

On the other hand, our results are much less sensitive to wetland storm surge attenuation. Figure 6 reports the average life cycle costs, excluding environmental and economic impacts, for the three scenarios. Figure 6 assumes that five hurricanes are expected to impact the project area over the 50-year life cycle, and that a discount rate of 8% applies. In short, Fig. 6 suggests that life cycle costs for Micropolis are not sensitive to changes in the wetland storm surge attenuation rate over the range of reported surge attenuation rates. Although utility and private losses are decreased by approximately 30% over the range of attenuation rates under Scenario 1, the probability that no costs will be incurred is much less sensitive. This may be due to the small range between the minimum and maximum storm surge attenuation rates observed. Nonetheless, these results, when considered alongside the literature investigating storm surge attenuation over wetlands, reinforce the importance of detailed wetland modeling for local risk analysis and investment planning purposes. While our results show that damages in Micropolis are not sensitive to wetland storm surge attenuation rate, Gedan et al. (2010) report that 60% of the variation in damages inflicted on US coastal communities in 34 major hurricanes since 1980 is explained by differences in coastal wetlands.

5.2.3 Sensitivity to public and private discount rates

The choice of discount rate for evaluating public projects is controversial, especially with respect to evaluating climate change mitigation investments. In fact, one of

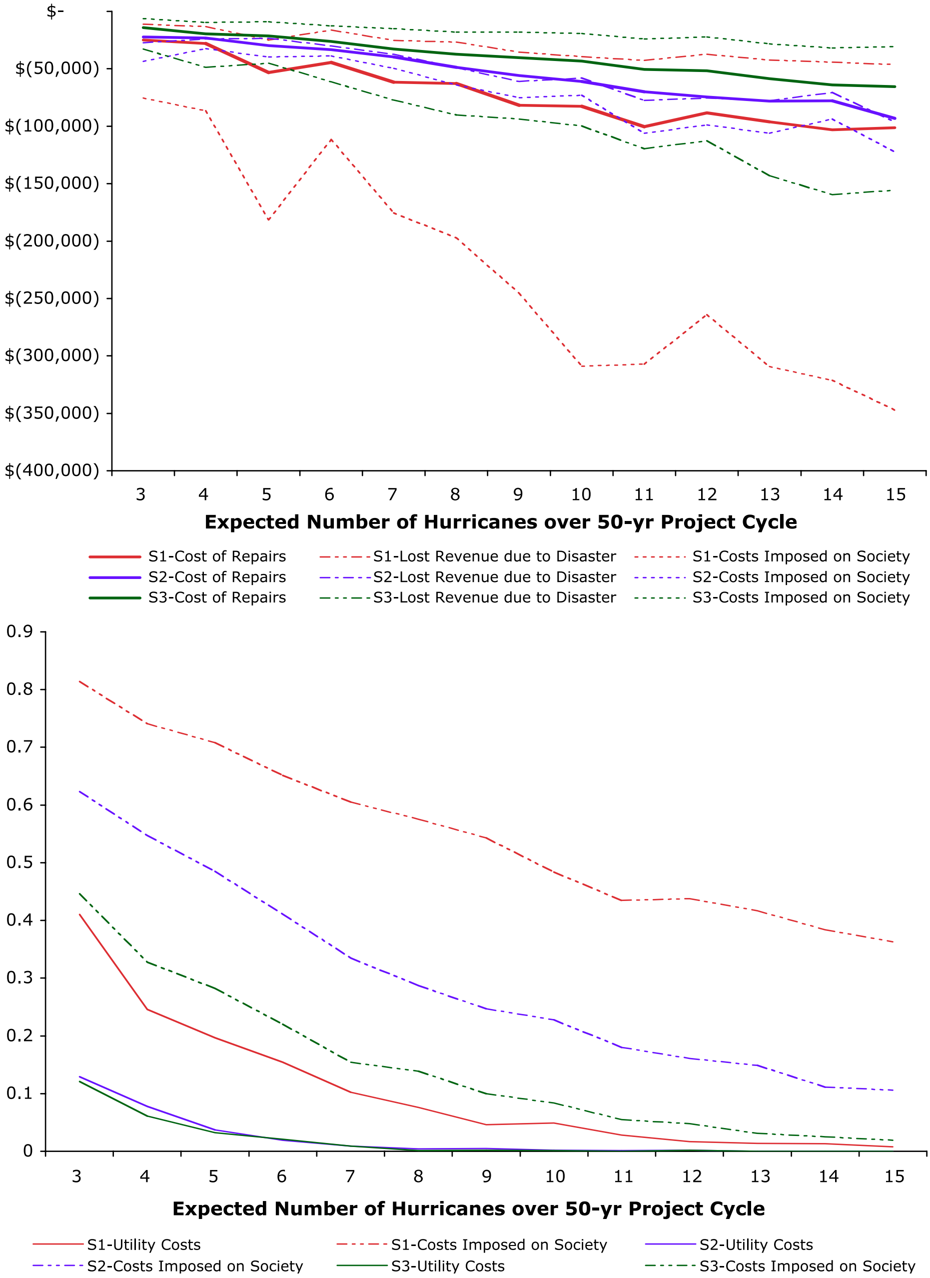
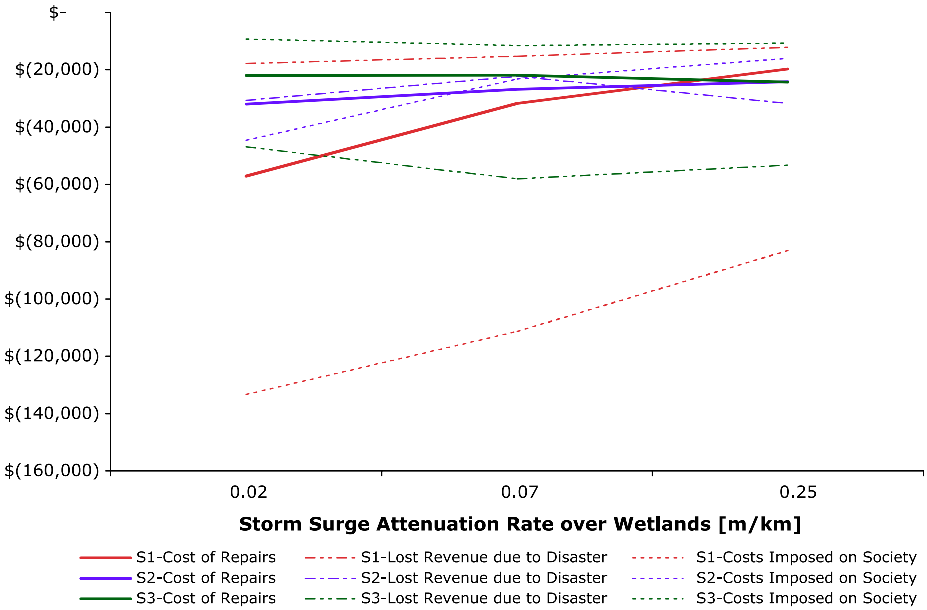


Fig. 5 Sensitivity of average 50-year life cycle costs (excluding environmental and economic impacts) and probability that no losses are incurred to the number of hurricanes expected over the 50-year project cycle

the principal streams of criticism of the *Stern Review on the Economics of Climate Change* (Stern et al. 2006) concerns the assumptions made surrounding the choice of an appropriate discount rate (Nordhaus 2007; Weitzman 2007; Tol and Yohe 2009).



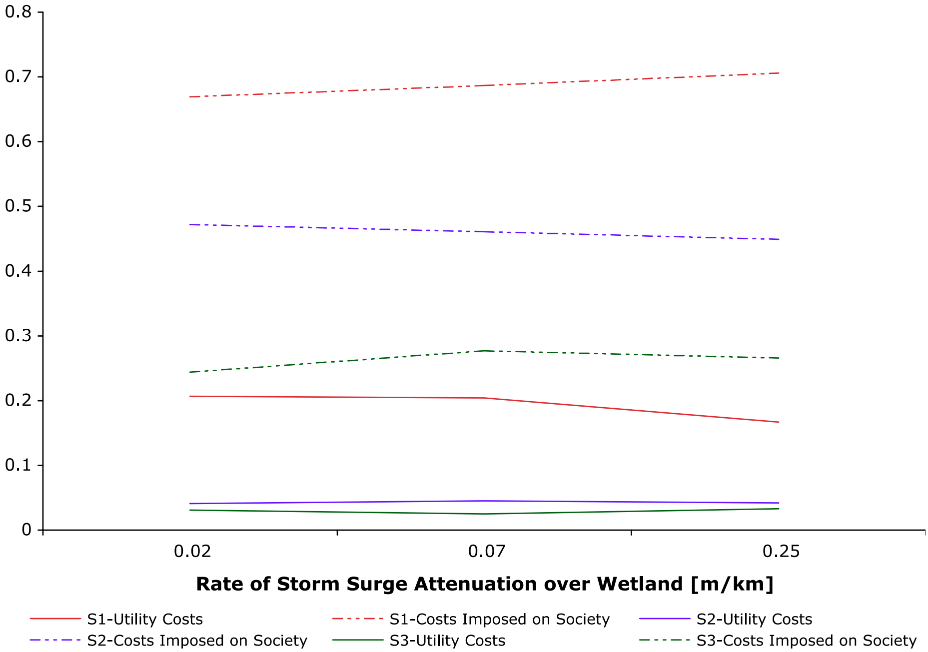


Fig. 6 Sensitivity of average 50-year life cycle costs (excluding environmental and economic impacts) and probability that no losses are incurred to the rate of wetland storm surge attenuation

While we do not wish to enter this debate, this discussion indicates the gravity with which time preferences must be considered when evaluating private investments that impose considerable public costs and benefits. Consequently, we do consider it necessary to discuss the role of the social and private decision makers when evaluating the potential synergy between wetland restoration and infrastructure disaster loss mitigation. As indicated, we have assumed a 50-year time horizon for evaluating the electric power hardening investments. This time horizon is symbolic of the difficult negotiation among public and private benefits, as the utility is expected to develop and manage the infrastructure, while the public must reckon with the externalities. In addition, this time horizon amplifies the importance of this negotiation because this relatively short time horizon implicitly requires that the private (utility) decision makers and the public (social/government) decision makers be represented separately since their benefits accrue on different time scales. For the private utility investments and expected costs of repairs and lost revenues, then, we assume an 8% discount rate. This reflects the private utility's preference to accrue benefits earlier in the project life cycle, as only approximately 2% of the expected costs and benefits accrued at the end of the 50-year life cycle are included in the present value. On the other hand, the choice of a social discount rate for the costs imposed on society by service interruptions and utility investments is assumed to

Table 7 Sensitivity of average costs for 50-year life cycle of three hardening scenarios to two-decision maker scenario, including wetland restoration, and induced economic output and environmental costs. (Millions USD) assumes 8% private, 2% social discounting rate

	Scenario 1, with wetlands	Scenario 2, with wetlands	Scenario 3, with wetlands
Maintenance costs	$(0.490)	$(0.527)	$(0.534)
Mitigation investment	$(138)	$(131)	$(130)
Planned utility costs, C1	$(139)	$(132)	$(130)
Economic output induced by maintenance	$1.461	$1.571	$1.591
Economic output induced by mitigation	$170	$161	$159
Environmental costs of maintenance	$(13,629)	$(14,649)	$(14,836)
Environmental costs of mitigation	$(1,584,700)	$(1,500,100)	$(1,484,500)
Economic value of wetland ecosystem services	$1,199	$1,199	$1,199
Wetland carbon sequestration	$1,295	$1,295	$1,295
Planned costs imposed on society, C2	$(1,596,000)	$(1,512,000)	$(1,497,000)
Cost of repairs	$(0.0148)	$(0.0211)	$(0.0158)
Revenue loss due to disaster	$(0.00374)	$(0.0298)	$(0.0360)
Expected utility costs, C3	$(0.0186)	$(0.0509)	$(0.0518)
Economic output induced by repairs	$0.0475	$0.0595	$0.0484
Lost economic output induced by revenue loss	$(0.0166)	$(0.107)	$(0.152)
Direct private losses	$(0.0565)	$(0.0714)	$(0.0189)
Environmental costs of repairs	$(442)	$(555)	$(451)
Environmental costs averted s by revenue loss	$1,521	$9,828	$13,919
Environmental costs averted by private losses	$0.000454	$0.000574	$0.000151
Disaster costs imposed on society, C4	$1,078	$9,273	$13,467
Total life cycle costs	$(1,594,707)	$(1,502,913)	$(1,483,394)
Average number of hurricanes in project cycle	3.41	3.51	3.44

be 2%. This reflects the public's general unwillingness to bear the costs imposed on them by electric power infrastructure construction, repairs, or failure. An 8% discount rate incorporates approximately 37% of the expected costs and benefits accrued to society at the end of the 50-year life cycle are included in the present value. This public–private tradeoff implies that costs over the duration of the project life-cycle and beyond should more greatly influence public decision-making when considering electric power infrastructure hardening investments. We report results for this case, including wetland restoration investment, and induced social, economic, and environmental costs, in Table 7. Table 7 shows that, while the environmental and social costs and benefits associated with risk mitigation investments take on increased importance if a social rate of discounting is assumed, the decision is still dominated by the price of carbon. We also evaluated 16 pairwise combinations of social discount (0%, 1%, 2%, 3%) and private discount (6%, 8%, 10%, and 12%) rates. These results are not reported here, as the results are not sensitive to changes in the discount rates over these ranges. Nonetheless, our sensitivity analysis indicates that the decision is still dominated by the price of carbon emitted during construction and maintenance of restored wetlands and electric power network hardening. Thus, when evaluating risk mitigation and natural restoration decisions, the choice of discount rate may be most important for larger projects, especially if the price of carbon is not included.

6 Lessons learned

In summary, our multi-criteria life cycle framework suggests several interesting implications for future research and planning for wetland restoration projects when applied to disaster loss mitigation. Table 8 summarizes the results for each scenario for each of the three cases examined. For all cases, no infrastructure hardening and no wetland restoration is justified in our case study location. However, we do suggest a few specific areas for additional research:

1. The life cycle analysis must consider non-monetized ecological benefits of wetland restoration and account for the CO_2 production they avert. For example, when considering CO_2 emissions in the analysis, the potential for the restored wetland to become a carbon sink must be evaluated. Even modest amounts of wetland CO_2 sequestration may improve the attractiveness of the project when

Table 8 Summary of the results for each infrastructure hardening scenario for each case

Case:	1	2	3
Wetland restoration:	Excluded	Included	Included
Induced economic output:	Excluded	Excluded	Included
Environmental impacts:	Excluded	Excluded	Included
Scenario	E[NPV]	E[NPV]	E[NPV]
1: Underground all eligible components	($9,294)	($0.0396)	($1,500,000)
2: Underground only the commercial district	$(1,969)	($0.0280)	($1,418,000)
3: No undergrounding	($0.543)	($0.006)	($1,402,000)
Preferred alternative	Do nothing	Do nothing	Do nothing

Costs are in million of US dollars

considered in conjunction with the economic value of the wetlands ecosystem services and the CO_2 emissions averted through ecosystem process production.

2. In the future, simulation of storm surge propagation over constructed or natural wetlands using more sophisticated models such as SLOSH or ADCIRC may be the most accurate method of disaster risk assessment. This approach has been performed in several of the studies cited here (Loder et al. 2009; Resio and Westerink 2008; Wamsley et al. 2009, 2010), and may more accurately capture the effects of spatial and temporal heterogeneity in wetland topology, composition, and continuity. Furthermore, storm surge simulation may allow for more flexible examination of the influence of factors not yet considered, including wetland morphology and wave setup. In addition, because the response of wetlands to storms, and storm surge to wetlands, may be interactive in nature, stochastic simulations may be necessary to capture any potential feedback cycles between wetland morphology and storm surge attenuation (e.g., consider findings of Wamsley et al. 2009)
3. This work must be replicated using either a larger model city testbed, or a testbed with a different distribution of residential, commercial, and industrial customers. This work suggests that the attractiveness of a wetland restoration project for disaster loss mitigation may be sensitive to the customer mix, although we do not evaluate this sensitivity in this paper. Furthermore, detailed regional economic resilience models should be developed and employed when applying our framework to a real case. The economic model may become more important when extending the framework to interdependent infrastructures.
4. Although our case study reports that undergrounding and wetland restoration may increase social costs relative to a completely overhead electric power network configuration, the probability that no social costs are imposed is greatly increased under the undergrounding and wetland restoration scenarios proposed in this paper. Future investigation may find this property of electric power network hardening valuable, and should be investigated in conjunction with storm surge simulation and interdependent infrastructure evaluation.

Overall, our results have important implications for coastal adaptation. Natural ecosystem restoration may be difficult to justify as an approach for coastal adaptation without considering the valuation of biodiversity, ecological services, and carbon sequestration. While these issues pose difficult valuation problems, the more directly quantifiable benefits of wetland restoration may not offset the significant cost of restoring or building wetlands in many locations.

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