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Analyzing the Effects of Policy Options to Mitigate the Effect of Sea Level Rise on the Public Health and Medically Fragile Population: A System Dynamics Approach

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Abstract

A critical question related to climate change concerns to how rising sea level will affect underserved populations and medically fragile population in coastal zones and floodplains. As sea levels rise, coastal waters will regain near-tidal areas and co-mingle with human-made pollutants, resulting from decades of industrial and commercial activity. This poses potential threat and risks to public health and the environment. It is critical that decision makers will initiate a process of parsing resources to the mitigation and management of these issues. The purpose of this research is to model the inherent dynamics of this process and understand how near-term policy decisions will condition the dynamics of population health within traditionally underserved and medically fragile populations. We use a System Dynamics (SD) approach to model and simulate the sensitivity of affected populations to a range of remediation policy options intended to address these contaminated environments. Our research will assist policy makers to explore and prioritize policies with a specific focus on vulnerability, guarantee that remediation funds will be utilized effectively and equitably, and increase effectiveness of mitigation and management effort.

1. INTRODUCTION

Climate change and associated sea level rise have the potential to substantially transform the social and cultural geography of many regions. A large portion of the world population lives on or near the coastline. More than half (53%) of the US population resides in coastal counties (Coast, 2010). Sea level rise is likely to influence the regional economies, impact the livelihood of many, and influence public health.

Extreme weather events have been forecasted to alter in magnitude and frequency (Greenough et al., 2001). The intensity of hurricanes in coastal areas may escalate (Emanuel, 1987). Coastal flooding and storm surges may be more severe as well (Dasgupta et al., 2009). Coastal flooding is also likely to disturb and exacerbate dangerous pollutants that impact air and water quality. Increasing temperatures promote growth of pathogens in climates were they previously were unsuited (Harvell et al., 2002). These factors will change the level and type of health, economic, and security risks posed to coastal populations. Populations already facing healthcare and socio-economic disparities such as medically fragile populations are particularly vulnerable to these challenges. The purpose of the present study is to model the potential impact of projected sea level rise on public health and the environments stemming from the reclamation of coastal areas. A system dynamics simulation model is proposed to understand the long-term health impact of coastal communities. Our modeling and simulation model allows stimulating the dynamic interaction and 'ripple effect' of adopting any combination of remediation options over time. Such approach could assist policy makers to prioritize policy on effectively allocation of resources for remediation and interventions on climate changes impact on public health, specifically, of underserved population.

The proposed model is divided into two modules. The first module takes into consideration the effects of sea level rise at a regional socio-economic macro level. The second module models the impact of sea level rise at a micro level at individual land parcels. At the macro level, essential issues such as economy, demography, and employment are explored. Changes in the regional economy stemming from sea level rise can act upon the vulnerability of populations by affecting employment patterns and hence health insurance. For example, a decrease in maritime and tourism in the region may lead to a rise in the unemployment level and loss of healthcare. At the micro level, projected sea level rise will impact land parcels in two ways. First, relatively higher valued residential properties more are likely to be occupied by better-off socio-economic (income and education) households who have better access to the healthcare system. Second, exposure to contaminants due to sea level rise affects health. The vulnerability of a particular parcel to pollutants can be accessed in terms of the anticipated level of inundation of that parcel and the level of pollution in the surface and groundwater water and adjoining areas.

Frequent exposure to such pollution has a detrimental effect on the health of individuals, especially the more sensitive population subgroups including children, elderly, and citizens with chronic and/or immune-compromised conditions. An incremental effect on health due to prolonged exposure to contaminants may aggravate other healthcare issues.

The central objective of this research is to understand how our near-term policy decisions, with regard to the extent and placement of remediation and containment efforts, will condition the dynamics of population health of traditionally underserved populations. Specific aims are to 1) identify and model critical variables that characterize the relationships among vulnerability and sea level rise, and 2) model the sensitivity of vulnerable and medically fragile populations to the various remediation and containment policy options.

1.1. Research Question

Policy makers are faced with central decisions in relation to the prioritization of remediation and containment efforts meant to mitigate the impact of potential sea level rise on the habitability of property and public health. Those land parcels that are expected to be reclaimed due to sea level rise are at increased vulnerability to flooding and storm surge. As sea levels rise, coastal waters will reclaim near-tidal areas and co-mingle with human-made pollutants from over a century of industrial and commercial activity. Some reclaimed sites will contaminate more than others and, hence, pose a bigger general public health threat to their surrounding communities.

Policy response to mitigate the impact of potential sea level rise may take the form of either containment (structures to hold back or reduce the potential for flooding) or remediation (cleaning contaminated sites that likely to be either reclaimed by rising waters or likely to be subject to increased storm surge flooding). Over the coming years there necessarily will be a process of parsing resources dedicated to the remediation and/or containment of some sites, while other sites will receive little or no attention. There likely will also be discussion of structural response (e.g., sea walls, revetments, gabions, levees) to protecting some areas, while leaving others vulnerable. It is within the next decade that the rough outlines of a regional remediation-reclamation-containment strategy will begin to take form. The setting of priorities and logic inherent in initial planning documents are developed in this initial period.

1.2. Research Approach

By modeling and simulating the interactions among sea level rise, public policy, and public health, an experimental framework will be established to measure and explore the second and third order effects of interventions. The behavior of a system is the result of dynamic interaction (e.g., feedback) among variables within the system. SD offers the ability to measure this dynamic interaction among system components. The ability to capture the complexity within a system is an advantage relative more simple mental models which are limited in their ability to envision the complexity of interactions that are some distance from the immediate problem. Through a SD framework, the extent of the dynamic impacts of multiple mitigation strategies over time may be quantified. These measurements are purposed to allow stakeholders, such as policy makers and traditionally underserved communities, to understand visualize the long term impacts of early policy options.

Conventional approaches have not been well suited to anticipate the second and third order consequences of competing and, many times, conflicting policy options upon the wellbeing of particular population segments. The SD approach permits decision makers to better understand the dynamic behavior of community health over time. It may reveal changes in the system's behavior which may be counterintuitive or would not have been apparent if approached using other methodologies. While system dynamics allows for a systemic view of the variables' interactions at an aggregate level, it is disadvantaged in that the approach does not capture stochastic variation and resolution down to individual or condition level. Nonetheless, SD is the tool of choice, since it offers the ability to produce technically representative models that are persuasive to stakeholders.

This research proposes a system science approach based on SD to represent and simulate interactions between sea level rise and public health. The four basic steps that gird our approach are as follows: 1) represent the general flow of populations for a given region, 2) represent the main factors that affect vulnerability, 3) represent the driving forces that act upon public health in the context of sea level rise and potential interventions to minimize it, and 4) simulate the system and validate results. In the following sections, the authors describe the salient features of the model that include both the macro and micro levels of analysis.

2. THE MODEL

It is hypothesized that the impact of projected sea level rise on populations is twofold. First, the effect is direct in the form of inundation and flooding of the properties located in proximity to the cost. The second effect is indirect involving the economic impact, unemployment, declining parcel and property values, and dwindling population. While the macro factors determine the exposure of a particular region to sea level rise, the micro factors determine the ability of the residents of a particular parcel of land to mitigate their risk from sea level rise.

Vulnerability is a comparative measure of the risk faced by any entity and the capability of such an entity to alleviate that risk(Adger and Vincent, 2005). The risk faced by any parcel or property can be described as a function of the property's elevation, distance from coast, and the rate of sea level rise. The ability of the residents of that property to mitigate that risk is more complex and depends on the property value, income, and employment status. These factors, in turn, are affected by the prevalent market conditions and the level of economic activity in the region. Sea level rise impacts these factors by reducing the attractiveness of a region as a consequence of the increased magnitude and frequency of extreme weather events which negatively affect maritime logistics activities, agriculture, fishing, and tourism. Thus, we are in the presence of a dual negative effect wherein the sea level rise not only increases the risk to the population, but also reduces their capability to respond to their risks.

2.1. The Macro Level

The causal loop diagram in Figure 1 below illustrates the high level causal relationships exposited it the macro level view of the system. The causal loop diagram indicates that a rising sea level poses a threat to the maritime activities which are economically vital for the coastal region (Nicholls et al., 2008). Representative industries include shipping and allied services, beach tourism, and fishing. In the Hampton Roads area, for example, the military has a major presence and is a major employer. Several military bases are located in this area their low elevation subjects the territory to flooding. In addition, sea level rise may compromise the ship handling capacity and may negatively impact the Navy's willingness to further invest in the region. Thus, in general, rising sea level is likely to make investment in the coastal areas by both government and private sectors less attractive. A decrease in the economic activity of the region is likely to reduce the value of real estate. Hwang (Hwang and Quigley, 2006) describes a direct relation between real estate prices and economic conditions. Simultaneously, the unemployment rate increases as fewer businesses choose to invest or remain in the coastal areas.

The rising potential unemployment leads to an increase in out-migration as people leave the area in search of employment elsewhere (Miller, 1973). This reduces the demand for residential housing stock and contributes to a drop in the hosing value (Reichert, 1990). As the value of real estate drops, it becomes increasingly difficult to justify further investment in remediation or containment efforts (Fankhauser, 1995). Decreases in containment efforts will leave parcels exposed leave the region vulnerable to flooding.

The general changes in the level of employment and value of property in such parcels may potentially affect all households within the area. However, the level of impact of these macro changes on a particular parcel varies.

2.2. The Micro Level

The causal loop diagram in Figure 2 illustrates the high level causal relationships exposing the micro level view of the system. Exogenous variables in this model include actual sea level rise, elevation of parcel, average housing value, original value of individual property in the parcel, percentage unemployment, and health-related vulnerability.

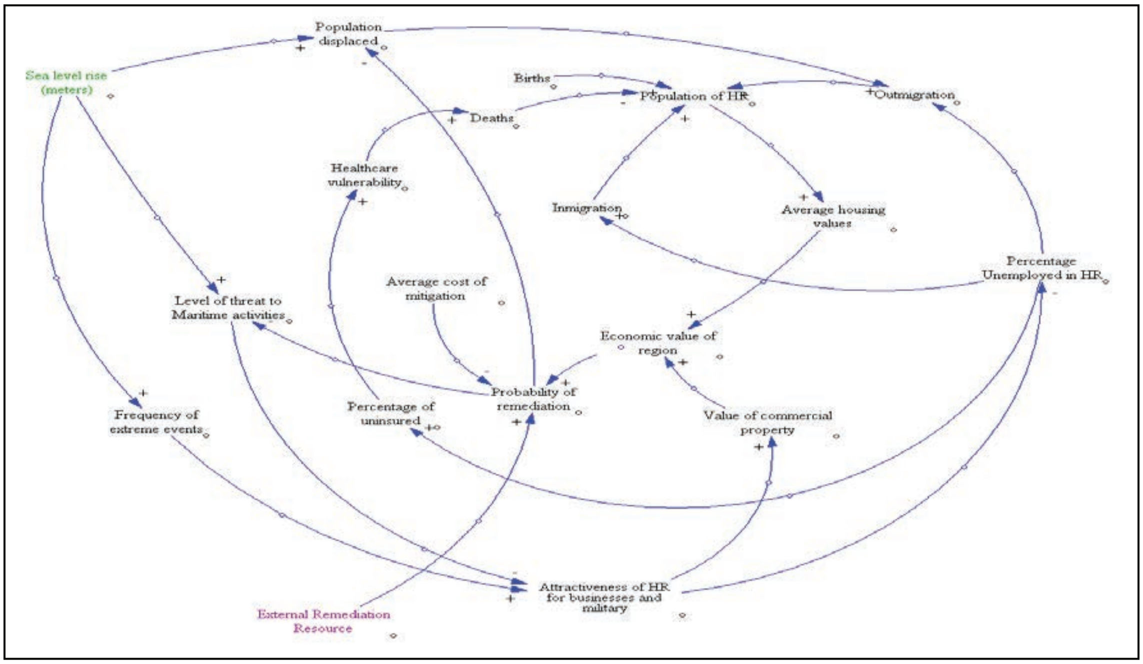

Figure 1 - Macro Level Model

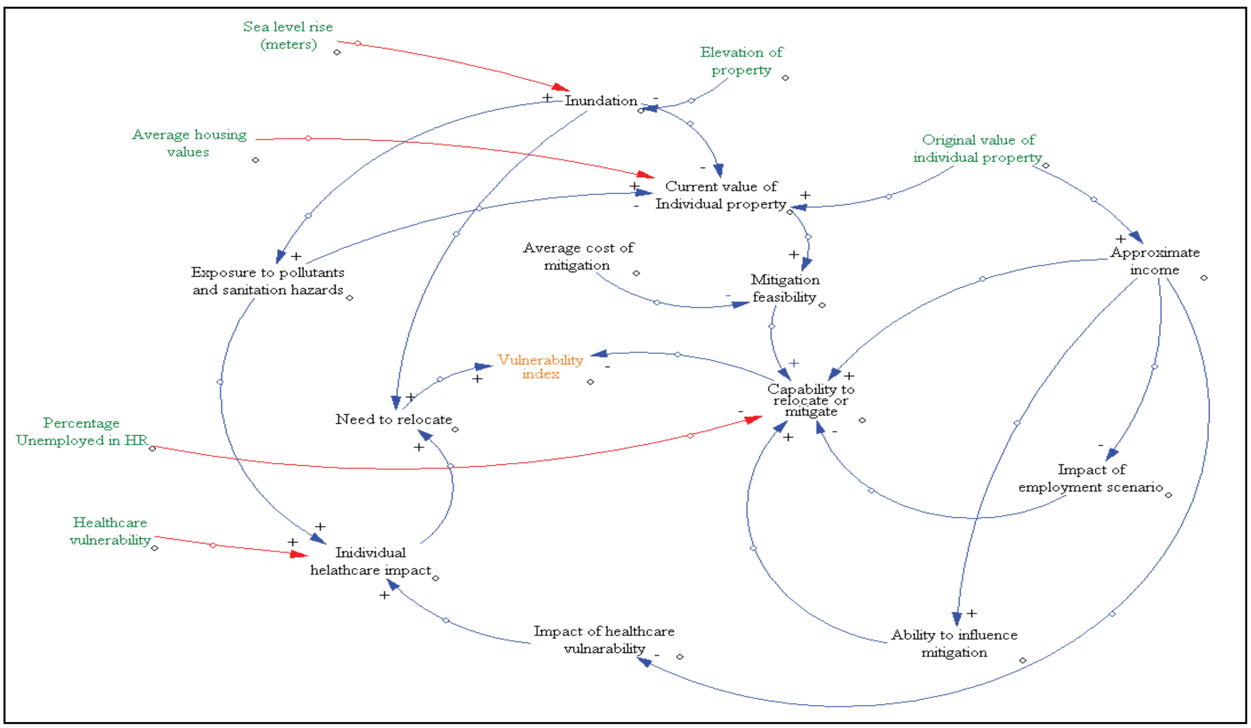

Figure 2 - Micro Level Model

Residential property values is assumed as a proxy for socio-economic status; residents living in high cost neighborhoods are likely to have a high household income and have a higher level of education, which further implies lower levels of unemployment (Ashenfelter and Ham, 1979). Wealthy neighborhoods are also assumed to exert influence within the public policy formation process; in particular, those relative modest and low income neighborhoods (add citation here). The containment of potential inundation by construction of protective structures may be more politically palpable when the cost of construction of such protective structures is less than the value of the parceled properties. The feasibility of mitigation is, by this logic, a function of the average cost of mitigation in the region and the value of the particular parcel(s).

While the above part of the model quantifies the capability of a particular parcel to contain sea level rise, the level of inundation and the healthcare impact determines population's need to relocate. A parcel and property located close to the coast and having low elevation is the most susceptible to inundation. In addition, such properties are susceptible to contaminants drawn out from the rising water, which in turn can negatively impact health. Five major contaminants found in the Chesapeake Bay, for example, include copper, mercury, atrazine, Ploychlorinated Biphenyls (PCBs) and Polycylic Aromatic Hydrocarbons (PAHs). The main health effects from exposure to these (Uriu-Adams and Keen, 2005), (United Nations, 2002), (Registry, 2003), (Registry, 1996) are exhibited in Table 1.

Issue	Negative effects
Copper	1. Effects on human health includes abdominal pain, nausea, vomiting, headache, lethargy, diarrhea, tachycardia, respiratory difficulties, hemolytic anemia, 2. Gastrointestinal bleeding, liver and kidney failure and death.
Mercury	1. Methylmercury is a well-documented neurotoxicant, which may in particular cause adverse effects on brain development of children. 2. It have been linked to increased risk of cardiovascular disease.
Atrazine	1. It affects the developmental and reproductive systems. 2. There are evidences linking atrazine use and some types of cancer
PCBs	1. PCBs are probably carcinogenic to humans. 2. It is linked to neurological and cognitive problems in young children. 3. PCBs could suppress normal immune responses.
PAHs	4. Some PAHs may cause short-term symptoms, e.g. eye irritation, nausea, vomiting, diarrhea, and confusion. 5. Some PAHs are probable human carcinogens 6. Long-term health effects of exposure to PAHs may include kidney and liver damage, and jaundice.

Table 1 - Five Major Contaminants and Health Effects

The healthcare impact has a cumulative effect; the more time the residents spend in proximity to the polluted property, the worse the health condition. Also, the ability to manage health-related impacts stemming from exposure is related to income and healthcare access; lower unemployment rates translates into better access to healthcare services due to insurance coverage.

3. PARAMETRIZATION AND RESULTS

The section provides the results of several simulations. The outcomes of these simulations provide useful insights about system behavior under particular scenarios. To demonstrate the model's functionality, a simple hypothetical case is developed. Tables 2 and 3 exhibit the variables and parameters used in this initial simulation demonstration. The simulated is played out for a period representing 100 years.

Variable	Value	Comment
Population	100	Initial Value
Fractional Birth Rate	0.125	Assumed
Sea Level Rise	RAMP(0.02, 0, 100)	Zero to 2 units in 100 years
House datum value	5	Average housing price in the region on a 1-5 scale
Commercial datum value	5	Average commercial property price in the region on a 1-5 scale.

Table 1. Basic parameters for the macro level model

Variable	Value	Comment
Actual elevation	5 units	Elevation of the particular parcel or property
Tide difference	3 units	Rise of sea level during high tide
Proximity to industry	3	Exposure to hazardous waste from nearby industry on 0-5 scale, zero equals no exposure and 5 represents major exposure.
Original value of property / parcel	1	Value of property / parcel relative to average value of property in the region on a 1-5 scale.

Table 2. Basic parameters for the micro level model

The primary metric of interest in this model is the public health 'vulnerability index' whose higher values signify a state wherein the parcel has a strong need for either structural protection from potential sea level rise (i.e., containment) or removal of toxic material from its or neighboring parcels (i.e., remediation), but is incapable of acquiring the resources required for the same. Here the model is executed under different sets of conditions and the behavior of the vulnerability index is analyzed.

3.1. Public Health Vulnerability

Figure 3 shows the dynamics of the public health vulnerability under two scenarios, one where no remediation efforts are implemented and another where remediation is absent. Under the scenario of a 'no remediation' policy, reclaimed parcels and parcels subjected to increased storm surge are not de-contaminated; co-mingling of water and pollution occurs resulting in an increased exposure and propensity towards associated health consequences.

The continuous line represents the scenario in which no remediation policy has been applied. The segmented line presents the situation in which a full remediation solution has been implemented. A visual inspection confirms that in the absence of remediation, the healthcare vulnerability increases at a higher pace relative to the scenario in which a solution has been implemented.

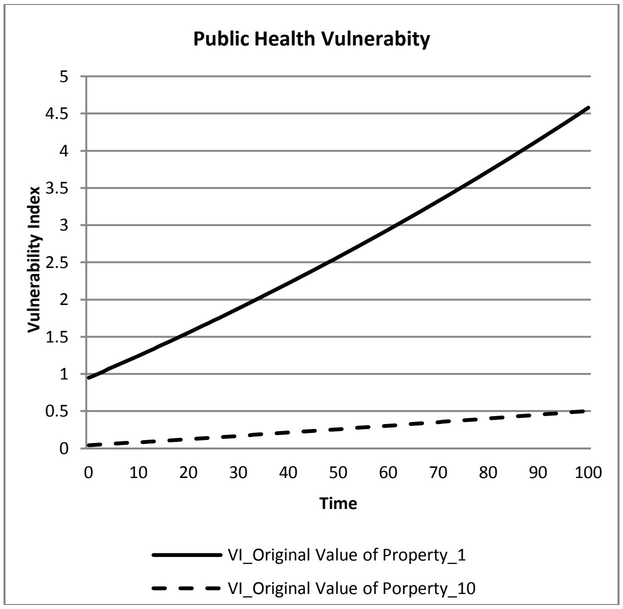

Figure 3 – Public Health Vulnerability

3.2. Effectiveness of mitigation

Figure 4 shows the overall vulnerability trend for two values of remediation effectiveness. The segmented line represents the case wherein the external remediation sources are fully used while the continuous line presents the case wherein the remediation sources are absent.

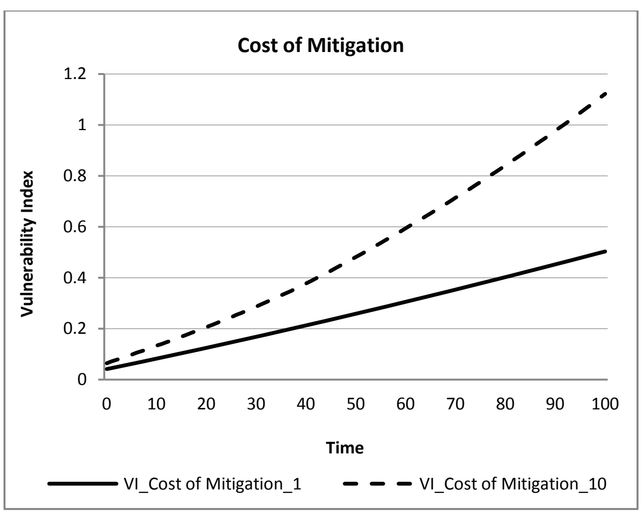

Figure 4 – Vulnerability Index produced from both effective and a less effective strategy

3.3. External remediation resources

The trend of the vulnerability index for two scenarios of external remediation resources is exhibited in Figure 5. This trend is evaluated in terms of the availability of resources for remediation. The first situation assumes the availability of sufficient resources while the second situation indicates a lack of required resources. The continuous line represents the case wherein the external remediation sources are fully used while the segmented line presents the case wherein the remediation sources are absent. Consistent with the other results, it is seen that vulnerability increases exponentially in a situation where no remediation resources are available.

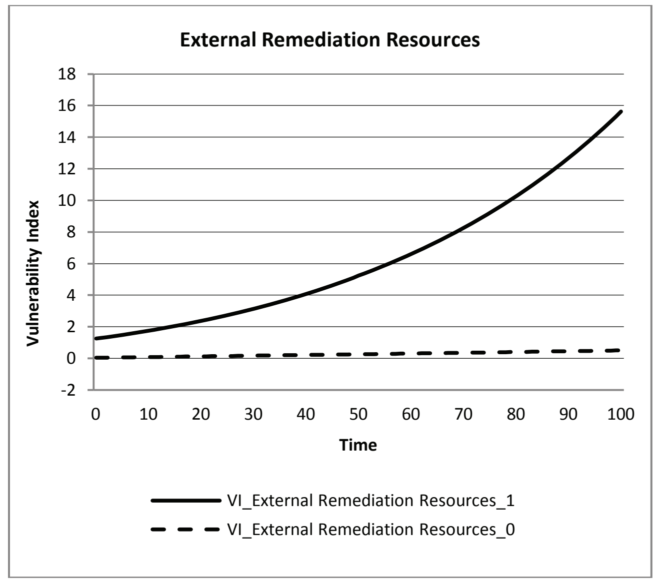

Figure 5 – Vulnerability in terms of availability of remediation resources

3.4. All above factors combined

Finally, Figure 6 shows all the above scenarios included in the sensitivity testing. It is seen that the individual parcels are the most vulnerable in absence of resources for remediation. This is applicable to developing countries that would be facing acute sea level rise. The least vulnerable properties have adequate resources for mitigation of sea level rise which can be done with a reasonable sum as compared to the value of the property.

This application produced insightful results. We have articulated a promising example of a process to develop a conceptual framework that informs a Bayesian Network model designed to provide an understanding of an intelligent adversary.

4. DISCUSSION AND CONCLUSIONS

SD is a simulation technique that can be employed to capture a holistic perspective of the complex dynamics between sea level rise and public health. In this paper, we constructed a SD model that is intended to replicate the behavior of the coastal population vulnerability to sea level rise. The model considered the impact of both the macro and micro levels on population vulnerability. At the macro level, the model considers the threat to the regional economy and vital activities characterized in typical societies. This level includes general aspects and dynamics such as sea level rise, population health vulnerability, population displacement as a consequence of increases in sea level rise levels, and economic value of the region.

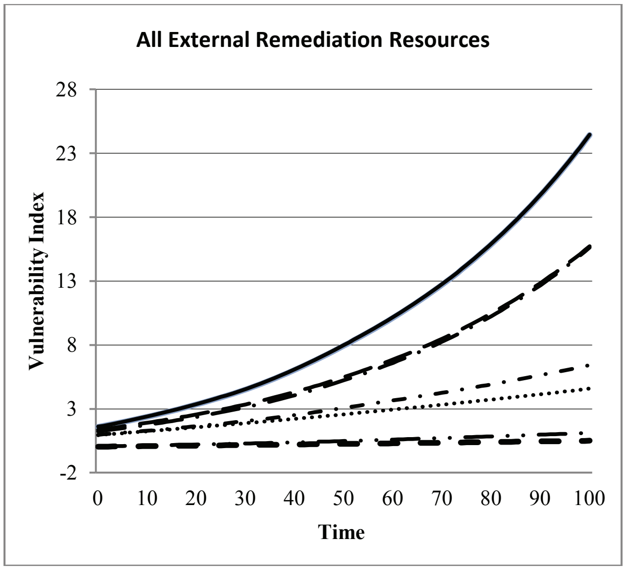

Figure 6 - Vulnerability Assessed Using all above factors combined

At the micro level, the vulnerability index is calculated considering population health and the capability to relocate in response to encroaching sea level rise and storm surge. Included are critical aspects such as elevation of parcel.

Empirical results from the execution of the model demonstrate that the model performs as expected. In the absence of mitigation altogether or a policy commitment of relatively meager resources towards remediation, the health vulnerability of coastal populations increases. The rise of unemployment as a result of government or private businesses departing the region increases the uninsured population that, in turn, diminishes access to healthcare.

The progressive exposure of populated parcels to pollutants from storm surges further increases the vulnerability of the population.

Potential extensions and refinement applications for this model are manifold, including: 1) investigating the mix of remediation and containment techniques that minimize risks and negative effects while maximizing resource distribution, 2) measuring the effects of delaying interventions, and 3) measuring effects sea level rise for purposively selected population segments.

The simulation model demonstrates the complexities associated with the studied system. Policy-making is benefited by additional layers of information and system behavior insights generated by SD simulation approaches.

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Biography

Rafael Diaz graduated from the Old Dominion University with a Ph.D. in Modeling and Simulation in 2007, and became a Research Assistant Professor of Modeling and Simulation at Old Dominion University's Virginia Modeling, Analysis, and Simulation Center (VMASC). He holds an M.B.A degree in financial analysis and information technology from Old Dominion University and a B.S. in Industrial Engineering from Jose Maria Vargas University, Venezuela. His research interests include operations research, operations management, production and healthcare and public health systems, dependence modeling for stochastic simulation, and simulation-based optimization methods. He worked for six years as a process engineer and management consultant prior to his academic career.

Joshua G. Behr received his Ph.D. training at the University of New Orleans specializing in urban and minority politics. He has taught a variety of public policy, state government, and statistical methods courses at the University of New Orleans, Southwestern Oklahoma State University, Eastern Virginia Medical School, and Old Dominion University. His is now a research professor at the Virginia Modeling, Analysis and Simulation Center (VMASC), Suffolk. He has published on a wide range of topics including presidential approval, times series methodology, minority employment patterns, public health, and emergency department utilization as well as a recent book (SUNY Press) on political redistricting and a book chapter addressing discrete event simulation. Currently, his research interests include modeling and simulating smart grid, transportation systems, and the flow of patients within a regional healthcare system.

Anna Jeng is an Associate Professor of Environmental Health at Old Dominion University. Her research focuses on environmental and public health assessment that identify health effects and diminished quality of life resulting from exposures to environmentally and occupationally hazardous substances in the environment. Her projects have involved site assessment, determination of contaminants of concern in affected communities and identification and evaluation of exposure pathways.

Hua Liu is a tenure-track Assistant Professor at the Department of Political Science and Geography, Old Dominion University. She received a B.S. in Computer Assisted Cartography from Wuhan Technical University of Surveying and Mapping, China in 2000, and M.S. in Cartography and Geographic Information Systems (GIS) from Wuhan University, China in 2003, and a Ph.D. in Geography from Indiana State University in 2007. Dr. Liu's research focuses on remote sensing and GIS analysis of urban ecological and environmental systems, public health, land-use and land-cover change, spatial modeling in coastal environments, and human-environment interactions.

Francesco Longo received his Ph.D. in Mechanical Engineering from University of Calabria in January 2006. He is currently Assistant Professor at the Mechanical Department of University of Calabria and Director of the Modelling & Simulation Center – Laboratory of Enterprise Solutions (MSC-LES). He has published more than 80 papers on international journals and conferences. His research interests include Modeling & Simulation tools for training procedures in complex environment, supply chain management and security. He is Associate Editor of the "Simulation: Transaction of the society for Modeling & Simulation International". For the same journal he is Guest Editor of the special issue on Advances of Modeling & Simulation in Supply Chain and Industry. He is Guest Editor of the "International Journal of Simulation and Process Modelling", special issue on Industry and Supply Chain: Technical, Economic and Environmental Sustainability. He is Editor in Chief of the SCS M&S Newsletter and he works as reviewer for different international journals. His Web-page can be found at http://www.ingegneria.unical.it/impiantiindustriali/index_file/Longo.htm