Dynamic Analysis of Levee Infrastructure Failure Risk:
A Framework for Enhanced Critical Infrastructure Management

Juan Carlos Lam

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Advisory Committee:

James R. Martin II, Chair

Jesus M. de la Garza

Sunil K. Sinha

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Abstract

Current models that assess infrastructure failure risk are "linear," and therefore, only consider the direct influence attributed to each factor that defines risk. These models do not consider the undeniable relationships that exist among these parameters. In reality, factors that define risk are interdependent and influence each other in a "non-linear" fashion through feedback effects. Current infrastructure failure risk assessment models are also static, and do not allow infrastructure managers and decision makers to evaluate the impacts over time, especially the long-term impact of risk mitigation actions. Factors that define infrastructure failure risk are in constant change.

In a strategic manner, this research proposes a new risk-based infrastructure management framework and supporting system, Risk-Based Dynamic Infrastructure Management System (RiskDIMS), which moves from linear to non-linear risk assessment by applying systems engineering methods and analogs developed to address non-linear complex problems. The approach suggests dynamically integrating principal factors that define infrastructure failure risk using a unique platform that leverages Geospatial Information System services and extensions in an unprecedented manner. RiskDIMS is expected to produce results that are often counterintuitive and unexpected, but aligned to our complex reality, suggesting that the combination of geospatial and temporal analyses is required for sustainable risk-based decision making. To better illustrate the value added of temporal analysis in risk assessment, this study also develops and implements a non-linear dynamic model to simulate the behavior over time of infrastructure failure risk associated with an existing network of levees in New Orleans due to diverse infrastructure management investments. Although, the framework and RiskDIMS are discussed here in the context of levees, the concept applies to other critical infrastructure assets and systems. This research aims to become the foundation for future risk analysis system implementation.

Acknowledgements

Defining success should look beyond our contributions to society and the impact of those contributions. Very few times, we take time to examine the essence of our achievements, missing on important parts of our accomplishments. The journey we embark, including the obstacles we overcome, the relationships we develop along the way as well as the primary source of our motivation and sustainment, helps build our character and transform our work into an experience.

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List of Abbreviations

ADF	Application Development Framework
AgsJWS	ArcGIS Java Web Services Application Programming Interface
ANL	Argonne National Laboratory
ANN	Artificial Neural Networks
API	Application Programming Interface
ASCE	American Society of Civil Engineers
BCR	Benefit-Cost Ratio
BEA	Bureau of Economic Analysis
California DWR	California Department of Water Resources
CAS	Complex Adaptive Systems
CBA	Cost benefit analysis
CEP	Complex Event Processing
CERL	Construction Engineering Research Laboratory
CIMS	Coastal Infrastructure Modeling System
CLD	Causal Loop Diagram
CSDGM	Content Standard for Digital Geospatial Metadata
DOI	United States Department of Interior

DRM-VT	World Institute for Disaster Risk Management at Virginia Tech
DSS	Decision Support System
EE	Enterprise Edition
EJLD	East Jefferson Levee District
EL	Environmental Laboratory
ENW	The Expertise Network for Flood Protection
EPA	United States Environmental Protection Agency
ERDC	Engineer Research and Development Center
ESRI	Environmental Systems Research Institute
FedRAMP	Federal Risk and Authorization Management Program
FEMA	Federal Emergency Management Agency
FGDC	Federal Geographic Data Committee
GCM	General Circulation Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information System
GSA	United States General Services Administration
GUI	Graphical User Interface

HAZUS-MH	Hazards U.S. Multi-Hazards
HEC	Hydrologic Engineering Center
HEC-FDA	Hydrologic Engineering Center Flood Damage Reduction Analysis
HEC-HMS	Hydrologic Engineering Center Hydrologic Modeling System
HEC-SSP	Hydrologic Engineering Center Statistical Software Package
HEC-RAS	Hydrologic Engineering Center River Analysis System
IaaS	Infrastructure-as-a-Service
IEEE	Institute of Electrical and Electronics Engineers
InSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
IPET	Interagency Performance Evaluation Task Force
IT	Information Technology
JDK	Java Development Kit
LCCA	Life-Cycle Cost Analysis
LCC-B	Life-Cycle Cost-Benefit
LDSME	Locally Distributed Simultaneous Model Execution
LevCAT	Levee Condition Assessment Technology
LID	Low-Impact Development

LiDAR	Light Detection and Ranging
MAUT	Multi-Attribute Utility Theory
MCA	Multiple-Criteria Analysis
MCEER	Multidisciplinary Center for Earthquake Engineering Research
MDG	Millennium Development Goal
MR&R	Maintenance, Repair and Rehabilitation
MTP	Markov Transition Probability
NCLS	National Committee for Levee Safety
NLD	National Levee Database
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NRC	National Research Council
NSDI	National Spatial Data Infrastructure
NSF	The National Science Foundation
OAS/DSD	Organization of American States / Department of Sustainable Development
OGC	Open Geospatial Consortium
OMB	Office of Management and Budget
PaaS	Platform-as-a-Service

PCI	Pavement Condition Index
PFP	Probable Failure Point
PMI	Prioritization Maintenance Index
PNP	Probable Non-failure Point
PRA	Probabilistic Risk Analysis
REST	Representative State Transfer
RiskDIMS	Risk-Based Dynamic Infrastructure Management System
ROI	Return on Investment
SaaS	Software-as-a-Service
SAR	Synthetic Aperture Radar
SCA	Services Component Architecture
SD	System Dynamics
SDK	Software Development Kit
SDTS	Spatial Data Transfer Standard
SLFPA-E	Southeast Louisiana Flood Protection Authority - East
SLFPA-W	Southeast Louisiana Flood Protection Authority – West
SOA	Service-Oriented Architecture
SOAP	Simple Object Access Protocol

SOE	Server Object Extension
SoS	System of Systems
SPH	Standard Project Hurricane
TNPW	Total Net Present Worth
TPWB	Total Present Worth of Benefits
TPWC	Total Present Worth of Costs
TPWR	Total Present Worth Risk
UDDI	Universal Description, Discovery and Integration
UN	The United Nations
UNEP	United Nations Environment Programme
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
W3C	The World Wide Web Consortium
WJLD	West Jefferson Levee District
WMO	World Meteorological Organization
WRDA	Water Resources Development Act
WSDL	Web Services Description Language
XML	Extensible Markup Language

Chapter 1 : Introduction

Historical Events and Motivation

Catastrophic failures of critical infrastructure remind us of the vital role these systems play within our society and economy. The failures of levees in New Orleans during hurricane Katrina and of the Fukushima Daiichi Nuclear Power Plant in Japan during the Tōhoku earthquake and tsunami, as well as the collapse of the I-35W Mississippi River Bridge in Minneapolis resulted in significant loss of life, extensive property damage, severe national and global economic disruptions, and profound psychological impact, calling for proactive risk management measures to prevent future failures, able to adapt to the dynamic world in which we live. Such critical infrastructure systems, which typically have long lifecycles, face increasing vulnerabilities from dynamic processes such as urbanization, climate change, globalization, deterioration, as well as growing system interdependencies. As a result, improving the management of these systems has become a challenging task of national interest. Risk-based decision making frameworks for critical infrastructure management must assess failure risk as defined by our complex environment, evaluate the impact of infrastructure management investments over the lifecycle of the infrastructure, integrate environmental and socio-economic factors into the decision making process, guarantee the preservation of knowledge among generations of engineers and decision makers, and effectively communicate risks to a wide array of stakeholders.

Our national levee system provides a good illustration of challenges faced by critical infrastructure systems. There are more than 100,000 miles of levees in the United States (NCLS, no date). Many of them are more than 50 years old and have deteriorated, subsided and protect areas that are more populated than when the levees were first built. Moreover, approximately two-thirds of all levees are not certified and as a consequence are not trusted by government officials (Lehmann, 2012). Aside from needing to improve the certification process (NRC, 2000) and the fact that many believe that a number of certified levees should not continue to be certified (Lehmann, 2012), this number is a reflection of the deteriorating state of our national levee system. In 2000, more than half of the American people lived in counties protected by levees (Boyd, 2009). To protect them, the American Society of Civil Engineers (ASCE) estimated that an investment equivalent to $100 billion is required to repair and rehabilitate our national levee system (ASCE, 2009). This exemplifies one aspect of a larger crisis related to the critical need to improve the condition of our nation's overall infrastructure system, which will require approximately $2.2 trillion (ASCE, 2009). As infrastructure ages, these amounts can only increase over time. In a recuperating economy, implementing infrastructure management policies that seek to effectively use available resources and efficiently allocate limited funds while maintaining a target level of protection and functionality is imperative.

In recognition of the growing vulnerability and need to enhance levee management, the Water Resources Development Act (WRDA) of 2007 was passed, along with its Title IX, also known as the National Levee Safety Act of 2007, to establish a committee for the development of a national levee safety program and to improve the inventory and inspection of levees across the United States (NCLS, no date). To support management of the data to be collected as part of the latter effort, a geographic information system (GIS)-based National Levee Database (NLD) was developed in 2007 by the United States Army Corps of Engineers (USACE) (USACE, no date). In 2009, in view of the need to improve management controls over infrastructure decisions, the Institute for Water Resources at the USACE, the organization ultimately responsible for the technical soundness of network-level infrastructure management decisions related to our national levee infrastructure system, created the Risk Management Center.

Problem Statement

All of these efforts reflect the interest and commitment of the USACE to advancing the field of infrastructure management for levee systems. Although these have been important milestones toward managing and reducing infrastructure failure risks, some challenges still exist. Current risk assessment models are linear. In other words, risk is presently calculated by only considering the direct influence of each parameter that defines infrastructure failure risk. These models do not consider the undeniable relationships that exist among these variables. In reality, the parameters that define risk are interdependent and influence each other in a non-linear fashion through feedback loops (Figure 1). Selected examples for these relationships are presented in Table 1.

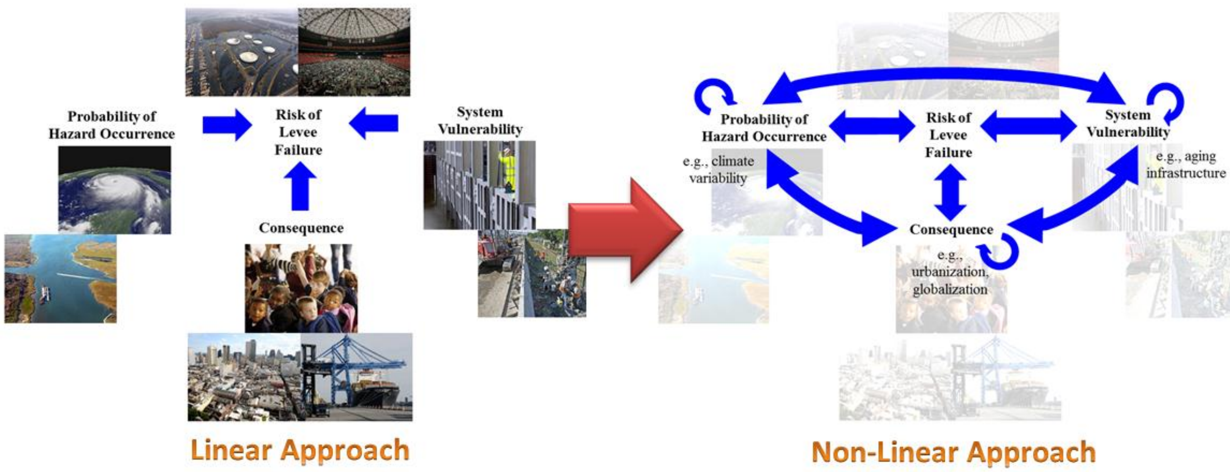

Figure 1 - Improved Representation of Risk by Moving from "Linear" to "Non-Linear" Relationships (various images obtained from the Greater New Orleans web site at www.nola.com)

Table 1 - Illustrative Relationships between Factors that Define Risk

Direct Effect →	Risk of Levee Failure	System Vulnerability	Probability of Hazard Occurrence	Consequence
Risk of Levee Failure	None	Upgrade of protection infrastructure to reduce vulnerability due to high risk level	Low impact development to mitigate flood hazard occurrence	Emigration due to high risk perception
System Vulnerability	Contribution of system vulnerability to definition of risk	Prioritization of maintenance, repair and rehabilitation activities	Potential environmental impact of protection infrastructure development and management	Real estate value fluctuation in areas where the condition of levees is deemed poor
Probability of Hazard Occurrence	Contribution of probability of hazard occurrence to definition of risk	Changing environmental conditions affecting infrastructure deterioration	Upstream environmental conditions effect on downstream conditions	Emigration due to previous flood experiences
Consequence	Contribution of consequence to definition of risk	Limited budget for system repair and rehabilitation due to infrastructure needs to directly benefit economic growth	Diminishing pervious area coverage due to urbanization	New housing development when population grows

Current risk assessment models are also static and do not allow infrastructure managers and decision makers to evaluate the long-term impact of risk mitigation actions. Factors from the built, natural and socio-economic environments that define risk are continuously changing over time, and therefore, risk needs to be regarded as dynamic and varying in time. Continuing to use static and linear risk assessment models for the management of levees and other flood protection infrastructure that do not adequately account for the complexity of these relationships and the dynamic nature of risk may lead to erroneous lifecycle estimation of risk, implementation of sub-optimal risk mitigation strategies, and a false sense of security. Our world is more complex than depicted by traditional linear and static risk assessment methods.

Building disaster-resilient and sustainable communities able to safeguard their long-term interests requires furthering the emergence of new critical infrastructure management frameworks, risk assessment models and decision support systems (DSSs) suitable for non-linear dynamic environments, such as those experienced along the Mississippi River and the east coast of Japan, and embodied in climate change, urbanization, and globalization. Responding and recovering from a flood are daunting, complex and costly tasks. Last year alone in the United States, flood events along the Mississippi River and in the Upper Midwest, along the Missouri and Souris Rivers, caused significant economic losses, between $5 and $6 billion, not considering damages in neighboring country Canada (NOAA, 2011). Knowing the unfortunate critical situation of the American economy today, the United States cannot afford facing disaster events of the magnitude of Katrina or Tōhoku, whose costs are in the hundreds of billion dollars. Our nation needs enhanced frameworks and tools to properly assess and manage infrastructure failure risk.

Proposed Solution

This research proposes the development of a new and innovative framework and supporting system to help manage levee infrastructure over their lifecycle. The proposed framework moves from a linear to a non-linear perspective by (A) applying systems engineering methods created to address non-linear complex problems and (B) dynamically integrating factors that define infrastructure failure risk using a unique platform that leverages the use of GIS services and extensions in an unprecedented manner. One of the systems engineering methods proposed to be used, System Dynamics (SD), has the capacity to provide insights into situations of dynamic complexity (Sterman, 2000), such as manufacturing and business profit studies. This research applies SD in a new way to address an urgent civil infrastructure problem, enabling a more refined estimation of infrastructure failure risk. This type of non-linear dynamic modeling produces results that are often counterintuitive and unexpected, but aligned to our complex reality. Specifically, this research will:

1. Propose a risk-based infrastructure management framework for levees that considers the temporal and spatial characteristics of factors that define levee failure risk, along with a system to support this framework,
2. Conceptualize a non-linear dynamic model –an entity of the overarching system– to simulate the behavior of risk over the lifecycle of the levee as a result of infrastructure management policies, namely maintenance, repair and rehabilitation (MR&R) activities to be implemented along the lifecycle of the asset, by relating factors from the built, natural and socio-economic environments that define risk in a way that risk may be probabilistically quantified throughout a geographic area over time,
3. Suggest an interactive DSS –another entity of the all-encompassing system– to evaluate the performance of such policies through a set of decision making algorithms, and
4. To illustrate the value added of temporal analysis and for proof of concept, design and implement a non-linear dynamic model to simulate the behavior of risk over time as a result of diverse infrastructure management investments on an existing levee network.

It is worth noting that the second point is the major contribution to future research on the area of disaster risk reduction. The proposed integration of temporal and geospatial analyses, resulting in geospatiotemporal analysis, by bringing together SD and GIS in an unparalleled manner as later described, will provide infrastructure managers with a holistic picture of infrastructure failure risk.

Research Scope and Methodology

The following points further define the scope and methodology used to develop the framework and supporting system, design and implement the proof-of-concept SD model that uses temporal analysis to estimate risk behavior over time along the lifecycle of a levee network, and evaluate the impact of infrastructure management investments as described by the SD model:

1. Through literature review,
   1.1. Expand understanding of critical dynamic processes and characteristics affecting the estimation of risk associated with infrastructure failure, including system interdependencies, interconnectivity, urbanization, unsustainable development and climate variability,
   1.2. Become familiar with recent research efforts in infrastructure management, SD and temporal analysis, GIS and geospatial analysis, risk analysis, and decision sciences and DSSs, and
   1.3. Increase awareness of key factors from the built, natural and socio-economic environments that define infrastructure failure risk,
2. Leverage learned concepts and previous research to propose a risk-based framework and supporting system for levee management able to evaluate the performance of infrastructure management policies over the lifecycle of levees,
3. Design and implement a non-linear dynamic temporal model that can be used to illustrate the usefulness of the temporal aspect of the framework using Vensim, a SD software, and that is especially engineered to support infrastructure failure risk assessment and management by applying the concepts of:
   3.1. SD to properly account for endogenous interdependent relationships among factors that define risk, existing feedback effects, as well as process delays, with the aim of assessing risk behavior over time, and

3.2. Markov chains to help determine the impact of infrastructure management investment on levee infrastructure condition at the network level,

4. Select a case study to demonstrate how the proposed framework could enhance the management of levees in a given locality,
5. Process the results obtained through simulation, and analyze such results as means to increase understanding of endogenous relationships affecting the behavior of risk,
6. Compare the impact of predetermined infrastructure management investments (no, minor, moderate and major investments) on risk behavior over time to enable sustainable risk-based decision making,
7. Rank alternatives based on their Benefit-Cost Ratio (BCR), where benefits are defined as the amounts of risk reduced from a baseline scenario (e.g., no investment) as a result of implemented infrastructure management decisions, and
8. Issue a series of recommendations to implement and enhance the proposed framework, along with the supporting system, based on literature review, proof-of-concept SD model development, and results of the final analysis.

Research Objectives and Broader Impact

Through the implementation of the proposed solution, this project aims to:

1. Increase the understanding of risk associated with the failure of levees, whose perceived societal value has been traditionally low despite their significance to our national security, economic development, and social welfare,
2. Demonstrate the need to improve risk-based management frameworks by modeling the non-linearity and dynamic nature of levee failure risk over the lifecycle of the asset,
3. Foster the integration of advanced technologies and systems engineering methods with clear application to risk-based infrastructure management,
4. Further the knowledge of existing endogenous relationships between factors from the built, natural and socio-economic environments that define risk, and

5. Evaluate and communicate the short and long-term impact of infrastructure management policies on risk variability over time.

At a broader level, this research will support the envisioned paradigm by the World Institute for Disaster Risk Management at Virginia Tech (DRM-VT) to meet the evolving infrastructure management challenges of the 21st century (Figure 2). This work will make important contributions to the realization of an integrated risk-based framework for the way we design, build, and manage critical infrastructure systems by closely integrating sensing, modeling, and decision support. Given the present emphasized role of geospatial technologies in infrastructure management and its essential foreseen role in the realization of the referenced paradigm, their integration becomes a fundamental element of the proposed framework. The research presented here offers an interdisciplinary approach leading to increased understanding of both, the anatomy of risk and of the impact of sustainable risk mitigation policies, or policies able to meet present demands without compromising the needs of future generations.

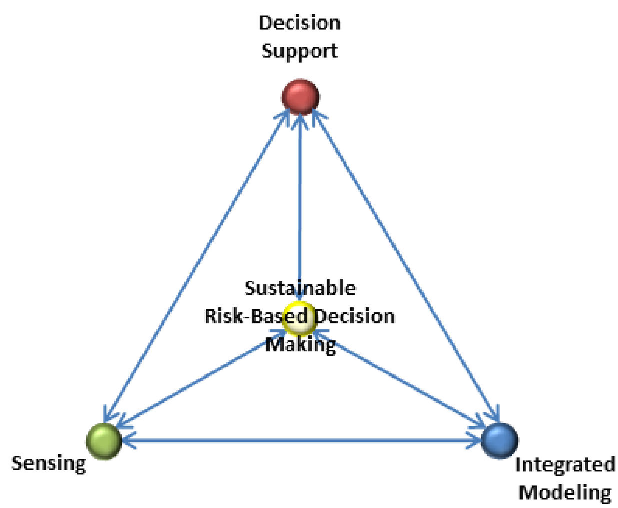

Figure 2 - Envisioned Critical Infrastructure Management Paradigm for 21st Century Challenges by DRM-VT

Organization of Thesis

Chapter 1 of this document introduced the problem at hand, and provided the scope of the research. The next chapter seeks to increase the awareness and understanding of some of the dynamic processes that affect levee failure risk, calling for interdisciplinary measures. Chapter 3 invites the reader to become familiar with past and current efforts in infrastructure management, SD and temporal analysis, GIS and geospatial analysis, risk analysis, as well as decision sciences and DSSs. The subsequent chapter details the proposed risk-based framework for levee infrastructure management, and the overarching supporting system. This will help set the tone for the next chapter. Chapter 5 discusses the principles behind the individual entities of the system, including the innovative geospatiotemporal model able to assess how risk changes throughout a geographic area over time, and the DSS to be used for evaluation of infrastructure management policies. The following chapter details the proof-of-concept SD model and analyzes the results obtained. At the end, chapter 7 summarizes the accomplishments of this research and makes additional recommendations for future work.

Chapter 2 : Understanding Risk

The complexity of infrastructure failure risk has increased over the past few decades. Currently, we live in a global economy and an interconnected world, where local disruptions can amplify and cause worldwide impacts. During the last few years, the world has also witnessed augmenting urbanization rates, unsustainable development, and climate variability. All of these events call for new methods and tools to help quantify and manage infrastructure failure risk. Indeed, as risk evolves, our understanding of risk, and therefore the tools that help making sustainable risk-based decisions, must also change. In consequence, understanding risk and the non-linear dynamic processes that govern its behavior becomes a primordial task in the realization of risk assessment and management frameworks and the development of tools supporting these frameworks.

Infrastructure Deterioration

Also known as dikes in other countries, levees prevent water bodies like rivers and oceans from overflowing into floodplains and coastal zones. These structures may be natural or man-made. Common failure modes include slope instability, piping and overtopping (Pender and Faulkner, 2011). Overtopping is shown in Figure 3.

Figure 3 - Levee Overtopped During Hurricane Katrina (Murdock, 2007)

Performance features linked to these failure modes include animal burrowing/vermin infestation, foreign objects in the crest or rear slope concentrating the erosion process, cracking and/or fissuring, third party damage (e.g., underground utility service lines cattle, and vehicle), direct evidence of seepage or piping (e.g., observable water presence, noticeable saturated soil), visible deformation of cross-section caused by piping, visible deformation of cross-section caused by slope instability, revetment condition, erosion of cross-section, vegetation condition in outer slope (Pender and Faulkner, 2011), and settlement. In other cases, failures are related to underperforming joints or sealant, sump pumps, valves, drain pipes and closures. Many of these deterioration processes are dynamic and/or relate to dynamic processes from the natural environment, and even the socio-economic domain. As a civil protection system, a levee should not fail under extreme conditions for which it was designed. The role of a levee is to protect our society and economy against natural events of different magnitudes.

System Interdependencies and Interconnectivity

Understanding existing levees' system interdependencies is an important step towards holistically assessing their physical and functional condition. Rinaldi et al. (2001) defined different levels of system interactions (Figure 4), which, in the near future, may be useful to explore in detail in the context of levee systems. In some locations, levees and underground utility infrastructure, for instance, are geographically interdependent as they share a common physical space. Broken underground pipes could compromise the integrity of levees. Interdependencies also exist among components of the same system. Levee infrastructure is interdependent in this sense as well. A breached levee section, for instance, may compromise the integrity of contiguous sections. To model the performance of an entire interdependent levee network, some have opted to use network-level approaches, as recommended by infrastructure

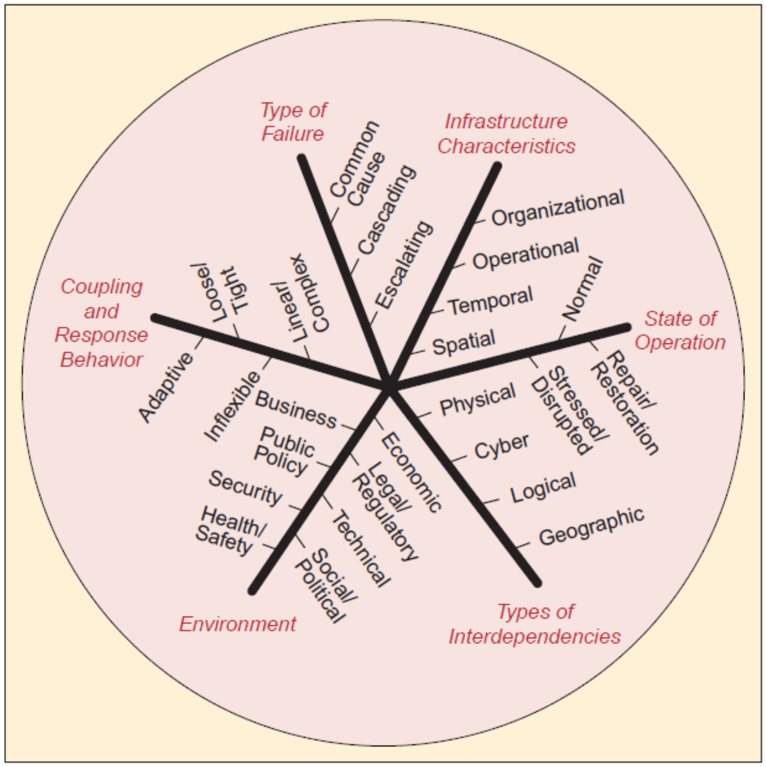

Figure 4 - Dimensions for Describing Infrastructure Interdependencies (Rinaldi et al., 2001)

experts in The Netherlands (Brinkhuis-Jak et al, 2004). This method in particular has led to an increased understanding of total network performance. Assessing system-level performance starts by understanding the dynamics of infrastructure systems (Amin, 2002). With this knowledge, infrastructure owners and operators could properly manage disturbances and prevent cascading effects throughout and between infrastructure networks. Amin (2002) also believes that modeling human thinking, and hence decisions, as pertaining to managers, operators, and users will be required to assess the total behavior of infrastructure systems, which he regards as complex networks, geographically dispersed, non-linear, and in continuous interaction among themselves and with humans.

Data Collection & Sensing

Another dynamic process already taking place in some critical infrastructure sectors relates to advances in information technology (IT), such as sensing, to enable the continuous collection of asset condition and environmental data. The evolution of data collection techniques, enabling the gathering and processing in some instances of data in real-time, adds another important level of dynamism. Scholars (e.g., Glaser and Tolman, 2008) are speculating on the impact generated by the vast amount of data that will soon be available to infrastructure managers by sensing devices such as transducers, and motes –term used to reference a network of individual nodes working cooperatively. As real-time data become the norm in industry, new ways that continuously predict physical and functional asset performance based on evaluated field conditions must emerge to provide asset managers with comprehensive infrastructure performance assessments and risk profile monitoring.

Urbanization & Unsustainable Development

According to the United Nations (UN) (2010b), by 2050, approximately 70 percent of the world population will reside in urban areas, most of this growth occurring in emerging and developing countries (Figure 5). Today, New York and Los Angeles metropolitan areas are among the largest regions in the world with more than 10 million people each (Brinkhoff, 2012). This rapid growth poses many problems, including unsustainable development, which often leads to a series of social issues (e.g., crime, poor education) as well as the formation of slums and neighborhoods with insufficient resources. One of the targets of the Millennium Development Goals (MDGs) is to have achieved improvement in the lives of at least 100 million slum dwellers by 2020. Although the lives of approximately 200 million slum dwellers have already been improved since the effort started (UN 2010a), much more remains to be done. While the percentage of the urban population living in slums has decreased from 39% in 2000 to 33% in 2010, the absolute number of slum dwellers has rapidly increased from 767 million people in 2000 to 828 million people in 2010. This is a reflection of how rapidly urban areas are growing and the need to include these types of patterns in risk assessments. As people move to large urban areas, motivated many times by apparent economic incentives, resources in those areas become quickly utilized, driving society closer to its carrying capacity. As a result, human settlements are inadvertently formed in highly hazardous areas.

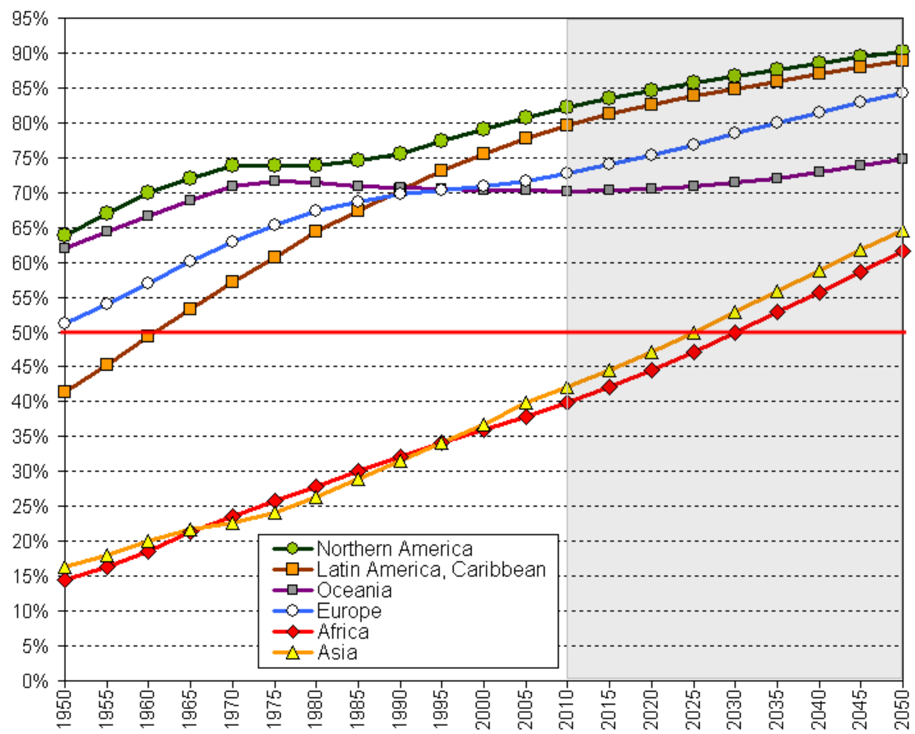

Figure 5 - Urban Population by Major Geographical Area in % of Total Population (UN, 2010b)

Furthermore, the demand for infrastructure, housing units and other assets with impervious surfaces augments as population increases. Pervious area coverage has an effect on how stormwater travels to water bodies, and therefore affects the natural hydrologic cycle, potentially causing flood problems during large storms. Decreasing pervious area coverage increases flood risk. To mitigate the consequences of growing demand for residential and commercial development, some cities have turned to low-impact development (LID). LID is an approach to manage stormwater such that the handling process resembles the natural cycle using uniformly distributed decentralized design techniques that infiltrate, filter, store, evaporate, and detain runoff close to its source (LID Center, no date). Green infrastructure is the result of LID. In the National Pollutant Discharge Elimination System (NPDES) website, EPA (2011) specifically states that one of the benefits of green infrastructure is the reduction and delay of stormwater runoff volumes.

Climate Variability

Despite being regarded as a controversial topic, scholars continue to debate the existence and consequences of climate change, as well as proper mitigation strategies. As these discussions continue, research has demonstrated that weather's variability is changing. In 2006, studies by the Glaciology Group Research of Swansea University and by glaciologist Dr. Julian A. Dowdeswell showed that the melting rate of Greenland's glaciers was accelerating (OAS/DSD, 2006). Increased climate variability will impact water cycle, availability, allocation, and demand (The World Bank, 2011). Snow and glacier rapid melting for instance will lead to water shortages in the long run during the summer times. Other expected effects throughout the world include shorter intense rainfalls resulting in groundwater depletion as more water resources are drawn from the ground than replenished through infiltration, coastal inundation and wet land loss, re-distribution of water resources, flooding and landslides, prolonged droughts, and water quality degradation (Climate Institute, 2010). Communities need to learn how these changes in climate variability affect their current exposure to natural hazard events. Since climate change will impact infrastructure-related risk during the 21st century, infrastructure design decisions need to be carefully considered since reversing implemented decisions may be very costly (Hall et al., 2006).

Chapter 3 : Literature and Concepts Review of Methods and Tools

Risk-based infrastructure management has made important strides in selected sectors such as energy and transportation. The energy sector, particularly the nuclear industry, is heavily regulated due to the catastrophic consequences that can occur in the event of a disaster. Failures in the nuclear sector and other similar industries critical to our society are very dynamic. This level of dynamism is portrayed by the recent failure of the Fukushima Daiichi Nuclear Power Plant in Japan during the Tōhoku earthquake and tsunami (Appendix A). In consequence, this sector must keep rigorous infrastructure management practices, some of which require infrastructure managers to consider worst-case scenarios. Another industry that has advanced the practice of risk-based infrastructure management is transportation. Highways, roads and bridges are indeed part of our daily lives, and therefore, have more tangible public value than levees and other flood protection systems. Currently, the transportation sector in the United States reaps the benefits of having an asset management program and several information systems that support decision making. Much progress is yet to be done in this sector, however. Public works agencies that have adopted new technologies possess vast amounts of structural and functional infrastructure condition data, which are accumulating but not being used to address management needs (Durango-Cohen and Tadepalli, 2004). A number of data collection and modeling tools are not fulfilling their ultimate purpose in this sector –enabling decision making for infrastructure management.

Advanced management practices for flood protection infrastructure may be found in The Netherlands. Today, this country is the world leader in flood protection infrastructure design, construction, operations and maintenance. The Dutch Ministry of Infrastructure and the Environment maintains information related to infrastructure management, and makes this valuable resource available on its Helpdesk Water and Inspection of Flood Defense System websites. In addition, The Netherlands has several organizations working together towards the enhancement of the entire Dutch flood management system, and the dissemination of best practices. One of these organizations is the Dutch Floodplanning Initiative, which is a consortium of government agencies, universities, water research institutes, private engineering firms, and financial institutions formed to help people prevent floods. Other organizations include the Netherlands Water Partnership and the Dutch Delta Design 2012. For a list of resources, please refer to Appendix B.

Conscious of the various modes of failure of levees as well as the need to strengthen the large stock of aging civil protection works, federal, state and local governments from around the globe have taken interest in furthering the field of risk-based infrastructure management –some countries have gone further and formed comprehensive asset management programs. Asset management in the Netherlands emerged due to increasing budget requirements for operation and maintenance, social pressure, rising complexity in decision making process, reduced availability of funds, and growing private sector involvement (Opdam, 2002). Despite private sector engagement, flood control structures in The Netherlands continue to be managed by public water boards, whose jurisdiction was established in the fifteenth century (ENW, 2012). Managing risk of civil protection infrastructure failure is a longstanding Dutch tradition.

Other governments around the world also have the mandate to maintain target protection levels throughout the lifecycle of flood protection systems while effectively using resources at acceptable risks. Strategic investments of this kind are needed to guarantee the operational continuity of civil protection infrastructure, which are essential elements in our societies, protecting us from natural hazards and supporting economic development activities. Moving towards a business-oriented, level-of-service-based (Zobel et al, 2009) risk-based approach like asset management can produce long-term benefits.

In the United States specifically, industry and academia have a shared interest in improving flood risk management, including risk-based decision making for flood protection systems management. Over the past four years, The National Science Foundation (NSF) has funded projects aimed at strengthening flood risk management capacity. Some of these projects include: 2008 Midwest Levee Failure Investigation (2008-2010), Data Integration and Model Development to Mitigate Urban Flooding Hazards Linked to Sea Level Rise (2008-2012), Evaluation of Seismic Levee Deformation Potential by Destructive Cyclic

Field Testing (2008-2012), Examining the 100-Year Floodplain as a Metric of Risk, Loss, and Household Adjustment (2011-2013), Exploring Flood Mitigation Policy: A System Dynamics Approach (2004-2008), and Field Data on Levee Breaches (2011-2012) (NSF, 2012). In addition to the NSF, research-focused organizations such as the National Academies also have a vested interest in enhancing the field of flood risk management. In 2000, the National Academies issued a series of recommendations to the USACE to refine the risk-based analysis framework used for flood damage reduction project formulation, economic justification, and minimum engineering and safety standards (NRC, 2000). Later, in 2011, the National Academies, under the sponsorship of FEMA, launched a project named "Integrating Dam and Levee Safety and Community Resilience," which sought to expand the knowledge base of flood protection infrastructure risk management (The National Academies, 2012).

The interest of practitioners and researchers throughout the world, including the United States, in building decision making frameworks and support systems able to effectively mitigate infrastructure failure risk and efficiently manage critical infrastructure systems for a sustainable society, economy and environment, is evident. The following sections provide insights of specific industry and research projects in meeting the referenced interest with applications to flood protection systems and other critical infrastructure as appropriate. This study acknowledges that advancements in other critical infrastructure sectors will help understand how to best improve the management of levee systems.

Sensing

The use of sensing technologies can improve the condition of our levees. Although these technologies have an immediate financial impact on municipal, state and federal budgets due to capital investments for equipment and software acquisition along with installation costs, in the long-run, these agencies can expect to save considerable financial and human resources as inspection and decision making processes become streamlined. Automating data collection is an important step towards achieving optimal infrastructure condition and a more efficient use of internal resources. Continuous locally-performed inspection of every infrastructure asset by federal, state and local governments, and even private sector contractors is too costly and unrealistic. Therefore, we must rely on today’s technologies, such as sensing, to address the challenge of data collection, storage and processing.

Light Detection and Ranging (LiDAR), Synthetic Aperture Radar (SAR) and Interferometric SAR (InSAR) can facilitate the monitoring of levee displacement and deformation. Levee infrastructure protects the lives of those living and working in coastal zones and floodplains. This protection is a function of the levee crown's elevation along its entire length, the levee's structural integrity, the stage or height of the flood against which the levee is designed to provide protection from, and the functioning of the appurtenant structures, all of which are subject to substantial change over time (Interagency Levee Policy Review Committee, 2006). Therefore, keeping a thorough inventory of existing levees and their most recent conditions is an important step towards guaranteeing protection. Regrettably, despite levees’ critical role in flood prevention, neither the federal government nor state governments have yet been capable of building such detailed inventory (ASCE, 2009). Sensing can certainly be used to expedite the data collection process.

The levees of the Sacramento-San Joaquin Delta hold back water all the time not just during major storms since the land they protect is below sea level. Maintaining adequate elevation of levees is critical to prevent floods in this area as the difference between a typical storm stage and a 100-year flood stage is only a matter of inches (Dudas, 2010). Levees have the tendency to settle back to its original elevation. Therefore, efforts to increase levee infrastructure height only become short-term solutions. In view of this situation, the California Department of Water Resources (California DWR) decided to use LiDAR to collect levee elevation data to improve levee asset management and safeguard the lives of the Delta region residents. A visual sample of LiDAR data collected is found in Figure 6. In order to implement a reliable data collection program, California DRW took some steps towards maximizing the capability of LiDAR. Due to data accuracy issues when vegetation is present, California DRW decided to collect elevation data during leaf-off seasons. Also, with the objective to improve the quality of the data, the maximum scan angle was decreased. This change, however, implied a large number of flights to cover the entire region. California DWR accepted the implied higher cost due to the criticality of the measurements – notice here the importance of having levee condition data. In addition to this example, other success stories exist today. For instance, through the Levee Condition Assessment Technology (LevCAT), which partially relies on data obtained through LiDAR, the Engineer Research and Development Center (ERDC) of the USACE has been able to assess the condition of levee infrastructure in Texas, New Mexico and California (ERDC, 2007).

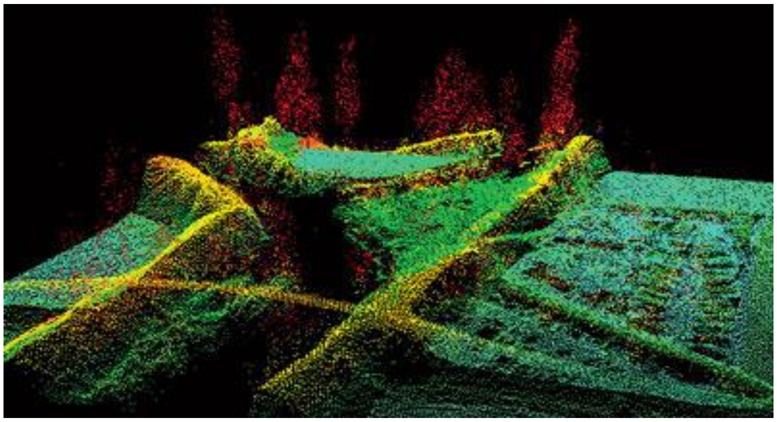

Figure 6 - 3D View of Raw, Unprocessed LIDAR Data Displaying Levees (Dudas, 2010)

System Dynamics and Time Dimension

SD has become a powerful tool in addressing problems that have a wide variety of interdependent system elements that change over time. A few research projects have taken advantage of the concept of SD for the assessment and management of flood risk. Using SD, Deegan (2007) presents a model to evaluate the effectiveness of structural and non-structural flood risk mitigation policies in reducing the number of properties vulnerable to floods. Non-structural policies include flood risk awareness, hazard mapping and vulnerability assessment, zoning restrictions, and restoration of natural barriers. This study demonstrates that well-intended policies could lead to unintended consequences. Also using SD, Simonovic and Li (2004), propose a hydrologic model to facilitate the performance assessment of flood protection systems in terms of reliability, vulnerability and resiliency. As part of the analysis, this research includes the future impacts of climate change on streamflow by using climate temperature and precipitation data obtained through widely-used general circulation models (GCMs) as indicators to changes in flow. The results of this study state that changing climate conditions may lead to an increase in annual discharge as well as a shift ahead in starting time of flood and streamflow peak. Ahmad and Simonovic (2006) integrate expert knowledge and artificial neural networks (ANN) to build a SD model able to simulate flood control operations. The proposed system uses modeling tools created by the USACE for hydraulic analysis and estimation of flood damage and benefits of flood damage reduction options. The ANN model forecasts runoff hydrographs based on precipitation, a melt index, and an index of the south-north time phasing of the runoff. SD is also suggested for the management of other types of civil and non-civil infrastructure systems such as transportation infrastructure (de la Garza et al., 1998), water systems under drought conditions and changing demands (Bhatkoti and Triantis, 2011), residential units (Xu, 2011), urban infrastructure (Vo et al., 2002), and river ecological systems for flood prevention, water purification, water quality, and habitat and biological life security (Wang et al., 2011).

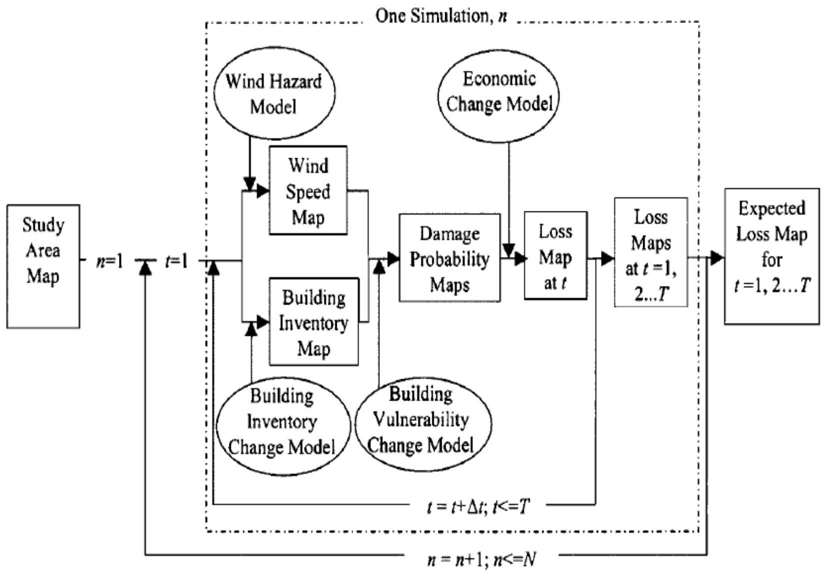

Figure 7 - Hurricane Risk Forecasting Methodology (Jain et al., 2005)

Although not using SD, other research projects give deserved attention to time dependency. For instance, Hallegatte (2006) conducts an analysis of the New Orleans flood protection system, arguing that cost benefit analysis (CBA) for flood risk mitigation investments need to include second-order disaster impacts, changing conditions like climate change, and amplification factors for recovery costs. The author considers post-disaster conditions as part of the evaluation process of potential risk mitigation solutions. Jain et al. (2005) develop a methodology for capturing changes in hurricane risk over time by integrating four models: wind hazard, building inventory change, building vulnerability change, and economic change (Figure 7). It is worth noting that although this methodology is linear and relies on a static wind hazard model, Jain et al. recognize that factors that define risk change over time.

Geographic Information Systems and Geospatial Dimension

The use of geospatial analysis for infrastructure management is of great research interest as well. Initiatives, such as those undertaken by USACE, have led infrastructure managers and decision makers to rely on GIS-based systems. Serre et al. (2008) recommend a GIS to support the performance assessment and management of levees in France by modeling failure scenarios in accordance with performance indicators relevant to infrastructure failure. The suggested system acts as a data warehouse for levee physical and functional characteristics. These data include location and description of defects, visual aids like photographs, comments related to the defects and their evolutions along with potential MR&R options, and records on levee performance as defined by performance indicators and triggers associated with failure mechanisms of interest.

The integration of geospatial analysis into decision making has yielded positive results in other infrastructure sectors as well. For example, governments could benefit from geospatial technologies to manage water pipelines using failure probabilities, criticality of pipe segments and optimal replacement time (Kong et al., 2008). Figure 8 shows how infrastructure data could be visually presented, and thus, easily understood when using a GIS. Information displayed in this manner empowers infrastructure managers as they are able to see the overall condition of the system –commonly referred to as the "big picture." Aside from visualization, other reasons to use a geospatial platform for management systems include data collection, extraction, management and manipulation (Sharifi, 2008).

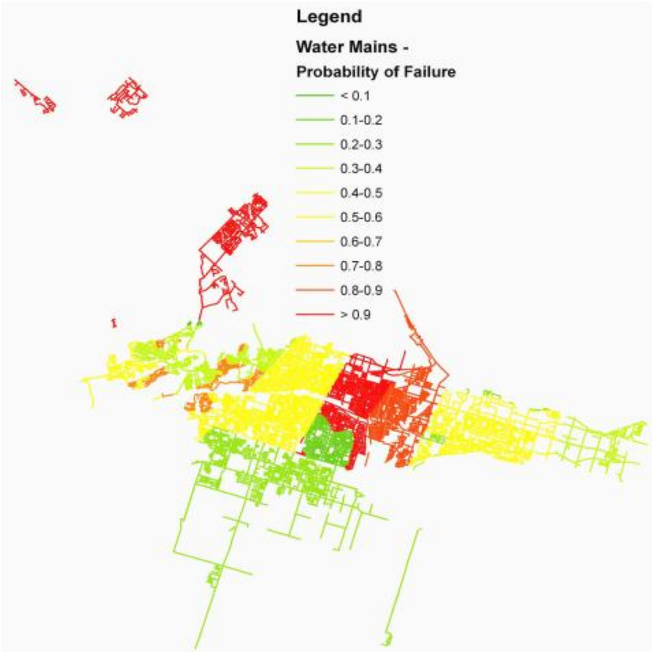

Figure 8 - Visual Data of Water Main Failure Probabilities (Kong et al., 2008)

Combining Time and Geospatial Dimensions

The richness of increasingly-available sensing data makes its adequate processing and presentation extremely important. Despite the many successes of geospatial analysis, Yuan (2008) advocates for dynamics GIS, a system able to represent, analyze and model geographic dynamics, and thus, combine the power of temporal analysis and geospatial analysis to assess how a particular phenomenon changes over time throughout a geographic area. In fact, accounting for the large number of interacting components distributed through space and their time-dependent behavior is required to effectively analyze infrastructure systems (Hall et al., 2006). Unfortunately, past research has traditionally opted to use SD software for simulation and a GIS only for visualization of data. Efforts attempting to capture the temporal and geospatial attributes of phenomena have not looked specifically at creating a single integrated environment that would truly enable geospatiotemporal analysis.

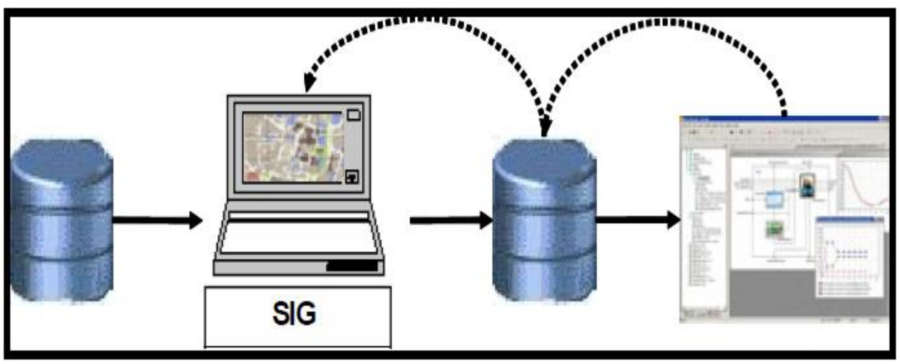

Figure 9 - Sequence for Transferring Data from SD Models to a GIS (Quijada et al., 2005)

Xu (2011), for instance, uses City Engine –software that enables the creation of 3D cities– to display data obtained from residential development SD models based on housing sector, societal, economic, and environmental indicators. Under this framework, the user specifies how the data are to be displayed in the 3D environment. Alternatively, Quijada et al. (2005) proposes a tighter integration to evaluate delinquency and crime policies, where results may be analyzed in both, a GIS (on the journal article, referred to as SIG, which is the acronym for GIS in Spanish language) and a SD model built in AnyLogic software (Figure 9). Geographic coordinates are assigned to interacting elements of a SD simulation. The GIS acts as the interface for the time-space representation of simulated data.

Another approach is presented by Croope (2009), who proposes creating an integrated DSS for the management of critical infrastructure, using a case study for transportation infrastructure. The DSS uses Hazards U.S. Multi-Hazards (HAZUS-MH), a tool owned by FEMA that relies on a GIS to assess the impact of natural hazards, to generate input for a SD model for post-disaster recovery operations. The results obtained from the SD model are then visually presented in a series of maps. While her research focuses on resilience in post-disaster contexts, the study is plausible from many perspectives. Croope acknowledges that infrastructure systems operate under complex and interdependent environments, and also understands the value of enhanced DSSs to improve infrastructure resilience. Croope also recommends building more comprehensive models as means to account for other aspects of critical infrastructure management, highlighting that improved temporal analysis can lead to more complete results. The integrated DSS follows the following logic: (A) selects critical infrastructure system for analysis, (B) determines infrastructure condition before disaster, (C) defines performance measures, (D) conducts vulnerability assessment, (E) performs impact damage assessment after disaster scenario using HAZUS-MH, (F) develops potential recovery strategies, (G) establishes condition/performance transition from pre to post-disaster status, (H) identifies needed resources to support normal operations, (I) forecasts resources required to recover and mitigate damaged critical infrastructure, (J) accounts for all decision makers and factors, (K) reviews the complex-system problem, constraints, and requirements, and (L) evaluates opportunities to improve system resilience and communicating the results.

System Architecture

The successful integration of some of the methods and tools discussed thus far greatly depends on the communication between systems. Wallace et al. (2001) discuss the design and development of a prototype modeling system that incorporates remote and real-time data acquisition, a distributed model execution and control, and multiuser access to and monitoring of DSSs for coastal infrastructure management. The motivation behind this distributed system lies on the increasingly amount of data to be available for infrastructure decision making as well as advances in IT. The Coastal Infrastructure Modeling System

(CIMS), inspired by a client/server computing architecture (Figure 10), enables the monitoring of environmental conditions near-shore Lake Michigan affecting the condition of coastal infrastructure (e.g., harbors, piers, beach protection devices). Client/server architecture is an open platform allowing the mix-and-match of networked components (Orfali et al., 1999). In general terms, data are transmitted through the Internet, from a sensor device to servers containing a number of models whose responsibilities are to process incoming data. Users can then remotely access these processed data through an interface, which may also be housed in a remote server. As field conditions are assessed on one end, models are dynamically updated and results presented on other ends of the architecture.

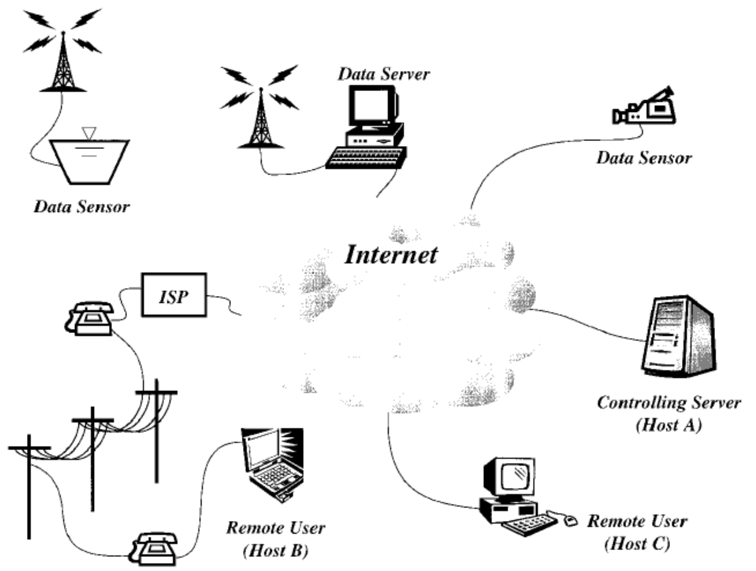

Figure 10 - Connectionless Client/Server Computing Architecture (Wallace et al., 2001)

Risk Analysis

Evaluating risks can help infrastructure managers make informed decisions and build resilient systems. While this study is not directly concerned with resiliency, the risk-based framework presented here supports resiliency. It is important to set these terms apart from each other. Resiliency depends on the strength of a system to withstand external demands without experiencing degradation (robustness), the system's ability to use alternate options to maintain a certain level of functionality (redundancy), the system's capacity to mobilize resources and services during emergencies (resourcefulness), and the recovery speed of a system from an interruption (rapidity) (O'Rourke, 2007). On the other hand, risk is the result of a threat with adverse effects to a vulnerable system. Modeling risk requires knowledge on the probability and severity of adverse effects, along with the vulnerabilities and threats to the infrastructure system (Haimes, 2006). Knowing the various elements that define risk (i.e., potential threats, system vulnerabilities, consequences and their likelihoods) is then highly valuable to effectively, in the framework of resiliency, increase system robustness, redundancy, resourcefulness and rapidity.

To learn about risks associated with infrastructure systems, particularly infrastructure failure risk, this study proposes an innovative risk analysis framework. Risk analysis is here defined as the quantification of risk, the identification of risk management options, the computation of potential benefits (e.g., reduced risk), and the communication of the results, without including expert preferences (Pate-Cornell and Dillon, 2006). This research believes that the estimation of potential benefits resulting from risk management options is needed to understand changes in risk, and thus risk itself. The following are selected research projects that conduct different types of risk assessment, or quantification of risk. Other aspects of risk analysis, including the estimation of benefits and tradeoff analyses, will be discussed in later sections.

Moss and Eller (2007) propose a top-down approach for estimating levee failure risk using failure frequency data. The researchers highlight that the fact that failure data for levees located in the California Bay Delta region lack temporal and spatial characteristics, and therefore, this situation introduces significant limitations to the analysis. For instance, Moss and Eller argue that the increasing number of levees over the last century and evolving engineering practices for levee design and construction should have an impact on the recorded number of levee failures. Additionally, failure data are not broken down by the various types of foundation materials across the Delta region. More information about the relative number of failures and the engineering practices used, as well as data partitioned in accordance to foundation material would have led to a better understanding of trends, and in consequence, a more accurate quantification of risk. To account for the probabilistic nature of parameters that define risk, Moss and Eller run a series of Monte Carlo simulations to randomly sample from the probabilistic distributions of the annual of number of levee failures (negative binomial distribution) and the flooded area per failure (shifted gamma distribution). Levee failure risk is mathematically defined as:

$$R_i = p(f_{i,n}) \times \sum_n c_n$$

, where R_i is the risk of the i^{th} simulation in terms of area flooded, n is the number of annual levee failures in the i^{th} simulation, $p(f_{i,n})$ is the probability of failure in a given year of the i^{th} simulation given n failures, and c_n is the consequence for failure n.

If an expert is tasked with prioritizing risk mitigation projects that attempt to reduce failure risk of different infrastructure systems, risk comparison methods and tools will be needed in addition to risk quantification techniques. Li et al. (2009) suggest a framework for small communities to assess and rank infrastructure-related risks from multiple hazards using probabilistic risk analysis (PRA), decision analysis and expert judgment. The framework follows a four step process:

1. Identify and screen natural and man-made hazards, as well as infrastructure and other assets,
2. Develop hazard and infrastructure failure scenarios seeking to account for cascading effects of such scenarios, estimate their probabilistic occurrences, and organize scenarios in event trees,
3. Construct a value tree to assess the impact of scenarios on population, the environment, physical property, and community activities and operations, based on agreed performance indices,
4. Rank risks according to (A) probabilistic failure risk, and (B) absolute (non-probabilistic) magnitude of risk.

These are all important contributions to the field of risk analysis. Nonetheless, risk evaluations of complex systems that do not consider the contributions of social, psychological, organizational and political processes may lead to solving the wrong problem (Bea et al., 2009). Bea et al. advise using agent-based modeling, GISs, technology delivery system design and high reliability organization management principles to accurately represent the inherit interdisciplinary complexity that exists between the system and its operational environment, along with system failure and failure consequences.

Human Behavior Modeling

In relation to the last point, it is important to discuss the performance of human agents in decision making for critical infrastructure systems. Amin (2002) provides a brief overview of recent accomplishments in modeling decisions. One of the advancements listed is the emergence of complex adaptive systems (CASs). Such systems provide insights of phenomena arising from multiple, simple but adaptive components. A CAS is a system that involves a large number of components or agents that adapt or learn as they interact (Holland, 2006). According to Holland, four major features are shared among all CASs: (A) agents simultaneously interact, sending and receiving signals, (B) actions of agents depend on the signals they receive, (C) agents can react by executing a sequence of rules, and (D) the agents change over time. Another definition also encompasses the interaction between these components or agents to their environment (ANL, no date). A CAS may be of particular importance to modeling the performance of an organization, for instance, an asset management agency.

Decision Making

Determining the economic feasibility of adequate MR&R activities is an important step towards guaranteeing an optimal lifecycle performance of civil infrastructure systems. Since infrastructure managers are often faced with budget constraints, selected infrastructure management policies must demonstrate their technical soundness and cost effectiveness in addressing short-term and long-term structural and functional deficiencies. It is then important to clearly define the criteria under which decisions are to be made, and apply that set of indices uniformly. Criteria may be clustered in two groups: costs and benefits (Hudson et al. 1997). Costs may include agency or direct costs (e.g., initial capital, maintenance, salvage return, financing), and non-agency or indirect costs (e.g., post-disaster damage, environmental impact, economic disruption). Selected costs may be translated into benefits, such as risk when viewed as reduced risk as a result of a mitigation action. Thus, when evaluating costs and benefits, analysts should be careful and avoid double accounting.

Brinkhuis-Jak et al. (2004) present a method to estimate the costs and benefits for flood damage mitigation practices in The Netherlands. In order to determine flooding probability, the authors advocate for a system-level assessment, called dike ring approach, which gives equal consideration to all failure mechanisms, and accounts for uncertainty prior to probabilistic analysis. Costs include cost of initial investment, as well as operational and maintenance costs. Benefits on the other hand are reduction of damage costs given a particular mitigation practice. As an example, a suitable solution for increasing the height of a levee would be one that results in larger benefits when compared against costs:

$$I_0 + I_H \times (H_h - H_0) < \left(P_{f,0} - P_{f,h}\right) \times \frac{D}{(r-g)}$$

, where I_0 is the initial investment, I_H is the variable cost per unit length to increase a levee, H_h is the new levee height, H_0 is the current levee height, $P_{f,0}$ is the flooding probability in the initial situation, $P_{f,h}$ is the flooding probability given the new levee height, D is the damage caused by the flood, r is the interest rate and g is the economic growth rate.

As discussed at the beginning of this chapter, much of the research in decision making for infrastructure management exists in the transportation sector. An approach that integrates natural and man-made stochastic events in the evaluation and comparison of bridge retrofit strategies is presented by Padgett et al. (2009). A lifecycle cost model, relying on bridge fragility curves, calculates the expected value of losses due to lifetime exposure of a bridge in different states to seismic hazard. Then, BCRs indicate the returns on investment (ROIs) of selected retrofit strategies, where benefit is defined as the difference in expected present worth of losses as a result of retrofitting a bridge. BCR and other CBA techniques may be used to evaluate risk mitigation alternatives in infrastructure sectors other than transportation. A CBA framework for lifeline systems (e.g., transportation, electric power and water distribution systems) prone to experiencing earthquake ground motions is presented in Figure 11 (Kunreuther et al., 2001). The final selection could be the alternative with the largest net value, or difference between benefit (present worth post-disaster loss reductions) and cost (present worth costs of the mitigation strategies).

As mentioned earlier, agencies face budget constraints, and as a consequence not all MR&R actions may be immediately funded, even if their BCRs demonstrate high ROIs. Prioritization of MR&R activities and policies then help agencies plan their budgets and forecast expenditures. In general, prioritization involves (A) data acquisition, (B) processing and interpretation, (C) determination of current and future needs, and (D) priority analysis and results (Hudson et al. 1997). These tasks become complex when evaluating a group of interrelated projects. For illustration purposes, some examples from the transportation sector are presented here. Although, the following research works are presented in the context of transportation, their application could be extended to other infrastructure sectors. Frangopol and Liu (2007) use dynamic programming, an algorithm that decomposes a problem into sub-problems or stages in order to simplify the amount of computation needed to solve the problem, to develop lifecycle infrastructure management strategies for a network of bridges. The objective of this method is to identify bridge maintenance policies that improve the condition of the bridges without compromising safety at reasonable costs. Dynamic programming organizes technically-feasible treatments along the life of a bridge such that the present worth of total cost is reduced. Each of these resulting lifecycle strategies enters a binary integer program that maximizes their selection throughout the network. Chen and Flintsch (2007) suggest an alternative method to determine the appropriate timing of MR&R actions, arguing that suitable treatment application time leads to realistic lifecycle costs. This method uses Fuzzy Logic, a decision algorithm that advocates for approximation rather than exactness to represent how human decisions are made based on experience. This model can be best understood through IF-THEN-ELSE statements. For instance, IF the priority of the rehabilitation treatment is higher than the priority of the baseline (do-nothing) policy, THEN the rehabilitation is scheduled for that year; ELSE only routine maintenance is set. Priorities are based on agency policies

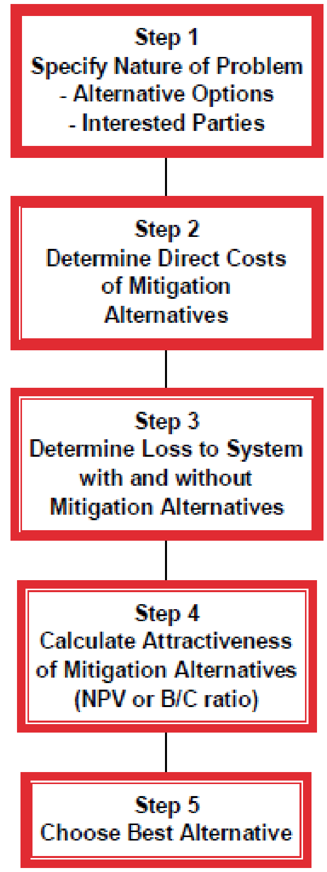

Figure 11 - CBA for Lifelines (Kunreuther et al., 2001)

(e.g., level of service, physical condition), or expert opinions. Hai (2009) proposes a methodology for a network of bridges using a prioritization maintenance index (PMI), which is a summation of three indicators: bridge specialty, the health condition, and the benefit obtained from the MR&R activity. Tsamboulas (2006) demonstrates how multinational transport infrastructure investment could be evaluated using a multi-attribute utility theory (MAUT) given the conflicting priorities among different stakeholders. Projects are prioritized into four categories: immediate, short-term, medium-term, and long-term implementation. Examples outside of transportation also exist. Martin et al. (2007) propose a multiple-criteria analysis (MCA) methodology to implement stormwater best management strategies in France. This methodology is based on an outranking method, which (A) establishes a consultative process allowing a wide array of stakeholders to participate, (B) considers stakeholders' preferences through assigned weights, and (C) accounts for uncertainty through the use of fuzzy logic algorithms.

Conclusions

Transforming data collected through sensing into information for decision makers poses a challenge for the infrastructure management community. This challenge will continue to grow as the need to survey our vast, geographically-dispersed and deteriorating infrastructure systems increases over time. As presented, GISs are important managers, integrators, and presenters of these data in today's enterprises. This specific system, combined with the power of SD in a single integrated environment –unlike previous research efforts that have kept temporal and geospatial analyses in different domains– will provide plausible short-term and long-term evaluations of infrastructure management decisions. Integrating risk and human decision making into this modeling environment are fundamental steps towards refining such assessments. After all, as learned here, no analysis should isolate society, the economy, our environment, or even cognitive processes from infrastructure systems. This study has also reviewed a number of methods, most of them applied to transportation infrastructure, to compare MR&R actions or policies whether applied to a single asset or a network of assets. While several evaluation techniques exist, the objective is the same: seeking the most optimal solution. Sustainable risk-based decision making indeed needs all of these elements, from sensing to geospatiotemporal modeling, to risk-based decision support algorithms, in conjunction with computer architectures able to integrate all the physical and logical components required to successfully deliver highly-reliable information to decision makers.

Chapter 4 : Risk-Based Dynamic Infrastructure Management Framework and System

Based on the envisioned critical infrastructure management paradigm by DRM-VT (Figure 2), this research proposes a framework and supporting system "**Risk-Based Dynamic Infrastructure Management System (RiskDIMS)**," where an integrated geospatiotemporal model and DSS, combined with sensing, enable sustainable risk-based decision making for levees and other flood protection works. Ultimately, the overall framework and RiskDIMS may be extended to manage other critical infrastructure assets.

Framework Definition

The main goal of the framework is to enhance the management of levee systems, and eventually other critical infrastructure systems, throughout their lifecycle. The framework, illustrated in Figure 12, enables the interaction between:

1. Sensing, entity responsible for data feeding,
2. Interdisciplinary non-linear dynamic modeling, entity that captures the temporal and spatial characteristics of factors that define levee failure risk, and
3. Decision support, entity that ultimately delivers information (processed data) for decision making.

Two levels of decision making occur. The first level is inherited in the system and relates to decision making about the elements that enable the framework. Physical entities such as sensors, servers and applications provide status to IT managers, who will react to this information. Furthermore IT managers may also alter the physical elements based on the needs for storage, analysis, etc. The second level of decision making relates to the selection of MR&R policies given the scenarios evaluated and the operation of RiskDIMS. Here, the DSS becomes the gateway enabling users to interact with modeled and sensed data. The framework is best described by the specifications of RiskDIMS.

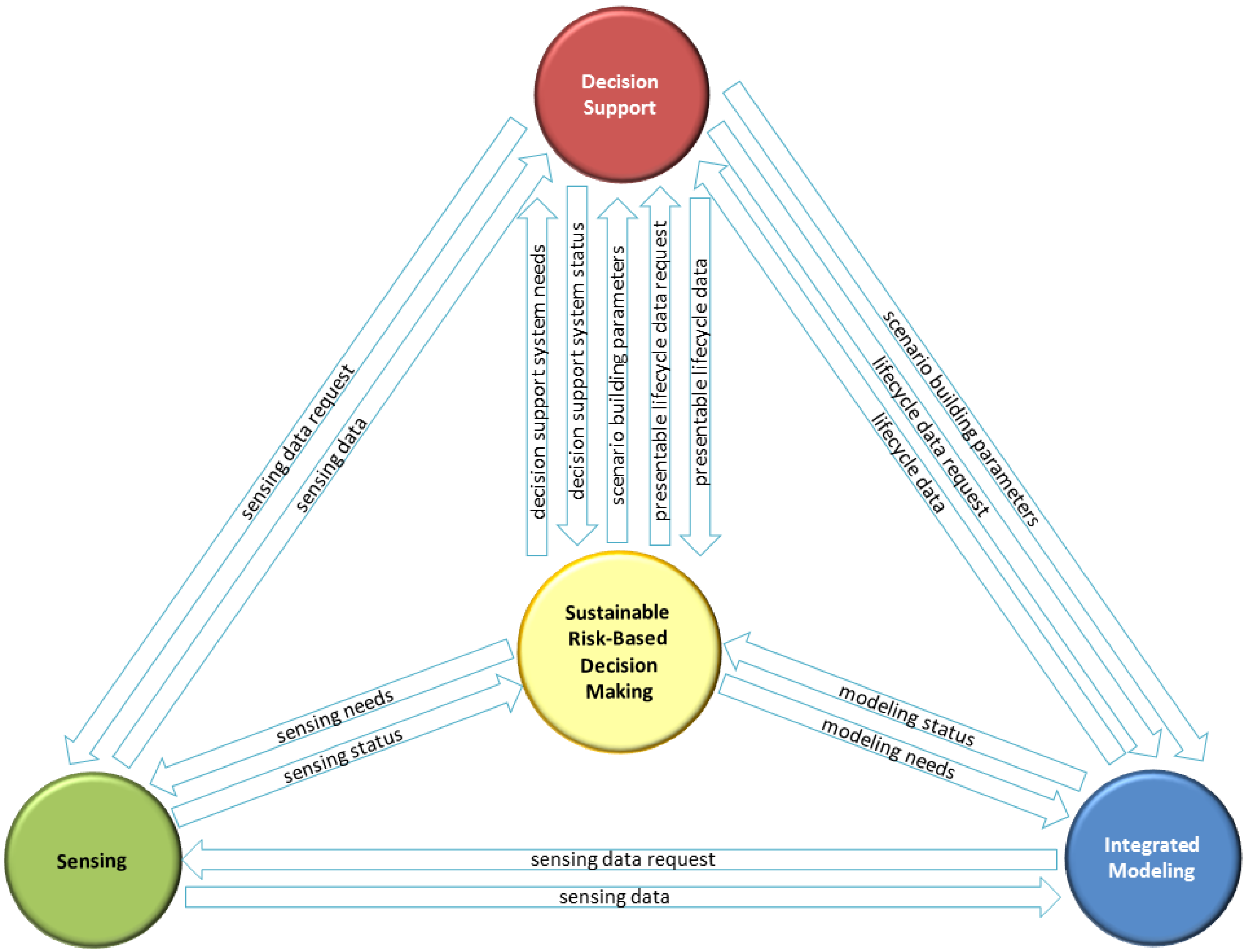

Figure 12 - Risk-based Dynamic Infrastructure Management Framework Applicable to Levee Systems and Other Critical Infrastructure

Functional Definition

In broad terms, Figure 12 presents the functional relationships between sensing, modeling and decision support. This framework serves as the foundation for the dynamic assessment and presentation of risk and other decision criteria resulting from infrastructure management decisions. The structure supports a number of basic functions, which help guide the physical architecture of RiskDIMS. It is important to be mindful of the target audience of RiskDIMS. The long-term vision of this project is to provide information regarding levee failure risk to a wide audience, including field staff, decision makers, policy analysts, and local residents. The immediate release, however, should focus on providing a risk-based tool for federal, state and local officials, who are the primary group responsible for the management of levee infrastructure (FEMA, 2012).

Storing and Managing Data

Data obtained periodically through sensing, legacy data collected throughout the years –either through automated or manual means, simulation results, implemented infrastructure management decisions, and any other data generated must be stored and cataloged properly for easy retrieval. Since this research is concerned with the use of geospatial data, the study recommends using databases capable of storing this type of data (e.g. NLD, ESRI's geodatabases). Databases along with their data management tools for manipulation sit behind the functional representation in Figure 12. A widely-use method for cataloguing data is the use of metadata. Metadata are simply data about data: the name of the data, organization that created the data, a description of the data, the date when the data was created, etc. Metadata informs potential data users if the data meets their specific needs for area coverage, data quality and data currency (Chang, 2012). The Content Standard for Digital Geospatial Metadata (CSDGM), Version 2 is the current metadata standard used by the federal government (FGDC, 2011a). Therefore, it is suggested that CSDGM Version 2 is used as the metadata standard.

Exchanging Data

Three main user-driven processes will retrieve data from the databases: legacy data retrieval to access stored records, data retrieval to evaluate current conditions, and data retrieval to model future conditions. The latter two processes will request data in accordance to the modeling functions called for execution. While assessing current conditions only requires the most recent values of predetermined model parameters, modeling future conditions needs deep access to stored data to identify most recent trends of deterministic model parameters. Individual systems also send data on their status (e.g., sensor is offline).

The federal government has been following the Spatial Data Transfer Standard (SDTS) for geospatial data transfer (EL USACE, no date). SDTS is neutral, modular, growth-oriented, extensible, and flexible –all the characteristics of an open systems standard (USGS, 2010). Nonetheless, with the pursuit of open interoperability and the evolution of GIS products that directly read –and sometimes dynamically transform– data with minimal time delay, data transfer standards are no longer needed (ESRI, 2003). Instead, geospatial data may be shared using GIS-based web services. The World Wide Web Consortium (W3C) describes a web service as a software system designed to support interoperable machine-to-machine interaction over a network (W3C, 2004). The interface of the web service –described in Web Services Description Language (WSDL)– serves as a broker, enabling the communication between the service consumer (entity requesting a particular service) and the service provider (entity providing the requested service). The service consumer and the service provider communicate with the broker using Simple Object Access Protocol (SOAP). Universal Description, Discovery and Integration (UDDI) protocol is used to register and locate web services, serving as a directory of available web services. The service consumer and the service provider communicate using Extensible Markup Language (XML). Another approach to building web services is based on Representative State Transfer (REST). RESTful web services are popular due to their simplicity. Each of these types of web services has an advantage over the other. However, SOAP-based web services are best suited for distributed environments. In using web services, a wide variety of clients and servers, not necessarily built in the same virtual environment, can communicate (ESRI, 2003).

Processing Data

Data are processed by each individual system, even by sensing components. For instance, embedding some local processing capability in sensors is desirable as this action reduces the amount of data transmitted throughout the network (Glaser and Tolman, 2008). Unlike the integrated modeling environment that estimates the variability of risk over time and throughout a geographic area, and hence the variability of the factors that define risk, the DSS logically organizes these data for decision makers. Both of these processes are described in the next chapter in more detail. The processes run by the integrating modeling environment are foreseen to be computationally intensive, and hence, deserve careful planning and implementation.

Collecting User-defined Parameters

With the objective of truly empowering decision makers, RiskDIMS needs to capture user input. Data parameters coming from users is particularly needed for modeling the behavior of factors that define risk under a series of assumptions, and for the evaluation of alternatives. Examples of user-defined parameters include the type of MR&R policy to be evaluated, the length of the analysis period, and performance indicators of interest for the evaluation of MR&R policies among others. Users may interact with the system through a number of web-based user interfaces built for different devices such as desktop and laptop computers, tablets and mobile smartphones.

Presenting Information

While data are messages transmitted and understood, information is an interpretation of data bits from which conclusions may be drawn as a result of processing, manipulating and organizing data (Glaser and Tolman, 2008). Since suitable infrastructure management investments are important to avoid potential infrastructure-related crisis in the future (Amin, 2002), presenting the right information to decision makers is critical. Data could be presented in numerical or textual form as well as in graphical format, including dynamic maps. This latter category is a powerful way to convey information to decision makers. As a result, as described in the next chapter, this research proposes to exploit the power of dynamic web mapping.

Platform Definition

System of Systems

In order to guarantee the successful implementation of this paradigm, it is important to understand the first systems engineering concept: System of Systems (SoS). Although many definitions exist, a SoS is here described as the large-scale integration of many independent, self-contained systems in order to satisfy a global need (Purdue University, 2012). In this case, the sensing platform, model, DSS, and databases, each with its own independent functional mandate but operationally interdependent, are the systems of the SoS representation: the RiskDIMS. SoS is a concept widely used in the defense, aviation and space exploration industries. Luzeaux and Ruault (2010) propose four stages for the creation and control of such complex systems: (A) identification of individual system boundaries, components, interactions, and links which integrate them into an organized whole, (B) creation of a validated representation (model) of the SoS, (C) study of the SoS model behavior, and (D) regulation of the SoS's internal balance and adaptability to the evolution of its environment. With this guidance in mind, this research focuses on (A). The remaining steps, including the implementation of a proof-of-concept RiskDIMS, are proposed for future research.

Distributed Computing Environment

Our national levee system is geographically-dispersed in space. As a result sensors and remote sensing technologies used for surveying are equally spread. Furthermore, infrastructure management operations take place at the local, state and federal levels, which implies that the primary users of RiskDIMS are also scattered. Then, in order to integrate all of the physical equipment to enable sensing, modeling and decision support, this research acknowledges that a distributed computing environment, similar to the setup proposed by Wallace et al. (2001) (Figure 10), ought to be implemented. This distributed environment will allow for the progressive integration of clients (e.g., additional sensors) as well as connectivity through the internet.

Part of the Geospatial Platform

Nonetheless, as an interdisciplinary SoS with integrated modeling capability that needs data belonging to the built, natural and socio-economic domains, this project must move towards a more specific definition of distributed computing. Collecting and managing this vast amount of data cannot be the responsibility of a single organization. Data are expected to be gathered at the federal, state and local level. Furthermore, data collection and management should be (and is) the responsibility of domain-specific agencies. For example, the National Oceanic and Atmospheric Administration (NOAA) currently collects and manages weather-related data. No other organization at the federal level is better positioned to fulfill this function. The proposed architecture shall find the means to allow data sharing among interested parties. Such efforts would save resources across different agencies and prevent duplicity of data for analysis.

The Geospatial Platform was born to address this issue. The Geospatial Platform is a web-based gateway capable of providing shared and trusted geospatial data, services, and applications for use by the public and by government agencies and partners to meet their mission needs (FGDC, 2011b). Figure 13 illustrates how agencies could collaborate to build a national geospatial database and work towards achieving a National Spatial Data Infrastructure (NSDI) –the collection of technology, policies, criteria, standards and people to enhance geospatial data collection and use (FGDC, 2011a). To maximize the potential of the risk-based infrastructure management framework proposed here, RiskDIMS needs to be part of the Geospatial Platform. A more in-depth knowledge of this platform is required to properly design the integrated modeling environment and DSS. This implies learning about cloud computing, open-standard-based systems, and service-oriented architecture (SOA), which are elements of the

Geospatial Platform (FGDC and DOI, 2011) that lead to a more collaborative, accessible, financially-attractive, interoperable, scalable, and modular, among other positive attributes, way to work with geospatial data.

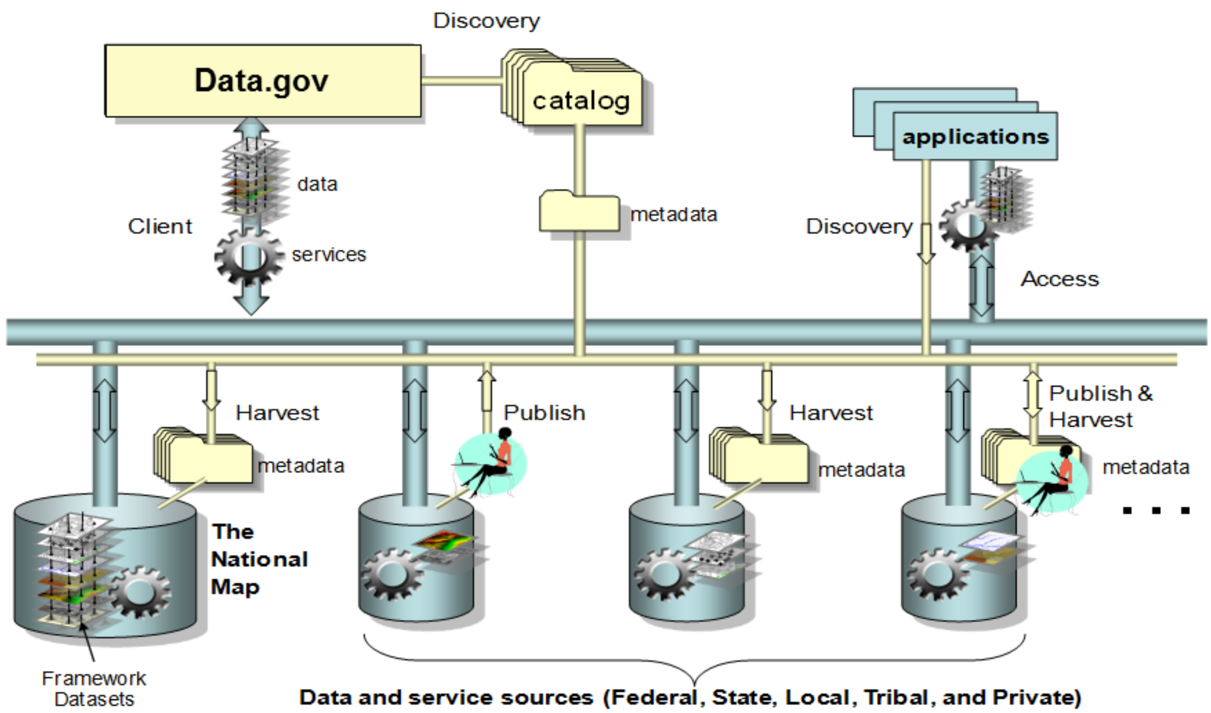

Figure 13 - Geospatial Platform for Collaborative Data Collection, Management and Sharing (McClure, 2010)

Cloud Computing

Cloud computing is a distributed computing paradigm that focuses on providing a wide range of users with distributed access to scalable, virtualized hardware and/or software infrastructure over the internet (Lewis, 2010). This framework can be of several forms. Based on capability, cloud computing could be categorized as: (A) Software-as-a-Service (SaaS) providing application access, (B) Infrastructure-as-a-Service (IaaS) offering computational infrastructure capacity, or (C) Platform-as-a-Service (PaaS), allowing for the creation and hosting of applications. On the other hand, cloud computing could be classified based on access as follows: (A) public, (B) private, (C) community –a group of entities that share the same needs, and (D) hybrid. Appendix C presents some of the advantages and disadvantages of cloud computing.

The federal government has launched an initiative to encourage federal, state and local agencies to use cloud computing to save human and financial resources, encourage collaboration, and become greener as a result of less energy consumption. Apps.Gov provides a wide array of SaaS, IaaS and PaaS services offered by private sector vendors, who have undergone procurement processes, and selected government agencies (GSA, no date). A parallel interagency initiative that enhances this experience is the creation of the Federal Risk and Authorization Management Program (FedRAMP), which is a standardized approach to cloud security (GSA, no date). Cloud computing, however, does not guarantee interoperability, which is a requirement for any SoS. The federal government is already working towards the development of cloud standards that will enable agencies to shift services between providers to reduce cost or improve functionality, and where services can seamlessly communicate (Kundra, 2011). To become interoperable, applications in the network will need to follow open source standards.

Open Source Systems

Open source software is defined as software whose program source code is freely available for the public to view, edit, and redistribute (ESRI, 2011a). The federal government is encouraging the use of standards-based open source software to increase interoperability between government applications. The standards available today for geospatial data products and services have been accomplishments of collaboration between companies, government agencies and universities part of the Open Geospatial Consortium (OGC), an international organization that seeks to address interoperability challenges (OGC, 2012). In addition to higher interoperability, there are other advantages: improved security, higher quality software, lower costs, and higher reliability (Shields, 2009).

Service Oriented Architecture

SOA is indeed complementary to cloud computing (Krill, 2009). Unlike cloud computing, previously-defined as a model for accessing applications, infrastructure and platforms, SOA is a paradigm that introduces the concept of building systems by designing and orchestrating a number of sharable services. Every SOA is comprised of: services that represent business or mission tasks, service consumers that request the functionality provided by the services, and a SOA infrastructure that connects service consumers to services (Lewis and Smith, 2007). Variations to traditional SOA have emerged to modernize SOA to today's current computing needs. Examples of these variations are event-driven SOA and real-time SOA, which can enhance client-service communication (Lewis, 2009). In the context of GIS, SOA may be best illustrated through Figure 14, where GIS services may be reused by the integration platform to perform a business function triggered at the consumption tier.

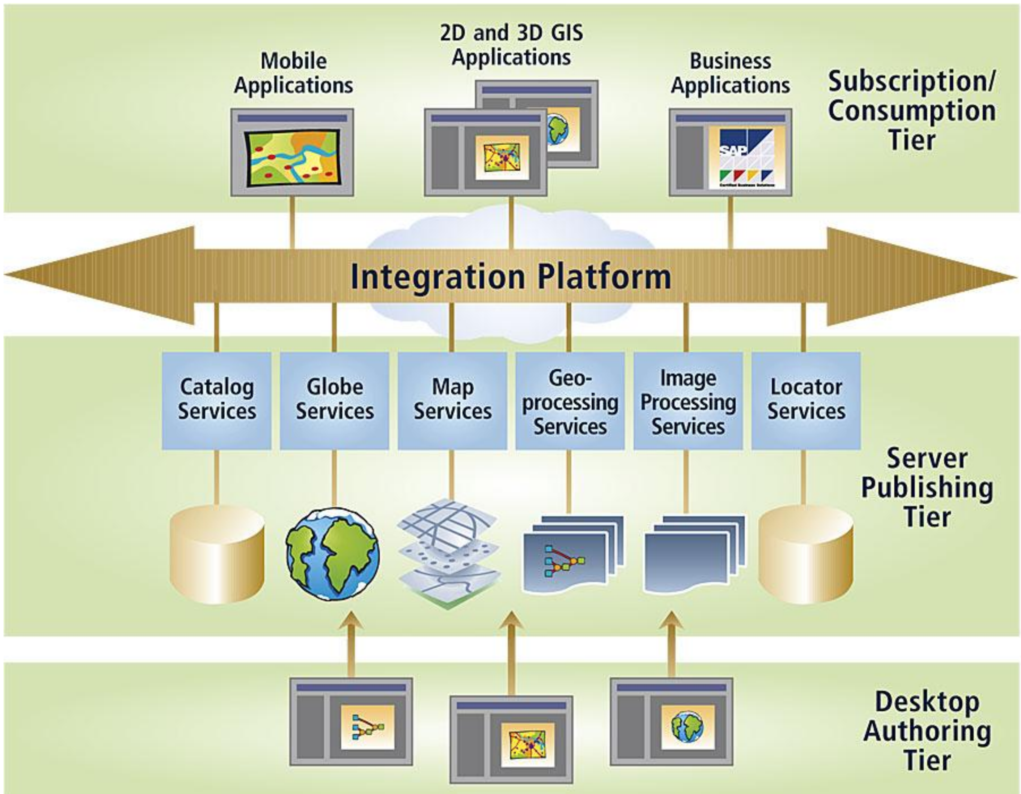

Figure 14 - A Geospatial SOA Delivering Common GIS Functions as Services throughout an Enterprise (ESRI, 2006)

Server Analysis

The server architecture of a web-enabled GIS typically has three main components: a database, a GIS server, and a web application server. This configuration is portrayed by Figure 15, with the GIS server playing a smaller role than depicted by its size in the figure. Other products in addition to those referenced here may also fulfill the referenced roles. Actual implementation should aim to utilize available cloud services (for implementation under the Geospatial Platform framework) that best meet the development, deployment and maintenance needs of the governing organization –in the case of levee infrastructure, the USACE could fulfill this role as the authoritative agency. The federal government continues to steer several procurement process that will lead to an increased number of cloud services.

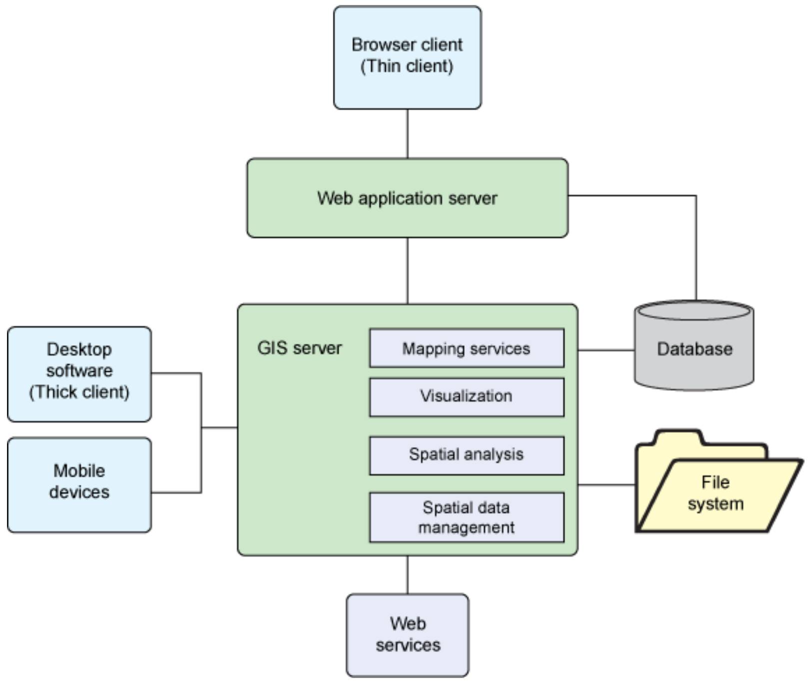

Figure 15 - Representation of a Basic GIS Architecture (Crowther et al., 2008)

Since the USACE is currently using Oracle databases to manage the agency's data, including the NLD (Khona, 2007), an Oracle database may be used to store data generated by RiskDIMS. Oracle recently released Oracle Spatial, an option to Oracle Database Enterprise Edition (EE), which enables the handling of geospatial data. Choosing Oracle as the database selection is not a requirement but certainly an advantage for USACE staff already familiar with Oracle's framework. Oracle also offers an open source option named MySQL, which also has spatial extensions. Another open source object relational database is PostgreSQL with PostGIS as extension.

As far as GIS server selection, the Environmental Systems Research Institute (ESRI) offers ArcGIS Server. ArcGIS Server distributes maps, models, and tools (ESRI, 2009). In addition to using some of the established GIS services such as mapping, geoprocessing, and geodata services, in the present version of ArcGIS Server, developers are given the opportunity to develop web applications in .Net, Flex, Java, JavaScript, and Silverlight to exploit GIS services and create a customized web experience. ArcGIS Server has a spatial extension that offers advanced raster data analysis and surface generation capabilities. An alternative open source option to ArcGIS is University of Minnesota's MapServer.

While ArcGIS Server may perform the role of a web application server (ESRI, 2012), the architecture would be best suited with a separate web application server to maximize user interactive experience and focus the use of ArcGIS Server to a GIS server. The project may decide to use a web application server that supports a Java EE platform for instance. The selection of a platform will largely depend on the programming language of preference for the development of web applications. Some open source options that support Java include Oracle's Glassfish, IBM's WebSphere Application Server Community Edition, and Apache Geronimo.

Chapter 5 : Systems Supporting Risk-Based Dynamic Infrastructure Management Framework

Overview

This chapter expands on selected systems that are part of RiskDIMS, specifically: the integrated geospatiotemporal model and the DSS. An overview of a few sensing technologies that exist and operate today has already been presented at the beginning of Chapter 3. While many other sensing technologies exist, this broad topic does not need to be covered in detail within this document. Levees and other critical infrastructure may be monitored using many of today's sensing technologies. Data captured through sensing means are stored in corresponding geospatial databases, which interact with the integrated geospatiotemporal model and the DSS.

Integrated Geospatiotemporal Model

This research proposes building an interdisciplinary model that brings together factors, and therefore processes, from the built, natural and socio-economic environments that define infrastructure failure risk. Sustainable disaster risk management can be achieved by using an interdisciplinary approach (Zobel et al., 2009). The goal of this research is not to increase or decrease the number of factors that define risk, or argue towards the use of a particular relationship –often represented by a mathematical equation– even though it is known that some research efforts have led to improved quantification of risk. Instead, the goal is to challenge traditional ways of evaluating risk by demonstrating that a dynamic non-linear model, that mimics the complexity of our world, can lead to a refined definition of risk. Thus, this interdisciplinary project aims to change the core of risk analysis processes.

Application of System Dynamics Concept

The development of the integrated geospatiotemporal model integrates existing concepts, available technologies, and previous research to address critical infrastructure management. Systems engineering helps integrate these ideas, tools and efforts in a logical manner. According to Chang (2011), Systems engineering represents a rational response or methodology to handle increasingly complex situations in modern society, involving deeper multidisciplinary consideration of not only technical, but also environmental, socioeconomic and managerial factors. As defined at the beginning of this document, SD is a systems engineering method that has the capacity to provide insights into situations of dynamic complexity (Sterman, 2000). The following are basic definitions of elements in a model built using SD.

A dynamic system consists of **variables** that are related in a non-linear fashion such that a change in a variable affects another one, characterizing the behavior contribution of one element to another. These relationships are established using causal links. Figure 16 illustrates the use of a **causal link**. The **link polarity** determines whether the causal variable has a positive or negative impact on the resulting variable. In this example, an increase in rainfall results in an increase of river stage. This relationship is positive because an increase or decrease in the causal variable results in a corresponding increase or decrease in the resulting variable, respectively. In a negative relationship, an increase in the causal variable would imply a decrease in the resulting variable, and vice versa.

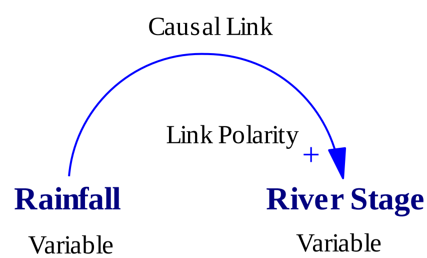

Figure 16 - Causal Relationship

In addition to relating dynamic factors using causal relationships in mathematical terms, in order to properly relate all these described system elements and assess their behavior, it is important to determine which of these factors are **stocks** and **flows**. In other words, which factors may accumulate or deplete over time (stocks), and which factors may determine the rate at which the stocks accumulate and/or deplete (flows). For example, as shown in Figure 17, while population may be considered a stock, immigration and

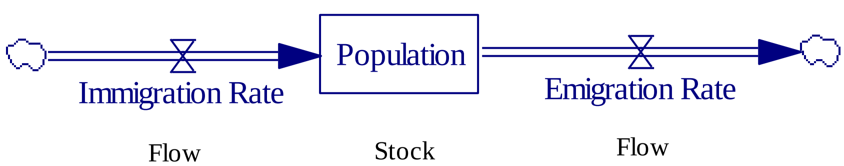

Figure 17 - Stock and Flows

emigration rates are flows. Not all variables need to be stocks or flows, only those that need to be represented in this manner for the benefit of the analysis.

In SD, the concept of feedback effects exists. These are represented by **reinforcing and balancing loops**. Figure 18 gives an example of a reinforcing loop, where a stronger economy leads to better infrastructure services, and in turn, better infrastructure services lead to a stronger economy. Notice that all the causal links must be in the same direction (clockwise in the example). In a balancing loop, an increase in a variable leads to its eventual decrease. On a more general level, factors from the built, natural and socio-economic environments change over time, and affect short-term operational and long-term strategic infrastructure management decisions. At the same time, these decisions affect the context under which future decisions are made, which, in turn, impacts and modifies the behavior of dynamic factors that define risk, causing a feedback effect.

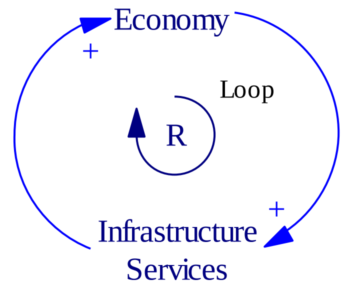

Figure 18 - Reinforcing Loop

Delays also play an important role in SD models. Having a notion of what processes occur immediately and which ones may take some time is critical to capturing real-world behavior. For instance, a storm upstream impacts the downstream environmental condition after a period of time has passed. A non-physical example relates to the time between the allocation of funds and the actual implementation of MR&R activities. SD requires the inclusion of temporal delays, whose advantageous addition becomes evident during the calibration and validation of the model.

Once dynamic non-linear relationships are defined using the elements described above, it is possible to model behavior of variables over time, capturing the temporal characteristic of infrastructure failure risk, and determine the immediate and long-term consequential risk from implemented infrastructure management policies.

Selected Dynamic Processes

The processes that affect infrastructure failure risk described here will serve to identify established individual parameters for the proposed model, their relationships, and potentially domain-specific models to use as components of the integrated geospatiotemporal model. This selection is not meant to be comprehensive but rather serve as a starting point for future development. The contribution of this research is the methodology and not the parameters or processes. The following processes have been identified based on the literature review and expert knowledge. Other processes may be explored to build more comprehensive assessments.

Built environment processes of interest:

1. Failure modes of levees attributed to diverse performance features, along with the estimated vulnerability of levees to natural events,
2. Impact of infrastructure management policies on the physical and functional performance of levees, and
3. Real estate and infrastructure development, considering urbanization rates, in areas exposed to flood hazards of different levels

Natural environment processes of interest:

4. Changing climate and environmental conditions, such as large and prolonged storms, associated with modes of levee failure,
5. Given recent assigned importance to environmental sustainability, safeguard of environmental assets whose value to the public is easily perceived (e.g., parks, green areas in highly impervious zones), and
6. Immediate and long-term damage reach of flood hazards of different levels

Socio-economic environment processes of interest:

7. Economic development, illustratively represented by gross product,

8. Population growth in areas exposed to flood hazards of different levels,
9. Effect that low value perception towards flood protection infrastructure has in the management of infrastructure (e.g., low value perception leading to social pressure to finance infrastructure sectors of higher daily value to residents and commuters and inadvertently underfund operational and capital budgets for levees),
10. Variable confidence of population towards reliability of flood protection systems reflected through public risk perception, and
11. Decision making for infrastructure management MR&R policies

Figure 19 shows a causal loop diagram (CLD) that integrates these processes. Factors from the built, natural and socio-economic environments are highlighted in blue, green and orange, respectively. Shadow variables –representations of already existing variables, which are used to improve the presentation of the image– are in brackets. A CLD demonstrates, at a high level, how factors could interact in a dynamic and non-linear fashion. Most CLDs are non-working model representations as their purpose is to summarize the system to be modeled. Using this CLD as a reference, a modeler can derive specific variables and corresponding relationships.

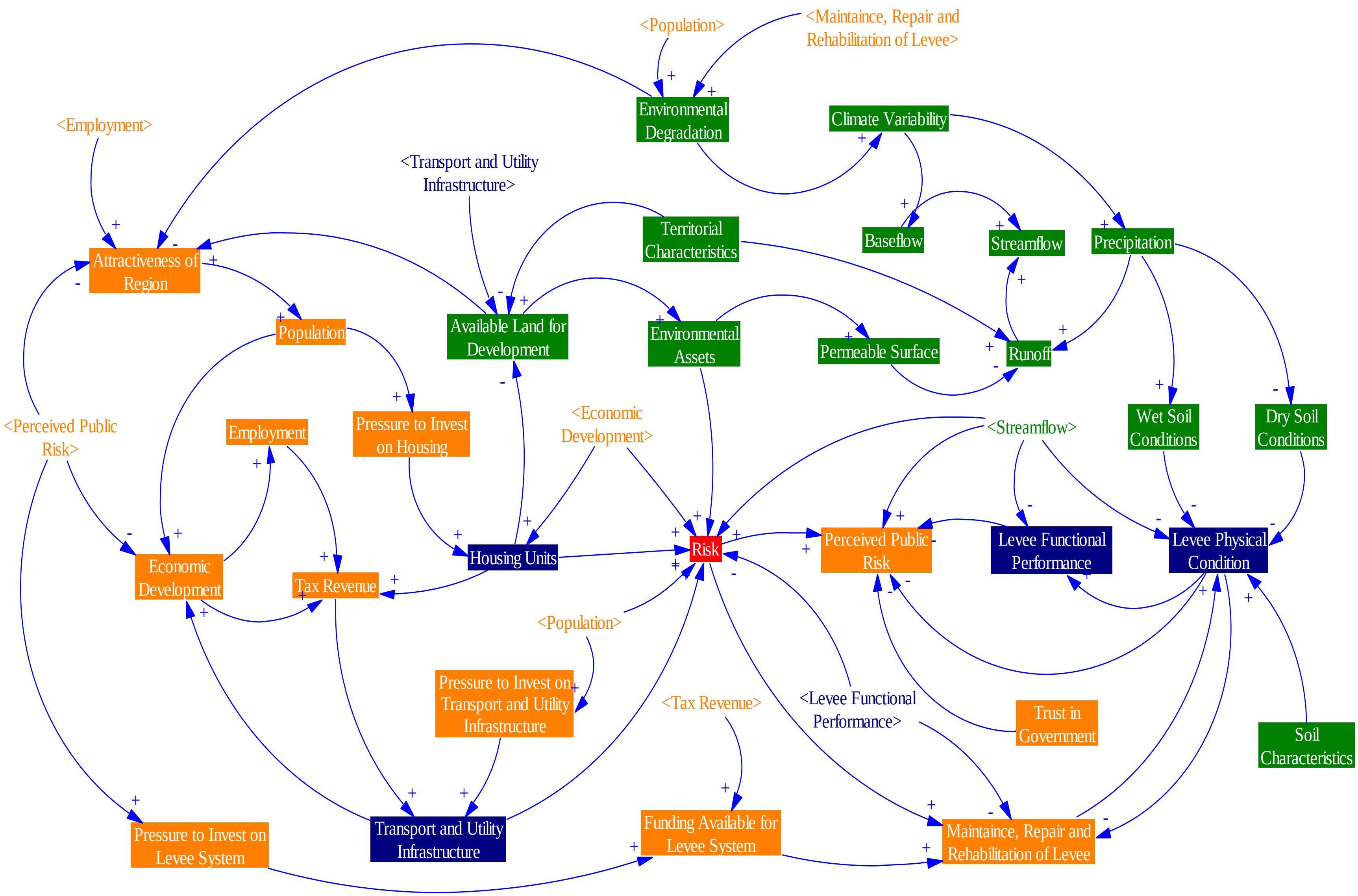

Figure 19 – Representative High-Level CLD of Factors and Processes from the Built, Natural, and Socio-economic Environments

Population changes according to the attractiveness of the region. The more attractive the region, the more people will decide to remain and immigrate. This attractiveness depends on employment, availability of land, perceived public risk, and environmental degradation. Employment, an indicator of economic growth, encourages people to migrate. Likewise, it is estimated that the more available land for development, the more new housing units could potentially be built, encouraging people to move to the region. Additionally, perceived risk is here defined as a function of risk information, trust in government, the physical condition of the levee, the functional performance of the levee, and the streamflow. Field surveys, as later suggested, will help refine the definition of public risk perception, which may also impact economic development through business investment. Also, environmental degradation may affect the attractiveness to the region –the quality of air, water and other resources influence the desire to remain or immigrate to the studied geographic area.

Population, in turn, has four effects. First, people are assumed to positively influence economic development. There are some exceptions to this effect, which are covered later on this document. Additionally, as population increases, the pressure to invest on housing and infrastructure (transport and utility) rises as well. This pressure, along with the state of the economy, is responsible for real estate development, which relies on private investment. While the transport and utility infrastructure sectors may also rely on private investment, the sectors have been traditionally viewed as public assets that benefit economic development. Hence, the CLD attempts to capture the impact of tax revenues collected through income, real estate and business taxes, on non-flood protection infrastructure sectors to contrast it with the use of tax revenue to finance MR&R activities for the levee system. Investments in the levee system may be impacted by pressure emerging from perceived public risk.

MR&R may also depend on the physical condition and functional performance of the levee, as well as thresholds on acceptable risk levels. MR&R actions serve to correct any structural deficiencies and functional performance gaps. Since functional performance is associated with physical condition, MR&R directly address the physical characteristics of the levee to influence functional performance. Performance itself may be assessed against streamflow levels. The condition of the levee is subject to soil attributes and conditions, as well as erosion due to streamflow. Both dry and wet soil conditions have a negative impact on the physical condition of levees.

Changes in precipitation patterns, which alter soil conditions and runoff, may be attributed to climate variability. Climate variability, resulting from environmental degradation due to population growth and development, may also have an effect on baseflow levels. As baseflow and runoff augment, streamflow increases. Runoff depends on the territorial characteristics and the amount of permeable surface. Permeable surfaces decrease runoff. Without low impact development, urbanization, including infrastructure development, decreases the availability of environmental assets, and thus permeable surfaces.

Finally, risk is defined as a function of vulnerability (i.e., levee functional performance), probability of hazard occurrence (i.e., streamflow), and consequence (i.e., population, real estate, infrastructure, environmental assets, and economic output). The definition of risk is further described in the next section.

Dynamic Infrastructure Failure Risk Definition

Risk may be derived using a number of factors from the discussed processes. Specifically, risk, R, is estimated in year t for MR&R policy x under implementation using the following function:

$$R_{t,x} = \sum_{i} v_{t,x,i} \times p_{t,x,i} \times c_{t,x,i}$$

, where $v_{t,x,i}$ is the vulnerability of the levee to a natural hazard level i in year t when MR&R policy x is implemented, $p_{t,x,i}$ is the likelihood of natural hazard level i in year t when MR&R policy x is implemented, and $c_{t,x,i}$ is the total value of elements at risk (consequence) in financial terms given natural hazard level i in year t when MR&R policy x is implemented (e.g., population, housing units, transport and utilities infrastructure, environmental assets, economic output). The relationships that exist among v, p and c are captured by the integrated geospatiotemporal model, and for that reason these do not need to be represented in the equation above. It is also known that:

$$\sum_i p_{t,x,i} = 1$$

Modeling in Interagency Cloud Computing Environment

Integrated geospatiotemporal modeling can be achieved through precise coordination of individual parameter and domain-specific model interaction. As discussed previously, data collection and management needs to be a decentralized task, where each government agency actively participates given their specialty area. Similarly, agencies may also be responsible for domain-specific models as to provide insights that unspecialized organizations may not be able to provide. Using the earlier example of NOAA, this organization would be best positioned to manage the domain-specific model related to climate conditions.

Despite displaying an obvious technical advantage, the implementation of a distributed modeling environment poses several challenges. First, this design creates dependencies among various agencies and their domain-specific models. What may be regarded as a small change to a particular domain-specific model may imply changing several interfacing models. Second, a distributed modeling environment might unintentionally expand the scope of RiskDIMS. For example, agencies responsible for a particular domain-specific model will use the model to monitor their own phenomena and as a consequence may need to expand that individual domain-specific model to include other data. This model extension will then unnecessarily add computation resources and increase the complexity of the analysis of RiskDIMS. Addressing these issues requires a high-level of interagency collaboration, establishing configuration management policies and procedures, and employing a modular approach to model design, where a particular domain-specific model is composed of smaller modules or molecules. In SD, molecules are the building blocks of SD models (Hines, 2005).

Model Orchestration

Combining built environment parameters and domain-specific models with parameters and domain-specific models from the natural and socio-economic domains in a logical and computationally-efficient form will be a key step in the development of the geospatiotemporal model. Decision making relies on the attainment of complete and accurate results. Therefore, the development of a robust coordinating system able to orchestrate the execution of domain-specific model in a non-linear fashion, including the exchange of data among simultaneous modeling processes, is a key step. Results obtained at a given simulation iteration shall be recorded in a database using timestamps as attributes. This characteristic will help the system relate data with a particular time in the simulation and present the information to users accordingly.

Although applied to a local network, Kumar (2012) demonstrates how related but separate models can be run in a simultaneous manner through the development of the Locally Distributed Simultaneous Model Execution (LDSME) framework and tool, which executes complex and computationally-intensive water quality models to manage and study watershed-waterbody systems. Models are executed via a common gateway on a server cluster of underutilized disparate computer resources. This setup is displayed in Figure 20.

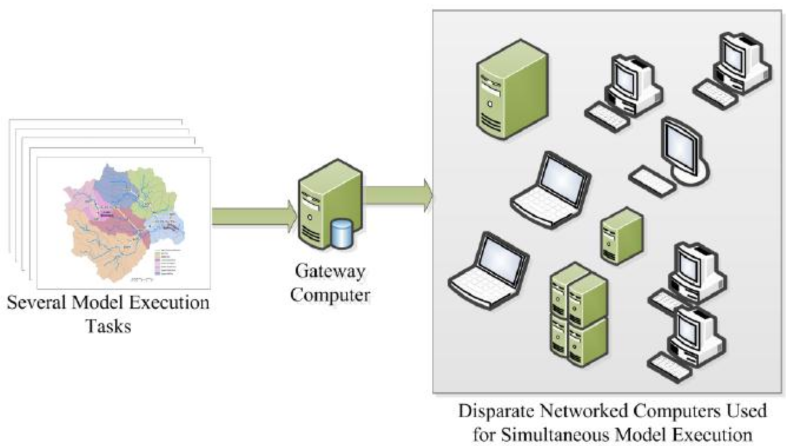

Figure 20 - LDSME Framework (Kumar, 2012)

Equally, in a cloud computing environment, a coordinating entity would be needed to orchestrate the data transfer between simultaneously-executed domain-specific models. Since the parameters that define infrastructure failure risk have a spatial dimension, geospatial location may be used to integrate datasets into the dynamic analysis framework. Each levee section resides in a particular geographic location, for instance. MR&R actions are implemented in selected sections of a levee network. As a result, improvements made are associated with a location as well. Instead of using a SD simulation software to integrate and model parameters, this study proposes the development of a versatile custom orchestrating entity that is able to work with domain-specific models, likely supported by different platforms (e.g., Java, .Net), off-the-shelf GIS services, and Server Object Extensions (SOEs). SOEs are extensions of ArcGIS Server functionality based on the use of ArcObjects –the core components under which ArcGIS is built– and implemented through a particular ArcObjects Software Development Kit (SDK).

The implementation of needed dynamic logic may be achieved through a SOA that leverages the use of GIS services and SOEs. Indeed, the integration of a SD method to achieve non-linear and dynamic modeling and the scale of the integrated geospatiotemporal model in a cloud computing environment calls for a sophisticated technology-based solution. ArcGIS Server supports an ample range of SOA implementations (ESRI, 2007), including the integration of GIS services using ArcGIS Java Web Services API (AgsJWS), a pure Java Web Services Application Programming Interface (API) (ESRI, 2011b).

Services Component Architecture (SCA) is a set of specifications for building applications and systems using a SOA (OASIS OpenCSA, 2011) that enables developers to focus on building the business logic behind a SOA (Tomala-Reyes and Vridhachalam, 2009). As a versatile solution able to integrate disparate services and components, SCA may be a good framework to architect the integrated geospatiotemporal model. Various vendors offer products for SCA development. Oracle has its own suite of solutions for SCA, including the extension Complex Event Processing (CEP) –based on the concept under the same name that enables the dynamic processing of events throughout a network leading to the detection of trends and patterns in real-time. With this solution, an updated dataset could trigger the integrated geospatiotemporal model, providing real-time risk-based information. Open source solutions for SCA such as Apache Tuscany are also available.

Implementation of Integrated Geospatiotemporal Model Proof-of-Concept

Using the principles outlined by Luzeaux and Ruault (2010) for the creation and control of complex SoS, a proof-of-concept representation of the integrated geospatiotemporal model, part of the SoS RiskDIMS, may serve to partially validate the proposed design of RiskDIMS. In order to accomplish this task, it is necessary to (A) translate the overarching computing paradigm into a simplified architecture for development, testing and implementation, possibly in the scale of the work performed by Kumar (2012), and (B) identify the individual domain-specific models, relationships, and parameters that form part of the integrated geospatiotemporal model. Research efforts have generated decades-worth of infrastructure management knowledge, including two decades of infrastructure and structural health monitoring (Moon et al., 2009) and three decades of infrastructure deterioration prediction (Sinha and McKim, 2007) research. New knowledge can be expected to emerge periodically, and therefore, a modular approach should be emphasized to guarantee that the latest advances are integrated in RiskDIMS.

This section presents selected current practices and research efforts that could be brought together to implement the proof-of-concept version of the integrated geospatiotemporal model. This initial set is aligned to the dynamic processes previously identified through the literature review and expertise. The integration of USACE established practices is important to ensure the acceptance of RiskDIMS as well as a seamless transition into the federal agency and potential state and local government organizations. The information presented here, although aligned to previously-listed dynamic processes of interest, concerns only one kind of failure mode due to soil settlement: overtopping leading to levee breach. The scope of this section is meant to be illustrative, and hence a starting point for a more holistic all-hazards approach. Overtopping of levees is of high concern, especially when overtopping is not meant to happen given the design levee crest height, and/or when overtopping exacerbates leading to breach. Additional failure modes and performance features may be added if concerned with such modes and features given that corresponding interdependent factors to those modes and features are also added to the model. An example of causal analysis for failure modes may be found in Serre et al. (2008).

Overtopping of Levees Attributed to Settlement Performance Feature

Settlement of levees contributes to overtopping by decreasing the crest height. Monitoring of levee settlement may be performed through the use of remote sensing technologies such as LiDAR and SAR. Collected levee cross-section measurements could be used to compare actual versus design crest height. These data could be used deterministically to forecast future settlement using historical data and surrounding environmental conditions as indicators for the level of settlement. Sources of stress in soil could occur from soil weight, surface loads, and environmental factors such as desiccation from drought, wetting from rainfall, and changes in depth to groundwater (USACE, 1990a). Hence, careful monitoring these parameters, especially environmental factors, could potentially indicate critical changes in settlement rates. The modeler may use the USACE Engineer Manual No. 1110-1-1904, "Settlement Analysis," which describes the agency's processes associated with the estimation of vertical displacements and settlement of soil under shallow foundations, to improve settlement understanding and refine settlement estimations. Assuming that levees are not exposed to earthquakes and other dynamic loads, Chapter 3 of the referenced document provides guidance on how settlement could be calculated through the sum of the immediate or distortion settlement, primary consolidation settlement, and secondary compression settlement.

Estimated Vulnerability of Levees to Natural Events

Unlike Simonovic and Li (2004) that define vulnerability as a measure of the severity of failure, this study proposes defining vulnerability as the probabilistic inability of a levee section to withstand a hazard, where 1 stands for complete vulnerability and 0 for no vulnerability. Moss and Eller (2007) use historical levee failure data to probabilistically estimate annual levee failures. While a negative binomial gamma distribution could be used, as suggested by Moss and Eller, along with a Monte Carlo simulation to generate annual probability data, a slightly different approach is here recommended, where historical data are parsed according to the (pre-disaster) condition of the levee, the type of soil, and the corresponding stream peak streamflow. These historical data could then serve to derive a levee-failure probability function, as outlined by USACE Engineer Manual No. 1110-2-1619, "Risk-Based Analysis for Flood Damage Reduction Studies," and illustrated by Figure 21.

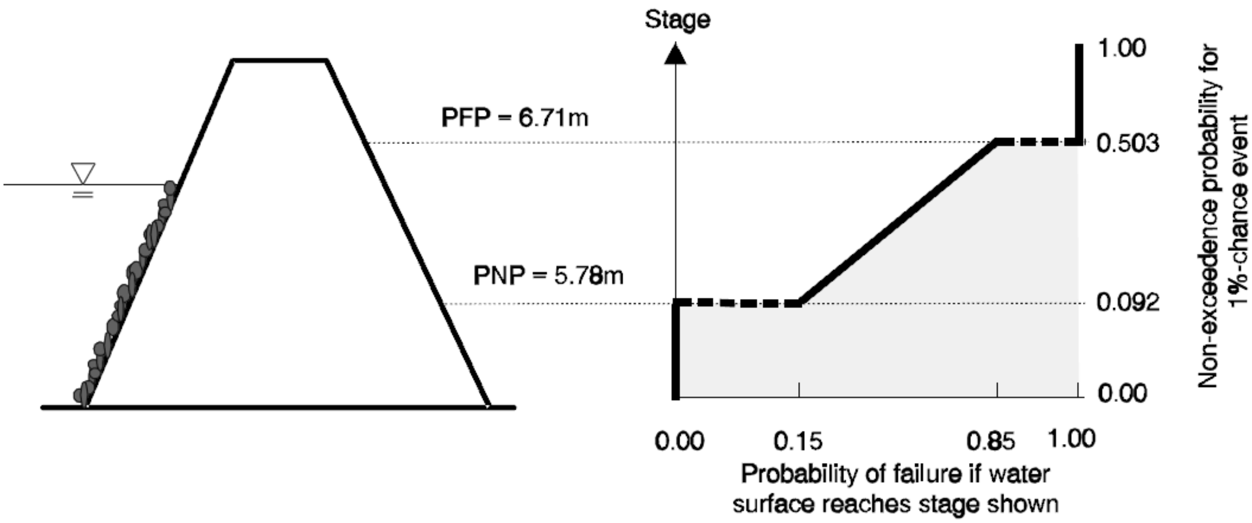

Figure 21 - Illustration of Levee-Failure Probability Function (USACE, 1996a)

The probable failure point (PFP) and the probable non-failure point (PNP) indicate the likelihood of a levee failure at particular water levels. The non-exceedance probability for a natural event attempts to incorporate uncertainty into the analysis by manifesting that a 1% exceedance probability event could generate scenarios of different stages. The expected value of failure given a natural event is therefore the total shaded area. Procedures outlined in the referenced manual are implemented by USACE's Hydrologic Engineering Center (HEC) Flood Damage Reduction Analysis (HEC-FDA) software. HEC-FDA computes conditional non-exceedance probability as required for levee certification (HEC USACE, 2008).

Impact of Infrastructure Management Policies on the Physical and Functional Performance of Levees

A five-level condition rating is suggested by the USACE for flood protection works (USACE, 1996b):

1. Excellent - No major deficiencies and none or few minor new deficiencies have been identified. All old deficiencies noted in the last inspection have been corrected.

2. Very Good - No major deficiencies and several new minor deficiencies have been identified. Most old deficiencies noted in the last inspection have been corrected.
3. Good - Few or no new major deficiencies have been identified. Numerous new minor deficiencies and/or several old minor deficiencies noted in the last inspection have not been corrected. Annual maintenance was performed, but additional effort is needed.
4. Fair - Major deficiencies have been identified that if not corrected immediately may lead to or cause deterioration of the project such that is incapable of providing the maximum protection. There is little or no evidence of minimum maintenance performed. A greater effort is required to reduce deficiencies.
5. Poor - Major deficiencies have been identified such that the structural integrity or the hazard control project will probably not withstand a major event. There is little or no evidence of maintenance performed.

Sensed data and inspection results will drive the development of MR&R policies for a network of levees, which is expected to be limited by available financial resources (e.g., budget). MR&R actions may be distinguished by their individual effects on the condition of a given levee section. In the context of levee settlement, an example of a maintenance action is increasing the levee crest height. The impact of a maintenance activity is usually very limited and therefore often regarded as a short-term solution. In the same context, repairing a levee could involve remediating the soil foundation without needing to rebuild the levee, and rehabilitation could imply rebuilding the entire levee section after remediating the soil foundation. The extent of maintenance and repair activities on a levee section will greatly depend on the beginning condition of the levee.

The challenge given the focus on overtopping is to use the rating system as pertaining to the condition of the levee in accordance to settlement features. Hence, it is important for infrastructure managers to associate the physical condition of a levee section with its functional performance goal in an attempt to provide a certain level of protection. After all, the ultimate objective of protection infrastructure is to safeguard against natural hazards, whose magnitudes are measured according to their devastating power and reach. Deriving the impact of MR&R activities require expert knowledge as well as pre-MR&R and post-MR&R data. Consultation of experts should be considered.

Urbanization in Areas Exposed to Flood Hazards of Different Levels: Population Dynamics, Economic Growth, Real Estate and Infrastructure Development, Land Use, and Social Pressure

The topic of urbanization has gained large interest within the research community. One of the most popular pieces of work in the area of urban dynamics is Limits to Growth –resulting in the World3 model, which highlights that global development is constrained by the finite capacity of the earth (Meadows et al., 2004). Due to its interdisciplinary nature, the urbanization phenomenon is studied in many fields, including social sciences, engineering, and natural sciences. Since research projects can take many forms, it is recommended that the core development of this already complex modeling piece be focused on research using SD and geospatial technologies that address major aspects of sustainable disaster risk reduction, as suggested by the previously-selected dynamic processes, and complemented with other research efforts as the need arises. Furthermore, it is worth noting that much of today's research focuses on capturing the dynamics of a geographically-bounded region. While linkages between dynamic factors exist quasi-uniformly across various cities and regions (e.g., public transportation may not play a vital role in defining immigration rates in a small town, but it would in a megacity; on the other hand, job availability encourages people to move), actual mathematical expressions that define those relationships could greatly depend on regression analysis and historical data belonging to the region of interest.

Xu (2011), Shen et al. (2009), and Vo et al. (2002) use SD to model a particular aspect of urbanization, bringing together factors such as population, transportation infrastructure, utilities, employment, gross product, the housing market, land area, and pollution. An effort to logically integrate these models in the context of sustainable disaster risk reduction, as well as the work on flood mitigation policy impact performed by Deegan (2007), which discusses how local community pressure for development affects infrastructure failure risk, will help understand the urban dynamics of floodplains. The result of this integration needs not to be complex, but focused and practical. In order to give a spatial framework to growth, Shannon's entropy could be utilized to measure the degree of spatial dispersion in the various zones within the geographic area of study. This approach has been used to assess urban sprawl (Yeh and Li, 2001; Sudhira et al., 2003; Jat et al., 2007). Shannon entropy, H_n, is defined as:

$$H_n = -\sum_{i=1}^{n} p_i \times ln(p_i)$$

, where p_i is the proportion of the variable being measure (e.g., population) in zone i with respect to all variable occurrences and n is the total number of zones.

Changing Climate and Environmental Conditions Associated with Modes of Levee Failure

Future climate variability is expected to change. Simonovic and Li (2004) use potential precipitation scenarios generated through GCMs to evaluate the impact of possible future conditions on streamflow. GCMs are numerical models that represent physical processes in the atmosphere, ocean, cryosphere and land surface, and serve to simulate the response of the global climate system to increasing greenhouse gas (GHG) concentrations (IPCC, 2011b). The Intergovernmental Panel on Climate Change (IPCC), an organization established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), and dedicated to the assessment of climate change, publishes estimated climate data (e.g., humidity, precipitation, air temperature, wind) based on 23 GCMs and 8 climate scenarios (IPCC, no date). These scenarios are considered consistent with global projections, physically plausible, applicable in impact assessments, representative, and accessible –meaning that data required for scenario modeling is available. Scenarios may be subject to an increasing rate of carbon dioxide concentrations, rapid economic growth, introduction of clean and resource-efficient technologies, and global population changes. These models are of particular importance to the generation of precipitation data under future scenarios.

These data could serve as input to current USACE statistical, hydrologic, and hydraulic procedures. HEC-Statistical Software Package (HEC-SSP), HEC-Hydrologic Modeling System (HEC-HMS), and HEC-River Analysis System (HEC-RAS) implement these procedures, respectively. Understanding the theory behind these individual software packages will enable the creation of a modeling environment that brings the best practices in flood risk management, widely accepted by federal, state and local governments. The aim is to conduct a deeper study of these systems and propose a logical framework under which parameters across these systems could be integrated in a non-linear dynamic form.

HEC-SSP performs analyses of hydrologic data, including flood flow frequency analysis based on Bulletin 17B of the Hydrology Subcommittee "Flood Flow Frequency" (HEC USACE, 2010b). Bulletin 17B recommends the use of a Log-Pearson type III statistical model to define median exceedance probabilities. HEC-HMS, on the other hand, simulates the precipitation-runoff processes of dendritic watershed systems (HEC USACE, 2010c). The application offers seven different methods for determining surface runoff based on excess precipitation. Finally, HEC-RAS performs one-dimensional hydraulic analysis for (A) steady flow as applied to flood plain management and the assessment of water surface profile changes due to presence of levees, (B) unsteady flow used in levee breaching and overtopping and dam break analysis, and (C) sediment transport for a full network of natural and constructed channels (HEC USACE, 2010a). While reference manuals that discuss the theory behind HEC-HMS and HEC-RAS are available, the reference manual for HEC-SSP is still under development.

Immediate and Long-Term Damage Reach of Flood Hazards of Different Levels

Natural hazard events may be grouped according to their intensity levels, very high (extreme), high, medium low and very low, each of which has different probabilities of occurrence and various damage reaches (here intensity considers the magnitude and size of the natural event). Considering climate variability patterns, these probabilities are expected to evolve with time. The integrated geospatiotemporal model should consider different failure scenarios along with their associated probabilities of occurrence and the consequences in monetary terms for each natural hazard intensity level. HEC-FDA performs an integrated engineering and economic analysis of flood risk management plans (HEC USACE, 2008). HEC-FDA implements Engineer Regulation No. 1105-2-100, "Planning - Risk Analysis for Flood Damage Reduction Studies," Engineer Regulation No. 1105-2-101, "Planning Guidance Notebook," and Engineer Manual No. 1110-2-1619, "Risk-Based Analysis for Flood Damage Reduction Studies."

In addition to estimating conditional non-exceedance probability as mentioned before, HEC-FDA computes annual exceedance probabilities (probability that an existing levee will fail in a given year due to maximum annual stage higher than levee elevation) and evaluates corresponding expected and equivalent annual damages. In order to quantify damage upon infrastructure failure, Engineer Manual No. 1110-2-1619 recommends estimating damages as the equivalent to without-project damages at that stage, regardless of whether or not the levee is overtopped (USACE, 1996a). This seems to be a practical approach to damage quantification that could be refined with a much tighter integration between statistical, hydrologic, and hydraulic procedures. Another widely-used application to estimate damage due to floods is HAZUS-MH.

Variable Confidence of Population towards Reliability of Flood Protection System

Ludy and Kondolf (2012) conducted a survey for residents living in areas protected by Sacramento-San Joaquin Delta levees to determine their understanding of flood risk. Unfortunately, despite potential flooding in protected areas below sea level due to residual risk, residents in these areas are not provided with information about flood risk or required to purchase insurance since their land is not legally considered part of the floodplain. This has led to lack of understanding of flood risk –for instance, many believe that a 100-year flood takes place every 100 years. Other perception surveys have led to important insights about unconscious attitudes and population reaction in Belgium (Kellens et al., 2011), Iceland (Pagneux et al., 2011), Romania (Armas and Avram, 2009), Slovenia (Brilly and Polic, 2005), and The Netherlands (Botzen et al., 2009; Terpstra et al., 2012).

Similarly, creating a survey could help understand the variability of the public confidence towards levees and other flood protection systems, and capture potential reactionary (post-disaster) or proactive behavior. Data should be analyzed based on geographic area (e.g., land exposed to different hazard level) as a correlation exists between flood risk perception and actual risk. Population living near a river or low-lying areas tends to have higher risk perceptions (Botzen et al., 2009). Research also shows that prior flood experience has an effect on the level of risk perception (Ludy and Kondolf, 2012). In fact, many are unable to relate to large-scale floods outside of their own geographic area (Terpstra et al., 2012). Without flood experience, communities can easily develop misconceptions, and even a false sense of safety when protected by levees and other flood defenses (Kellens et al., 2011). Hence, capturing previous flood experience of questionnaire participants is important. Finally, the format of the survey should consider that risk judgment of the public relies on qualitative factors (Kellens et al., 2011). Information to collect includes (Ludy and Kondolf, 2012):

1. Prior flood experience (Brilly and Polic, 2005; Burn, 1999),
2. General flood knowledge, including understanding of probabilities,
3. Personal assessment of flood likelihood and damages,
4. Self-protective or preparatory measures behavior, including moving to a different area (Pagneux et al., 2011), and
5. Trust in public expert knowledge and safety measures (Terpstra et al., 2012).

Decision Making for Infrastructure Management MR&R Policies

MR&R policies should be concerned with addressing the physical condition (e.g., very good) and/or the functional performance (e.g., against a hazard of high intensity) of a levee network. Decisions may also be taken in accordance to threshold risk levels. Although much more uncertain, risk information is inclusive of factors usually not accounted when attempting to meet levee deficiencies. Making decisions solely based on condition or level of protection without considering potential second order consequence is regarded as a challenge since well-intended infrastructure management actions could result in higher risk due to the non-linearity that RiskDIMS proposes. Reducing risk in the context of levee infrastructure management implies reducing the vulnerability of the system as this activity is within the set of responsibilities of the managing agency. Federal, state and local parties responsible for the management of levees need to work closely with other agencies to affect the impact and frequency of large-scale hazards (e.g. green infrastructure development, climate change mitigation) and decrease consequence (e.g., zoning). Furthermore, infrastructure management decisions are subject to conventional organizational constraints, especially budget limits. Information on the proposed functional design of decision making capabilities that should be offered by RiskDIMS is available in the discussion of the DSS.

PAVER, a pavement management system being used by USACE and other federal agencies, is a good example of an infrastructure management system able to simulate the impact of lifecycle MR&R policies through a work planning (Shahin, 2010). This tool identifies adequate maintenance treatment combinations over a number of years based on selected MR&R policy and derives lifecycle MR&R costs. Infrastructure managers may design policies using one of the three options provided by the system:

1. "Critical Pavement Condition Index (PCI) Method" (A) selects MR&R actions given a budget constraint, or (B) targets a specific condition performance level, determining the budget required to meet that target,
2. "Consequence of Localized Distress Maintenance" simulates the implementation of an MR&R action in the current year and records the cost and the condition after the treatment is implemented (no lifecycle analysis), and
3. "Major MR&R based on Minimum Condition" specifies a minimum threshold condition performance level that is allowed per year.

Decision Support System

The DSS is to provide the right information to the right people at the right time, thus avoiding reactive infrastructure management decisions. The DSS presents three critical sets of information for decision making. The first set relates to the current status of a levee network, where users are able to retrieve the most up-to-date information, including but not limited to present risk, the individual condition of levees, and population, using a dynamic web map. The second set is historical data, which are stored in the geospatial databases, and may be retrieved for background knowledge and assess previous and immediate trends. Finally, the third set is lifecycle data output by the integrated geospatiotemporal model transformed into information for decision making. Processing such data is triggered by users when running MR&R policy scenarios. Users shall be able to run several policy scenarios, and compare them. Comparison of MR&R policies is possible only when the individual analyses use the same length of analysis period.

Policy Design

A policy is defined as the set of MR&R activities for the entire infrastructure network. Each policy will have an associated cost and result in a quantifiable level of risk. Users shall be able to design MR&R policies in accordance to:

1. A target physical condition level (i.e., excellent, very good, good, fair, poor) across the network,
2. A desired level of protection as defined by the levee community (e.g., ability to withstand a high-intensity hazard, a medium-intensity hazard, or a low-intensity hazard) across the network,
3. Acceptable combined physical condition and level of protection targets,
4. Maximizing network physical condition or level of protection based on annual levels of investment, or
5. User-defined MR&R actions for individual levee sections.

Policy definitions impact the behavior of the integrated geospatiotemporal model, specifically the MR&R activities that may be implemented in the simulation as constrained by the organizational goals, available annual budgets, and the length of the period of analysis.

Measuring Costs and Benefits

Risk-based decision making involves comparing benefits and cost (Hall et al., 2006). Benefits are measured in terms of present worth of accumulated reduced risk as a result of implemented MR&R actions in comparison to a base case. The proposed base case for the analyses performed by RiskDIMS is defined as the “no implementation,” or “do nothing” option, where no MR&R actions are implemented in the network of levees throughout the period of analysis. Moreover, it is important to monitor additional evaluation indices, especially the economy’s gross product. Economic development has traditionally been, and continues to be, an important decision making criterion in the shaping and growth of society. Leveraging the previous definition of risk, here benefit associated with reduced risk, B, in year t given MR&R policy x is defined as:

$$B_{t,x} = R_{t,0} - R_{t,x}$$

, where $R_{t,x}$ is the resulting risk of MR&R policy x in the year t, and $R_{t,0}$ is the estimated risk of no implementation in the year t (baseline scenario). On the other hand, costs are directly associated with the implementation of MR&R activities, and consist of annual capital investments (if levee is rehabilitated) and maintenance and operational costs, minus the salvage value of the asset at the end of the analysis period.

Real Interest Rate for Present Worth Estimation

Both, costs and benefits, are aggregated for the period of analysis by adjusting values to present worth by using a real interest rate r_t for year t, where g_t is the economic growth rate for year t and δ_t is the discount rate for year t:

$$r_t = \frac{1 + g_t}{1 + \delta_t}$$

This equation is a slightly different version of the equation proposed by Hallegatte (2006), who considered g and δ to be fixed values throughout the period of analysis. Adjusting benefits and costs to present worth terms gives decision makers the opportunity to relate dollar amounts generated by the analysis to today's values.

Total Present Worth of Benefits

The total present worth of benefits (TPWB) for MR&R policy x, analyzed in a period of n years, whose investment was made d years before, is defined by the following equation:

$$TPWB_{x,n,d} = \sum_{t=0+d}^{n} B_{t,x} \times (r_t)^t$$

, where $B_{t,x}$ is the benefit of MR&R policy x in year t, r_t is the real interest for year t, and n is the number of years in the period of analysis. Additional evaluation indices such as the economy's gross product shall be estimated in a similar fashion. This equation was derived from the TPWB equation proposed by Hudson et al. (1997).

Total Present Worth of Costs

In the same way, costs need to be adjusted to present worth terms. The following equation defines the total present worth of costs (TPWC) for MR&R policy x, analyzed in a period of n years, whose benefit is expected in d years:

$$TPWC_{x,n,d} = \sum_{t=0}^{n-d} \left(CC_{t,x} + MO_{t,x}\right) \times (r_t)^t - r_{n-d} \times SV_{x,n-d}$$

, where $CC_{t,x}$ is the capital cost for MR&R policy x in year t; $MO_{t,x}$ is the maintenance plus operation cost for MR&R policy x in year t, r_t is the real interest for year t, $SV_{x,n-d}$ is the salvage value, if any, for

MR&R policy x after n minus d years, and n is the number of years in the period of analysis. This equation was derived from the TPWC equation proposed by Hudson et al. (1997).

Filtering Out Underperforming Infrastructure Management Policies

The first step in evaluating infrastructure management policies is identifying the alternatives that dominate within the set of policies under evaluation. This is accomplished by building a Pareto efficiency curve in a cost versus benefit diagram (listed as Risk-Cost Curve in Figure 22), where policies outside the curve are considered dominated, or inferior. For example, if MR&R policy A costs more than MR&R policy B and also produces more risk, then policy A dominates policy B. In other words, a non-dominated policy is one where any improvement of one evaluation index (e.g., reduced risk, cost, economic output) can be achieved only at the expense of degrading another (Haimes, 1998). Dominated policies may optionally be filtered out of the process by the user. Although dominated policies could be filtered out, users shall be able to access them at any time during the evaluation process. If a user decides to use other evaluation indices aside from risk reduction, then the DSS shall perform a multidimensional comparison.

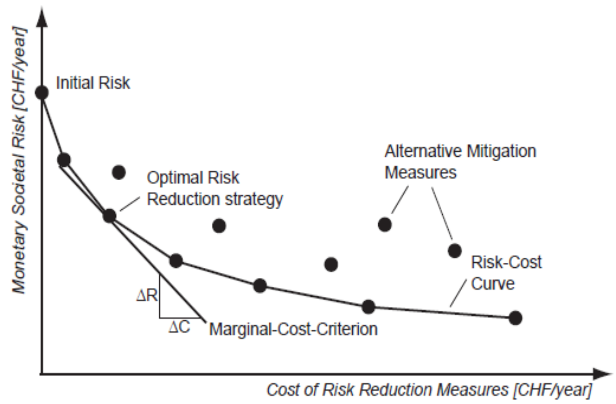

Figure 22 - Risk-Cost Diagram Based on Pareto Efficiency (Brundl et al., 2009)

Since RiskDIMS aggregates the costs and benefits of individual policies based on the preferred number of years in the analysis period, it is possible that a policy could be perceived to be inferior under short periods of analysis, but ends up dominating in long periods. This phenomenon occurs mainly because some policies only address immediate needs and tend not to perform well over time. Users should be conscious of this, and select periods of analysis that reflect the values of the organization and local community.

Evaluating Infrastructure Management Policies

Non-dominated policies, along with dominated policies included in the analysis, shall then be ranked according to: (A) $TPWB_{x,n,d}$, or (B) $BCR_{x,n,d}$, where $BCR_{x,n,d}$ = $TPWB_{x,n,d}$/ $TPWC_{x,n,d}$, based on user preference. Ranking aims to guide users in the exploration of MR&R policies as the DSS enables the detailed view of a given policy. The system presents an interactive web map interface of the geographic area of interest. The DSS shall dynamically display lifecycle data output by the geospatiotemporal model on the map (geographically-distributed) over time to give users a temporal perspective of how risk and the factors that define it vary throughout the period of analysis. Users should be able to click on a levee section to visualize the potential extent of damage associated with failure of that section due to natural hazards of different intensities.

In addition to having the ability to conduct this type of analysis, at the federal and state levels is critical to view national and state information as an aggregated set. State agency users shall view the condition of all levees in the state, their corresponding infrastructure failure risk levels, enabling economic development, and other associated evaluation indices. Comparable aggregation shall be implemented for national information. This information may then be useful in the allocation of additional resources and support to address at-large problems related to levee infrastructure.

Suggested Decision Support System Development

The DSS is the component that directly interacts with users, in this case, infrastructure managers, policy analysts and other decision makers at federal, state and local government agencies. These groups are the most familiar with the conditions and issues surrounding the development and management of the flood protection systems they own. Effective engagement of targeted groups will greatly depend on the designed graphical user interface (GUI) and the tailored information presented by the DSS through the dynamic web map –the communication of risk and other evaluation indices is important to understanding risk and to achieve sustainable risk-based decision making. Java EE SDK, a free development environment, bundled with Java Development Kit (JDK) could be used to build the DSS since previously-recommended web applications servers support Java EE-based applications. The versions to be used for RiskDIMS need to be carefully evaluated as to provide the most synergy between the individual supporting systems –not all applications servers support the same Java versions. The current version of ArcGIS Server offers a Java Web Application Development Framework (ADF) that has been used to build GIS web applications. However, the use of this component has been deprecated by ESRI, and as a consequence this component will not be part of future releases (ESRI, 2011b).

Chapter 6 : Proof-of-Concept System Dynamic Model

This chapter illustrates the value added of temporal analysis in the understanding and assessment of risk. Here the study proposes a proof-of-concept SD model to simulate the behavior of levee failure risk over time as a result of diverse infrastructure management investments. It is worth noting that the model aims to capture the behavior of risk, not predict risk levels. As later described, this model is not as comprehensive as the suggested scope for the proof-of-concept geospatiotemporal model and DSS of RiskDIMS. The SD model, built using Vensim software, does attempt to capture several important non-linear feedback effects that may lead to counterintuitive results.

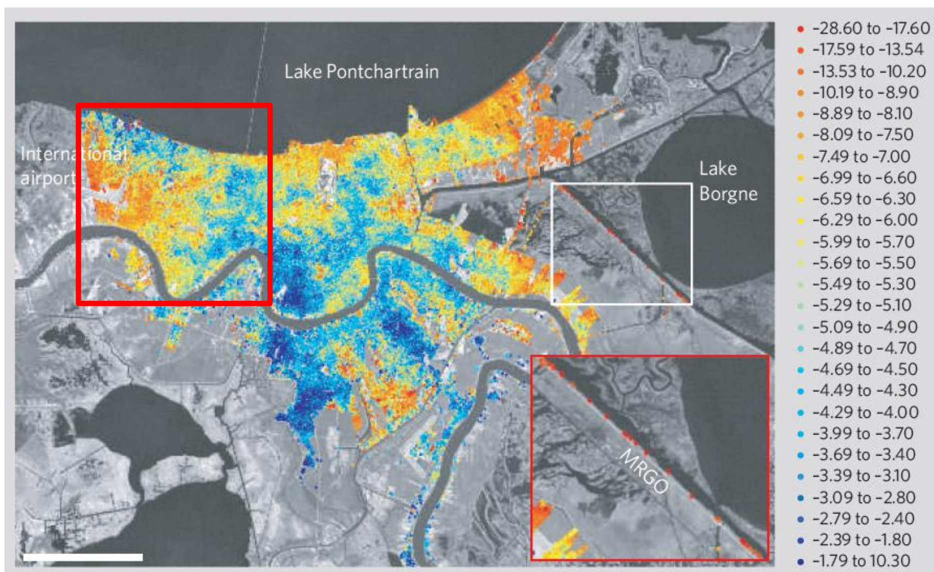

Figure 23 - Jefferson East (Red) Subsidence Rates in mm/year (Dixon et al., 2006)

In order to demonstrate the applicability of the model to real-world scenarios, this research used readily-available data from the east region of the Jefferson Parish, part of the Greater New Orleans area in Louisiana. The Jefferson Parish was established in 1825 and named in honor of Thomas Jefferson, who participated in the purchase of the Louisiana territory from France in 1803 (Jefferson Parish, 2012) as president of the United States. In addition to having been impacted by Hurricane Katrina in 2005, this area has also been experiencing significant subsidence rates (Figure 23). The proposed application is of direct utility to current infrastructure management efforts in the Greater New Orleans, and other large geographic areas protected by levees such as Sacramento, California and St. Louis, Missouri.

The large consequences generated by Hurricane Katrina captured the research interest of academia. While much data exist on pre and post-Katrina conditions, such as the Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System Final Report issued by the Interagency Performance Evaluation Task Force (IPET), carefully-considered assumptions are used here for the development of the model and analysis. Targeted data collection and research efforts must take place before model can be calibrated, validated and used for decision making in the field. Due to the diverse type of information available, zones affected by Hurricane Katrina are indeed excellent prospective areas of application for the foreseen proof-of-concept of RiskDIMS.

Definition of Model

The model is comprised of 6 modules and 187 dynamic stocks, flows and variables (Appendix L). Each of the modules contains factors associated with (A) levee infrastructure condition and vulnerability, (B) population dynamics, (C) building and residential home development, (D) economic growth, (E) levee infrastructure management, and (F) the risk construct. The intent is to incorporate many of the expected effects of the dynamic processes previously identified through the literature review and expert knowledge.

As indicated previously and as later highlighted, the length of the period of analysis may affect the proper impact analysis of infrastructure management investments. Since this study is concerned with potential long-term impacts, a period of 50 years is used here.

The CLD (Figure 24) displays the high-level structure of the model, which includes two balancing loops and four reinforcing loops. The Risk Mitigation balancing loop (B1) indicates the effect of risk aversion on infrastructure management investment decisions. As risk increases, so do investments. Improvements made on levees decrease their vulnerability, and thus risk. The Investment Pressure balancing loop (B2) is related to the emergence of social pressure to reduce risk through larger infrastructure investments. As condition improves, public risk perception decreases. Societal Consequence (R1), Built Environment Consequence (R2) and Economic Consequence (R3) reinforcing loops share similar variables and effects.

As the condition of levees improves due to risk-averse infrastructure management, population grows. Along with population, the housing stock and the economic output also augment. As a result, more

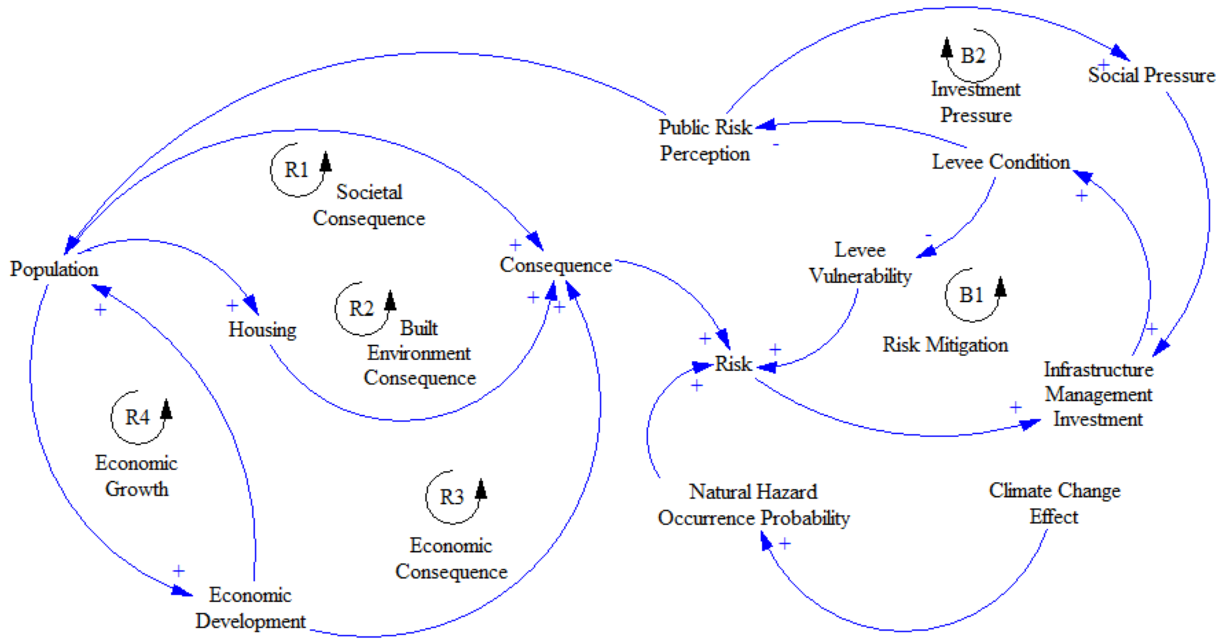

Figure 24 - CLD of Proof-of-Concept SD Model Developed for This Study

people, infrastructure and economic output are at risk. The last reinforcing loop, Economic Growth (R4), considering that Jefferson East is an urban environment, relates to the positive effect that population has on the economy and the impact economic development has on immigration rates.

Levee Infrastructure Condition and Vulnerability

The Jefferson Parish has two levee districts –the East Jefferson Levee District (EJLD) and the West Jefferson Levee District (WJLD)– now under the Southeast Louisiana Flood Protection Authority – East (SLFPA-E), and the Southeast Louisiana Flood Protection Authority – West (SLFPA-W), respectively (Figure 25). Prior to Hurricane Katrina, the former district was responsible for maintaining 11.6 miles of levees along the Mississippi River (USACE, 2000). The Jefferson Parish flood protection system also comprises other levees, flood walls, and structures, including some structures on Jefferson West, all of which are not part of this study. In the past, levees have been segmented into reaches according to their uniform cross-section, elevation, strength, and foundation conditions (IPET, 2009b). For example, East Jefferson levees and flood walls were divided into 18 reaches. Reaches JE12, JE13, and JE14 corresponded to the levees along the Mississippi River (IPET, 2009b). This, however, makes the comparison of infrastructure management activities more challenging, especially when comparing costs since reaches' lengths could vary. Lengthier levee reaches may require larger investments. For the purpose of this analysis, MR&R actions are assumed to be performed on sections within the 11.6 miles that have similar characteristics.

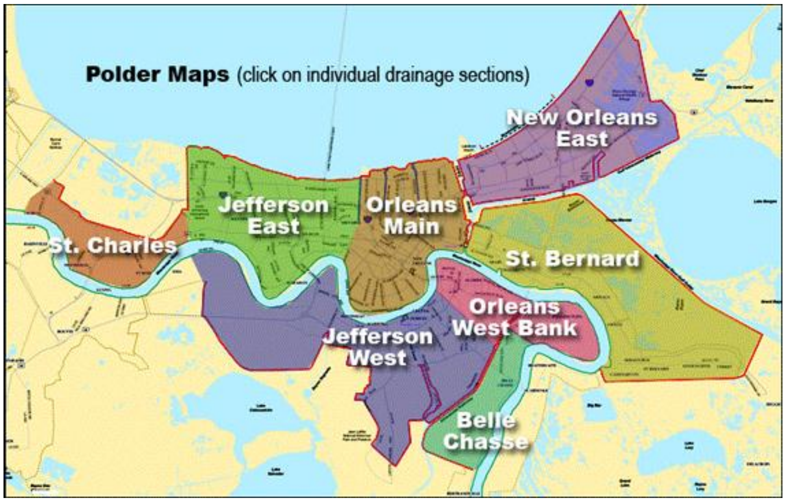

Figure 25 - New Orleans Levee Districts (USACE, 2011)

In 2000, the USACE found these levees to be in "outstanding" condition (USACE, 2000). Since this qualification is not part of the five-level condition rating suggested by the USACE (USACE, 1996b), it may be inferred that the corresponding condition level based on the established scale would be "good," "very good" or "excellent" as a few minor deficiencies were identified during inspection. These established categories are merged in the SD model under one single category labeled "good." One of the

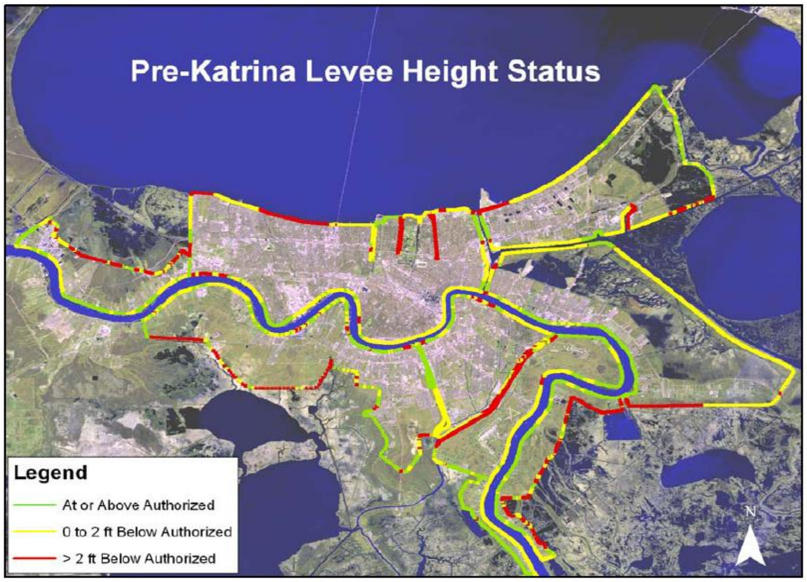

Figure 26 - Flood Protection Infrastructure Elevations to Authorized Elevations Based on SPH Method (IPET, 2009a)

advantages of having a system with less number of ratings is the reduction of ambiguity emerging from deciding what makes an element good versus very good, or very good versus excellent, for instance.

Earlier in this document, the need to cross-match physical condition with functional performance was highlighted as a solution to address potential changes in the environment (e.g., subsidence, climate variability). Figure 26 shows that a large portion of levees in the Jefferson Parish was below authorized levels prior to Hurricane Katrina. Despite the need to discontinue the Standard Project Hurricane (SPH) methodology as recommended by IPET, which was used to determine authorized levee elevations, this study uses Figure 26 –given that no other relevant data seems to be readily available– to reallocate the 11.6 miles to proper condition states according to level of protection. Refer to Table 2 for the results of the visual assessment, where miles at above authorized levels are considered to be in good condition, miles 0-2 ft. below authorized levels, in fair condition, and miles more than 2 ft. below authorized levels, in poor condition. The allocation of levee miles to various condition ratings according to their elevation then reflects an aspect of the levees' functional performance.

Table 2 - Number of Levee Miles by Condition Ratings

	Condition		
Jefferson Parish	Good	Fair	Poor
East	4.43	5.12	2.05

The levee infrastructure condition and vulnerability module was divided into four sub-modules: (A1) Markov Transition Probability (MTP) matrices for deterioration assessment, (A2) infrastructure condition, (A3) public risk perception, and (A4) system vulnerability.

Markov Transition Probabilities for Deterioration Estimation

A condition prediction sub-module based on Markov chains –a stochastic system that dictates how an element transitions from one state to another state independently of previous transitions– is used to estimate how levee deterioration could occur throughout the network given a particular MR&R investment level. This particular method for condition estimation is selected to provide network-level analysis that includes uncertainty. The literature review did not output any research on the application of Markov chains to levee condition. Hence, the data used for this part of the analysis is synthetic. Although outside of the scope of RiskDIMS, deriving MTP matrices for levees may be an area for future additional research. Table 3 to Table 6 show the MTP matrices used, given four different infrastructure management investment levels.

Table 3 - MTP Matrix for No Infrastructure Management Investment

		To		
	State	Good	Fair	Poor
From	Good	0.7	0.2	0.1
	Fair	0	0.6	0.4
	Poor	0	0	1

Table 4 - MTP Matrix for Minor Infrastructure Management Investment

		To		
	State	Good	Fair	Poor
From	Good	0.8	0.1	0.1
	Fair	0.2	0.7	0.1
	Poor	0	0.2	0.8

Table 5 - MTP Matrix for Moderate Infrastructure Management Investment

		To		
	State	Good	Fair	Poor
From	Good	0.9	0.1	0
	Fair	0.4	0.6	0
	Poor	0.2	0.4	0.4

Table 6 - MTP Matrix for Major Infrastructure Management Investment

		To		
	State	Good	Fair	Poor
From	Good	1	0	0
	Fair	1	0	0
	Poor	1	0	0

Infrastructure Condition

The MTP matrices are applied to the network of levees in accordance to the investment level under review. Each of the matrices indicates the probability that a given section moves from one state to another. Since selected MR&R investments do not result in immediate condition rating change –after all, this change will greatly depend on the specific MR&R action under implementation, the model accounts for a delay between states. This is achieved by inserting additional stocks between poor, fair and good condition states as shown in Figure 27.

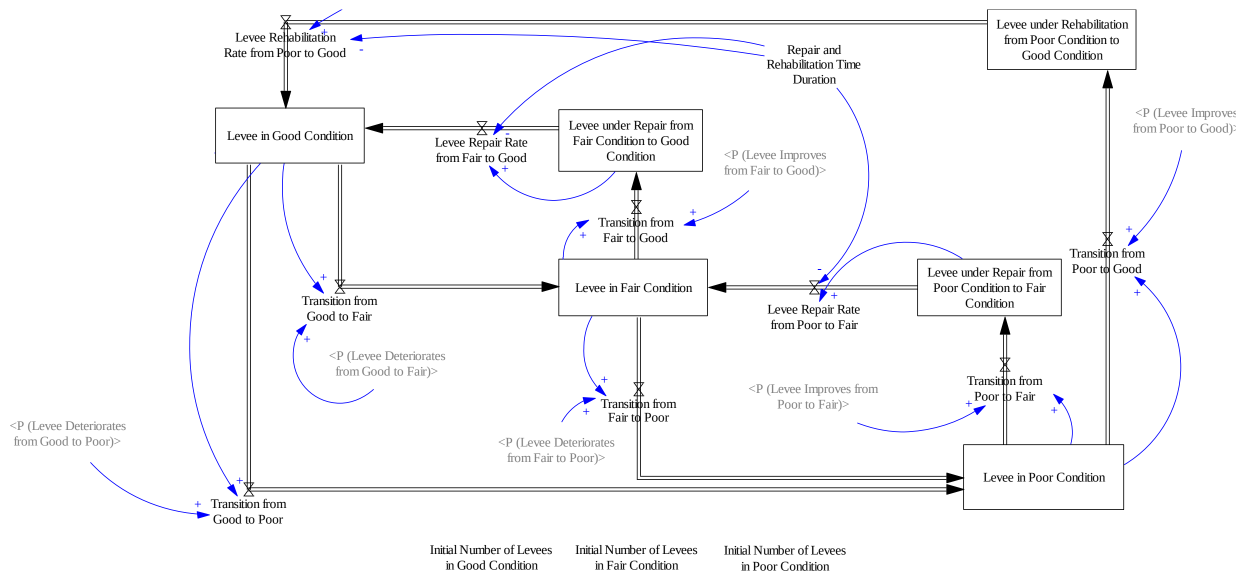

Figure 27 - Sub-Module for Levee Infrastructure Condition

Public Risk Perception

Provided the literature review of the dynamic processes to include in the proof-of-concept RiskDIMS, the consideration of public risk perception is an important element in the temporal model. It is anticipated that society perceives risk according to the condition of the majority of the levee stock. In other words, if the large majority of the levee network is in good condition and/or in any of the transition states moving from poor or fair to good condition, then the public perception is that the overall network is in good condition. In this example, risk perception would be low. This implies that deterioration patterns and unsuitable level of protections are evident and known to the public, possibly through media channels.

System Vulnerability

IPET derived a number of fragility curves for the flood protection system of the Great New Orleans area, which were based on foundation conditions, character of the structure, and the type of forces created by different water levels (IPET, 2009a). Static instability, under seepage, still water overtopping and scour, transition point, feature erosion, and wave run-up failure modes were used to calculate the fragility curves (IPET, 2009b). Fragility curves for JE12, JE13 and JE14 were not produced, possibly because design information was not available (IPET, 2009b). These are not the only levee reaches missing data, unfortunately. For illustration purposes, the study chooses to use the average of pre-Katrina fragility data associated with reaches JE5 and JE6 from EJLD, and with reaches CW4, CW5, CW6, WH2, WH3, WH4, WH5, WH6, WH7, WH8, WH9, HA3, and HA4 from the WJLD (Table 7). All of these are levees geographically-distributed throughout Jefferson Parish, and thus vary in characteristics. In order to enable a network analysis in the future, it is recommended that fragility curves be derived for all levees in the Jefferson Parish.

Table 7 - Expected Failure (Vulnerability as Previously Defined) of Levees within Jefferson Parish (IPET, 2009b)

Reach Name	Minimum Elevation	Design Elevation	Top of Levee	1/2 ft. Overtopping	1 ft. Overtopping	2 ft. Overtopping	3 ft. Overtopping
JE5	1.00E-12	0.5	0.678	0.678	0.678	0.682	0.937
JE6	1.00E-12	0.923	0.993	0.993	0.993	0.993	1
CW4	1.00E-12	0.039	0.063	0.063	0.063	0.375	0.678
CW5	1.00E-12	0.039	0.068	0.068	0.068	0.25	0.5
CW6	1.00E-12	0.005	0.008	0.008	0.008	0.25	0.5
WH2	1.00E-12	0.015	0.024	0.024	0.024	0.25	0.5
WH3	1.00E-12	0.311	0.484	0.484	0.484	0.61	0.897
WH4	1.00E-12	0.396	0.591	0.591	0.591	0.72	0.954
WH5	1.00E-12	0.032	0.052	0.052	0.052	0.319	0.604
WH6	1.00E-12	0.307	0.479	0.479	0.479	0.604	0.893
WH7	1.00E-12	0.455	0.66	0.66	0.66	0.785	0.975
WH8	1.00E-12	0.195	0.319	0.319	0.319	0.421	0.732
WH9	1.00E-12	0.006	0.009	0.009	0.009	0.25	0.5
HA3	1.00E-12	0.475	0.682	0.682	0.682	0.804	0.98
HA4	1.00E-12	0.633	0.831	0.831	0.831	1	1
Average	**1.00E-12**	**0.2887**	**0.3961**	**0.3961**	**0.3961**	**0.5542**	**0.7767**

The vulnerability of a levee varies, depending on the intensity of the natural hazard event. Knowing that the outdated SPH methodology was used to engineer the flood protection system by accounting for a 100-

year level of severity storm in the infrastructure design, relationships between the intensity of a particular natural hazard, levee elevations, and water stages could possibly be drawn for the purpose of this study to determine the vulnerability of the structures to natural hazard events of different intensities. As suggested previously by this study, conditions are associated with elevation standards. Table 8 proposes the values to use for the system vulnerability analysis.

Table 8 – Proposed Corresponding Vulnerability Values for Good, Fair and Poor Levees Conditions

Condition	Low Intensity Hazard (e.g. 50-year event)	Medium Intensity Hazard (e.g. 100-year event)	High Intensity Hazard (e.g. 500-year event)
Good	Minimum Elevation	Design Elevation	2 ft. Overtopping
Fair	Design Elevation	Top of Levee to 1 ft. Overtopping	3 ft. Overtopping
Poor	Top of Levee to 1 ft. Overtopping	2 ft. Overtopping	Vulnerability = 1

To derive network-level vulnerability, the assumption that one levee failure leads to consequences throughout Jefferson East is used. In general, total network vulnerability is defined as 1 minus the probability that no length of the levee network fails:

$$v_i = 1 - (1 - q_{L_g,i})^{L_g} \times (1 - q_{L_f,i})^{L_f} \times (1 - q_{L_p,i})^{L_p}$$

, where v_i is the vulnerability of the levee network to a natural hazard level i, L_g is the length of the levee network in good condition, L_f, is the length of the levee network in fair condition, L_p is the length of the levee network in poor condition, $q_{Lg,i}$ is the probability of failure of a levee section in good condition given a natural hazard level i, $q_{Lf,i}$ is the probability of failure of a levee section in fair condition given a natural hazard level i, and $q_{Lp,i}$ is the probability of failure of a levee section in poor condition given a natural hazard level i.

Population Dynamics

Considering that Jefferson East and Jefferson West are divided by the Mississippi River, the failure of a levee on the east side of the river should not necessarily lead to direct consequences on the west side of

Jefferson Parish. Therefore, the consequence analyses discussed in this and other sections only include Jefferson East data. In order to obtain such data, United States Census data available for the entire Jefferson Parish must be parsed. Data are obtained using the 75 census tracks that are within Jefferson East boundaries. Unless otherwise stated, all data are obtained from the United States Census Bureau website and data repository, accessed through the American FactFinder tool, belongs to the year 2000 (United States Census Bureau, 2012).

The population of Jefferson East in 2000 was 257,501. Given its land area of 49.64 square miles, the population density was 5,187 people per square mile. While Census Track 202.02 recorded the densest area within Jefferson East with 16,784 people per square mile, Metairie, River Ridge, Terrytown and Timberlane –four census-designated places within Jefferson East– and the city of Harahan, also in Jefferson East, were the densest places in the state of Louisiana with more than 5,000 people per square mile each. The analysis assumes that population density throughout East Jefferson could potentially reach 16,784 people per square mile, which corresponds to the density of Census Track 202.02, if the conditions for such growth are granted. In other words, the population saturation point is estimated to be 833,158 people. Note that this assessment does not account for possible zoning regulations in place, especially near the Mississippi River and Lake Pontchartrain levees. This estimation, nonetheless, does imply that some single-family housing units may need to be converted in the future to multi-family housing units or even apartment buildings as the demand for housing increases. To simulate population dynamics, this study uses the Louisiana annual birth rate (1.52%) and death rate (0.916%) for the year 2000 (Jindal et al., 2004).

A significant number of people 5 years or older living in Jefferson East in 2000 (39,835) lived in a different county, state or country in 1995. This amount is equally divided into an annual immigration rate of 7,967 people per year. An emigration rate of 3.6% is also derived using the 1990 population for the entire Jefferson Parish, the 2000 population for the entire Jefferson Parish, the 2000 Jefferson East population, historical Louisiana annual birth and death rates, and the estimated immigration rate. It is important to note that these rates do not offer significant population changes in East Jefferson over the period of analysis. Results, however, are aligned with the population dynamics of the entire Jefferson Parish whose 1980 population was 454,592, 1990 population was 448,306, 2000 population was 455,466, and 2010 population was 432,552. Population does not seem to change very much considering that part of the population left the Greater New Orleans area after Hurricane Katrina. The core elements of the population dynamics module are presented in Figure 28.

While the state of the economy encourages immigration to Jefferson East, public risk perception is assumed to impact the emigration rate when the risk is perceived as high due to observable poor levee condition, duplicating the emigration rate. Moderate and low public risk perceptions do not have an effect on emigration. Post-Katrina behavior, which is not considered in this analysis, could be expected to be substantially different given the first-hand experience of residents with flooding. The relationship between the economy and population will be discussed in the economic growth module.

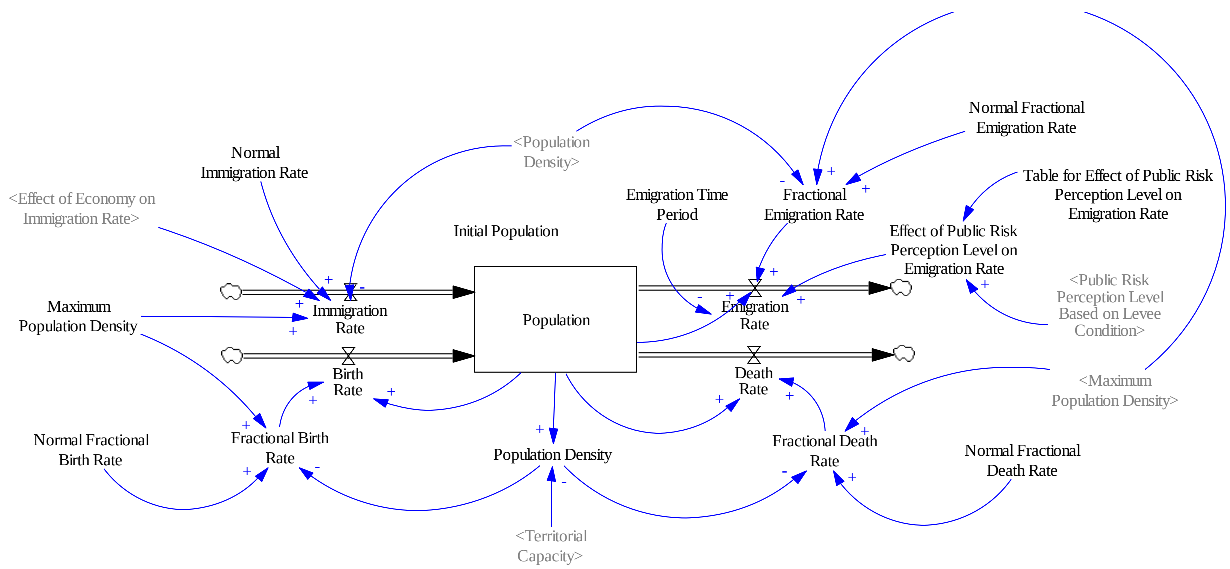

Figure 28 - Core of Module for Population Dynamics

In order to estimate consequences associated with flood risk, the study used the mean values of expected loss of life under pre-Katrina conditions when no pumping occurs derived by IPET (2009a). These data, belonging to sub-basins JE1, JE2, JE3 and OM4, is already parsed according natural hazard intensity.

Using total population in the year 2000, a percentage of estimated casualties for the entire Jefferson East is estimated (Table 9). This ratio is kept constant throughout the simulation, assuming that population changes occur uniformly throughout the region. Percentage of estimated injuries is assumed to be twice the percentage of casualties (Table 9). The Office of Management and Budget (OMB) suggests using a range between $1 million to $10 million for the value of a single casualty in government analyses (Robinson, 2007). This study uses the average for a single casualty ($5.5 million) and the lower bound value for a single injury ($1 million). Total societal consequence is finally adjusted to present value using a discount rate of 5% and a dynamic economic growth rate, which fluctuates depending on the state of the economy. The modeler may choose to use different values for the discount rate and normal economic growth (before endogenous effects). The OMB (2003) provides guidance on the selection of proper discount rates for different types of analyses.

Table 9 – Percentage of Population Severely or Moderately Vulnerable, Derived from IPET Report (2009a)

Population Exposure	Low Intensity Hazard (e.g. 50-year event)	Medium Intensity Hazard (e.g. 100-year event)	High Intensity Hazard (e.g. 500-year event)
Severely Vulnerable (Prone to Casualty)	0.03%	0.069%	9.148%
Moderately Vulnerable (Prone to Injury)	0.06%	0.138%	18.296%

Building and Residential Home Development

This module concerns the development of housing assets, and the potential consequences that may emerge as a result of urbanization. Commercial buildings, other non-housing assets as well as public and private infrastructure are not part of the analysis. Jefferson East recorded a total of 113,884 housing units. Housing data are then grouped into buildings –defined as structures with 5-9 units, 10-19 units, and more than 20 units– and residential homes –defined as 1-unit-detached, 1-unit-attached, 2-unit, and 3-to-4-unit structures. The size estimation of these groups results in 26,891 buildings and 107,331 residential homes.

The dynamics of these assets assumes that the residential homes may be converted into buildings, but not the opposite, in order to account for potential population growth. Developers are expected to need an area equivalent of eight times the size of residential homes for each building. This value is approximated to the national average size of new single-family homes developed in 2000, or 2,287 square feet. For the construction of a building, four residential homes are demolished. The remaining land needed is taken from a stock of local vacant land. Building construction accounts for delay between the beginning of construction work and building commission. The annual rate of development activities (e.g., conversion of residential homes into buildings) is influenced by the dynamics of Jefferson East population. Housing demand increases as population grows, incentivizing developers to convert more homes into buildings. This particular effect is included even though the year 2000 housing stock seems to have enough units to sustain a certain level of growth considering the year 2000 average household size of 2.4. Additional research should be conducted to refine the real estate development variables and relationships.

In 1998, the estimated percentage of vacant land in the south of the United States was 19.3% of total area, and in Baton Rouge, one of the largest cities in Louisiana, 9.3% (Pagano and Bowman, 2000). In the absence of data for Jefferson East, the latter was used as a representation of available land for development. Buildings may only be built if enough land is available. Figure 29 presents the main elements of the building construction process.

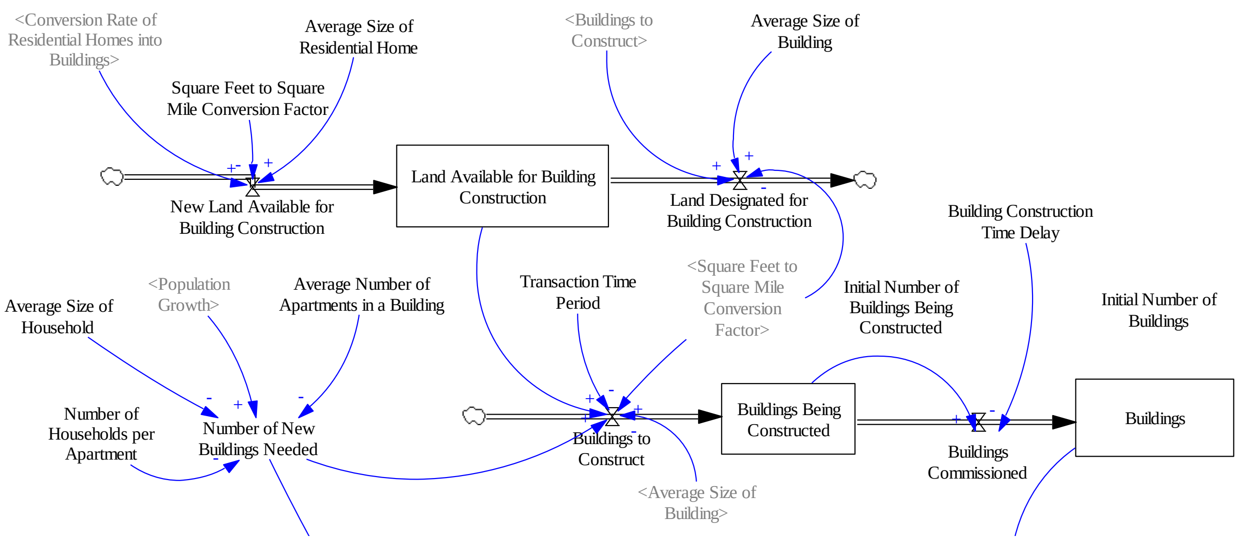

Figure 29 - Section of Module that Simulates Building Construction

Built environment (buildings and residential homes) consequences are associated with estimated property loss based on the intensity of a natural hazard event. Cost associated with providing alternative housing to affected population after the disaster is not included in this analysis. The value of a residential home is derived using the average value of median housing unit values for each of the Census Tracks within Jefferson East. The estimated value of a home is set to $133,117. The estimated value of a building, $1,996,755, is calculated by multiplying the value of a home by the minimum expected number of units in a building (15 units per building), based on census data. Percentages of property losses for various natural hazard intensities, also needed for consequence analysis, may be obtained from averaging estimated percentage of property losses as determined by IPET (2009a) for corresponding sub-basins in Figure 30, Figure 31 and Figure 32. Table 10 contains the estimations.

Table 10 – Estimated Percentage of Property Losses by Sub-Basin–Derived from IPET Report (2009a)

Sub-Basins	Low Intensity Hazard (e.g. 50-year event)	Medium Intensity Hazard (e.g. 100-year event)	High Intensity Hazard (e.g. 500-year event)
JE1	0% - 10%	10% - 30%	70% - 90%
JE2	0% - 10%	30% - 50%	90% - 100%
JE3	0% - 10%	50% - 70%	90% - 100%
OM4	0% - 10%	30% - 50%	90% - 100%
Average	**5%**	**40%**	**91.25%**

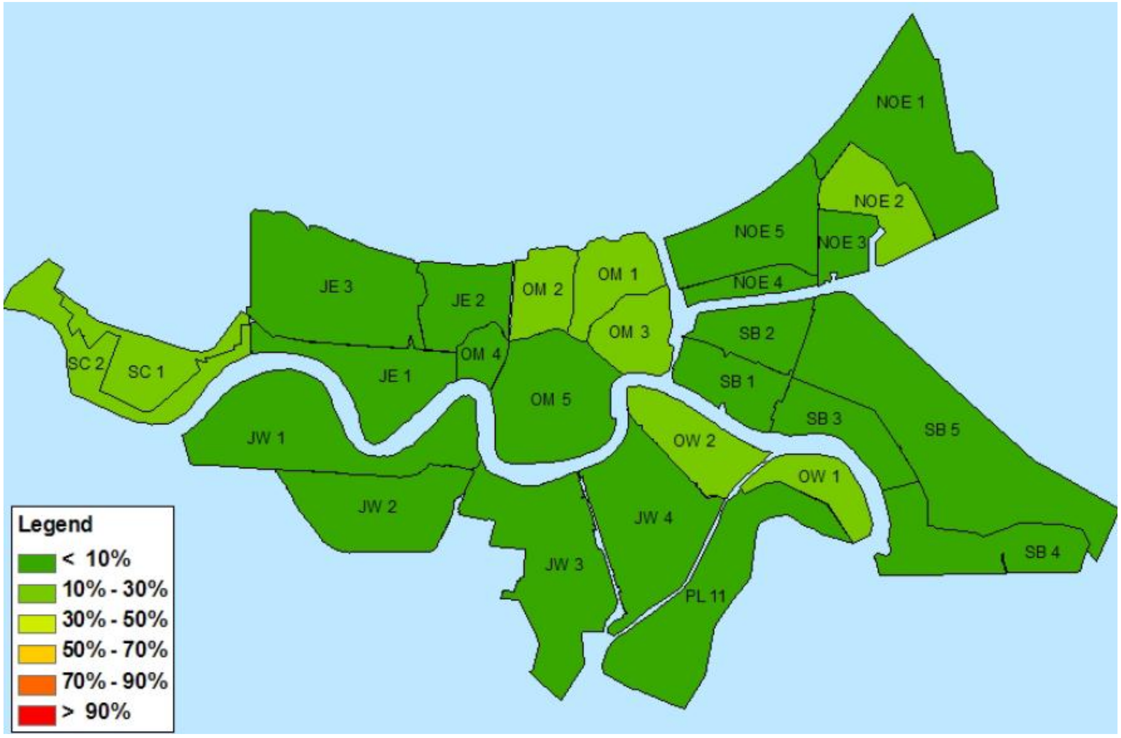

Figure 30 – Estimated Property Loss (% of Total Value) under Pre-Katrina Conditions and No Pumping for Natural Hazard Event of 1/50 Exceedance Probability (IPET, 2009a)

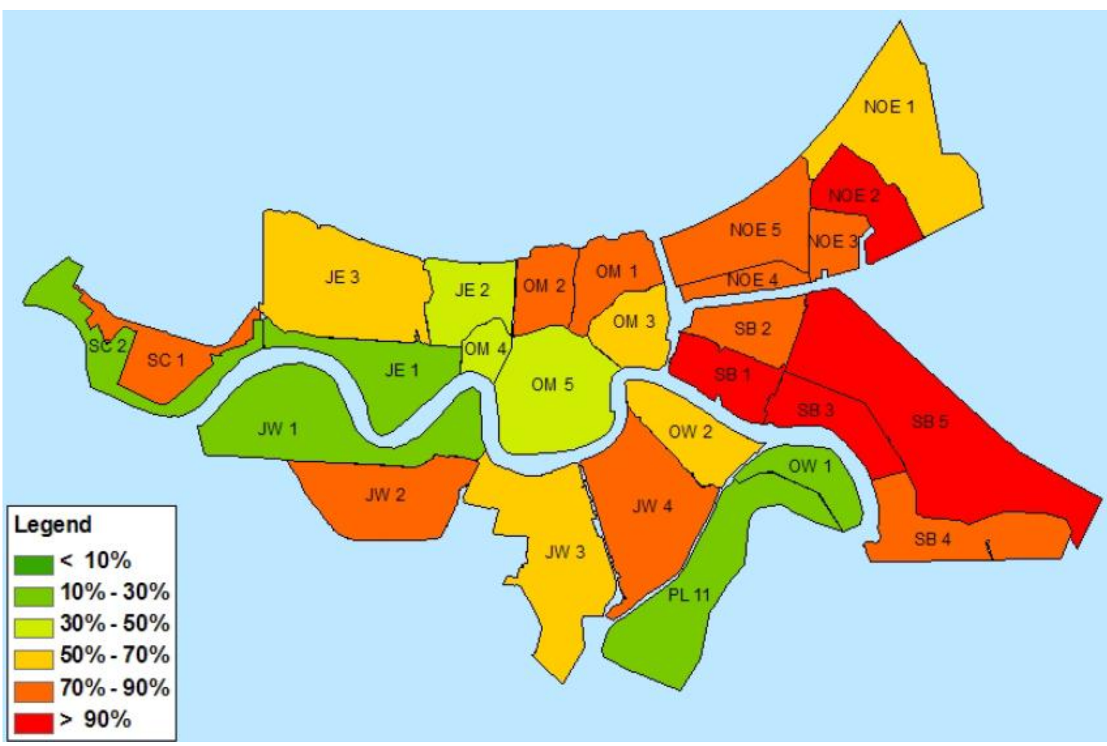

Figure 31 - Estimated Property Loss (% of Total Value) under Pre-Katrina Conditions and No Pumping for Natural Hazard Event of 1/100 Exceedance Probability (IPET, 2009a)

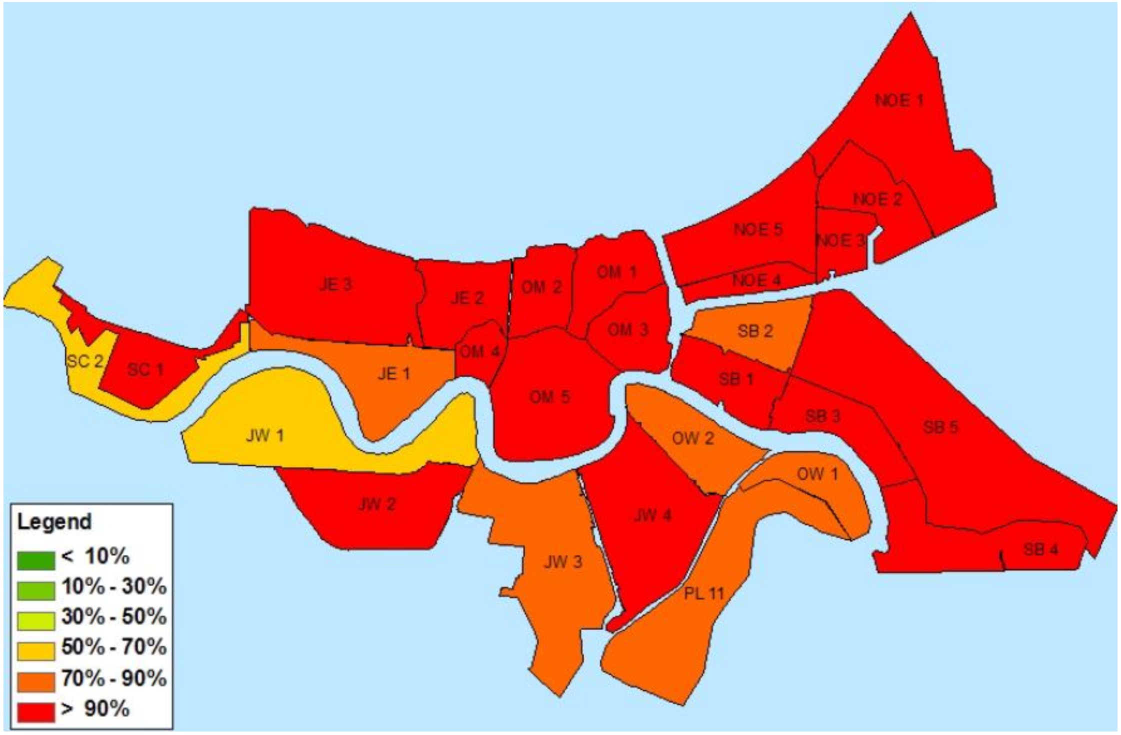

Figure 32 - Estimated Property Loss (% of Total Value) under Pre-Katrina Conditions and No Pumping for Natural Hazard Event of 1/500 Exceedance Probability (IPET, 2009a)

Economic Growth

The relationship between economic development and population growth does not seem to be quite clear. On one hand, experts suggest that population growth may result in a reduction in wealth per capital and significant environmental problems (Grenham, 2012). Others suggest the opposite, especially in urban economies, where increased density promotes specialization and greater investment in human capital, along with a rapid accumulation of new knowledge (Becker et al., 1999). It is then plausible to believe that other factors play a role in defining this interrelationship, and that the behavior of these phenomena varies with time. Age pattern of population, education policies (Headey and Hodge, 2009) and technological changes (Prettner and Prskawetz, 2010) are among some factors that may affect the relationship between population growth and economic development.

The SD model presented here includes the impact that the economy may have on immigration rates, where immigration rates progressively increase as the economy grows, as well as the impact that population increase may have on economic development (Figure 33). The relationship between economic growth rate and population is positively linear until the latter doubles. Then, the economic growth rate decreases until turning constant at the normal economic growth rate, simulating decreasing economic growth due to overpopulation. A normal economic growth of 6% is assumed, as denoted by the local Gross Domestic Product (GDP) growth described next, which can increase or decrease as population grows or shrinks, respectively.

Local GDP is used here to indicate the state of the economy. Official GDP data is only found publicly for the year 2001. In that year, the GDP of the New Orleans-Metairie-Kenner region was approximately $51.277 billion (BEA, 2012). Based on this information, Barreca et al. (2012) derived a 2001 GDP of $14,838,776,957 for Jefferson Parish. The model uses this information to estimate initial GDP for Jefferson East based on the proportion of population residing on Jefferson East (56.54%). This 2001 GDP is assumed to be $8,389,209,963. Considering that this GDP may have grown at an average rate of 6%, which seems to be aligned to the average growth experienced between 2001 and 2007, the 2000 GDP for Jefferson East is estimated at $7,914,349,022.

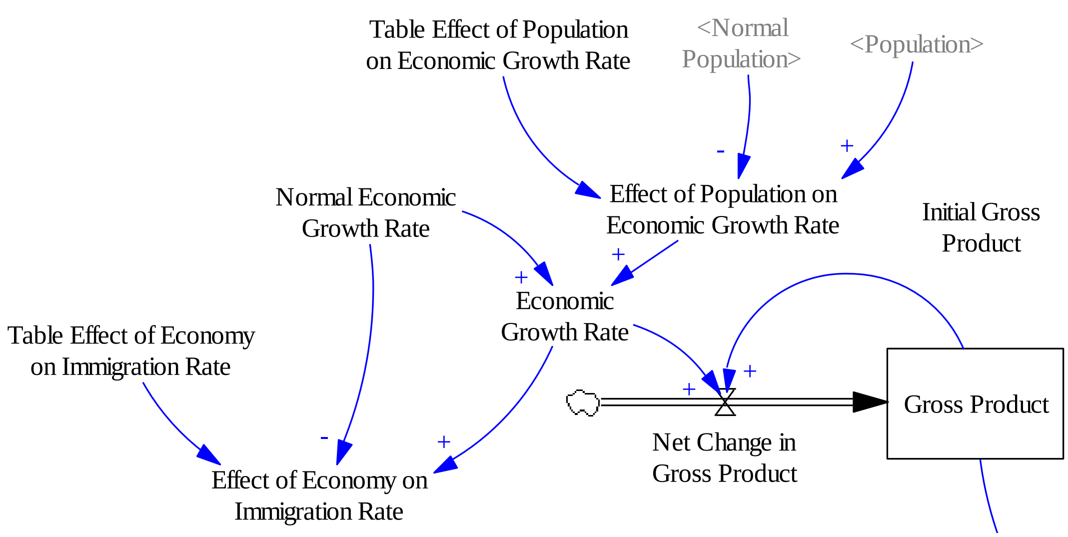

Figure 33 - Relationship between Population, Economic Growth Rate and Immigration Rate

When impacted by a natural hazard, local, regional, national and global economies may be affected depending on the magnitude of the disaster and the role the affected areas play in those economies. In this study, only local economic loss is estimated. After observing the non-linear behavior of GPD, instead of assuming a linear economic recovery, an exponential function is used to simulate how the economy may recuperate after a disaster. The estimated loss is then the total economic output (e.g., GDP) for the duration of economic recovery time (note that growth is not considered here) minus the exponentially recuperating economic output until the GDP is restored to the previous level before the disaster, as portrayed by Figure 34.

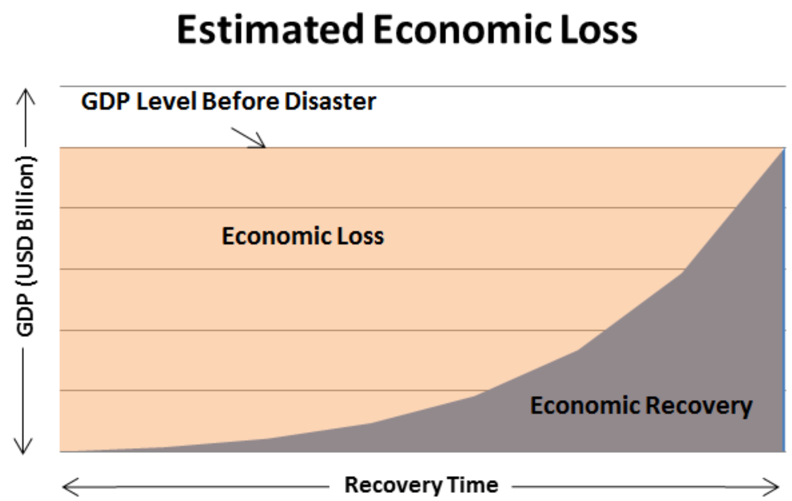

Figure 34 - Estimating Economic Loss When Using an Exponential Function for Economic Recovery

The economic recovery curve may be represented through the following equation,

$$GDP = t \times b^{t}$$

, where t is the recovery year, and b is a constant. Constant b may be found when the GDP level before the disaster, GDP_r, and the total recovery time, t_r, are known.

$$GDP_r = t_r \times b^{t_r}$$

$$\ln(GDP_r) = \ln(t_r) + t_r \times \ln(b)$$

$$\ln(b) = \frac{\ln(GDP_r) - \ln(t_r)}{t_r}$$

$$b = e^{\frac{\ln(GDP_r) - \ln(t_r)}{t_r}}$$

The area under the exponential function, EC, is found by calculating the integral of the area under the exponential curve.

$$EC = \int_0^{t_r} t \times e^{t \times \left(\frac{\ln(GDP_r) - \ln(t_r)}{t_r}\right)} dt$$

$$EC = \left(\frac{e^{(\ln(GDP_r) - \ln(t_r))}}{\left(\frac{\ln(GDP_r) - \ln(t_r)}{t_r}\right)^2} \times (\ln(GDP_r) - \ln(t_r) - 1) \right) - \left(\frac{-1}{\left(\frac{\ln(GDP_r) - \ln(t_r)}{t_r}\right)^2} \right)$$

The estimated economic loss, EL, is then defined as the normal economic output as if the disaster had not occurred minus the economic loss.

$$EL = GDP_r \times t_r - EC$$

The expected recovery times vary according to the intensity of the natural hazard, and the amount of resources available for recovery, among other factors. The illustrative values used in the analysis are 1, 5 and 10 years for natural hazards of low, medium, and high intensity, respectively.

Levee Infrastructure Management

This module provides the opportunity to model the impact of different levels of infrastructure management investments on the behavior of risk over time. Investment decisions may, in turn, be affected by risk in two important ways. The first one relates to the level of risk aversion of the decision maker. Risk aversion drives a decision maker to increase the level of investment when risk exceeds a maximum threshold. The second factor pertains to social pressure for larger investments when the condition of the levees is deemed poor and consequently public risk perception is high. Bea et al. (2009) discuss the importance of considering the contributions of social, psychological, organizational and political processes in risk analysis. Modeling risk aversion and social pressure may provide additional insights. As a result, sixteen scenarios may be modeled: no, minor, moderate and major investments under risk neutrality or risk aversion of the decision maker, and under dormant or emerging social pressure. The amounts corresponding to applied infrastructure management investments are simulated using uniform random distributions. The determination of upper and lower boundary values for each investment level requires, nonetheless, familiarity with costs of field activities.

Even though it may sound contradictory, the no investment policy is assumed to incur basic operating costs at the local level that do not directly affect the condition of the levees along the Mississippi River. The EJLD is responsible for the emergency operations during floods, mowing, inspection repairs of levees, floodgate structures, and equipment, as well as the operation and maintenance of the maintenance facility and administration office (EJLD, no date). Some of these activities, such as inspections, may be considered part of the no investment policy since they have no immediate impact on levee condition. General expenditure data for the EJLD was found for the 2008-2009 fiscal year. All expenditures of the district, including personnel, amounted to \$6.3 million (SLFPA-E, 2009). Considering that this amount resulted in the maintenance and operation of flood protection system assets throughout Jefferson East, 40% of this amount (\$2.52 million) is presumed to be needed for the levees along the Mississippi River according to the length proportion of these levees to the entire system in Jefferson East. Since this amount includes some repairs, the range for the no investment policy is estimated to amount to a quantity between \$0 and \$500,000. Minor investments may then fall between \$500,000 and \$2.5 million.

Moderate and major investments require additional federal and state funding since the revenue of the EJLD obtained from property taxes and other sources is not sufficient to cover the cost of significant repairs and rehabilitation. The capacity and resources to conduct such activities often requires the collaboration of federal, state and local government agencies. It is worth exploring a few projects to draw conclusions on representative levels of investments.

1. The St. Tammany Parish’s Schneider Canal Hurricane Protection System was proposed in 1990. The total cost of the project, which included 6.5 miles of levees, 2.5 miles of floodwalls, 8 floodgates, 3 major drainage structures and a small number of culverts, ranged between \$18.9 and

$26.7 million, depending on the selection of drainage system (USACE, 1990b). The levees cost were approximately $3.1 million (16.4%-11.6% of the total cost conditional to the drainage system selection). Extrapolating this amount to an 11.6-mile levee and assuming a 6% annual economic growth leads to an estimated value of $9.9 million for the year 2000.

2. The Morganza, Louisiana to the Gulf of Mexico Hurricane Protection Project included 72 miles of earthen levees, ten 56-foot-wide sector gate structures, three 125-foot wide floodgates, 13-tidal exchange structures, and a lock complex, and had an approximate cost of $968 million in year 2008 price level (USACE, 2009) –or the equivalent of $607.3 million in 2000, assuming a 6% annual economic growth rate. This amount, however, includes the development of structures foreign to the Jefferson East Mississippi River levees according to literature reviewed (e.g., floodgates). Unlike the previous case study, unfortunately, the cost in the report was not broken down by project component. Using the total amount to derive a representative portion for an 11.6-mile levee (and some appurtenances) results in $97.8 million.
3. In 2008, experts suggested that repairing a levee breach in the Sacramento-San Joaquin Delta would cost between $20 and $30 million (Suddeth et al., 2008). Assuming a 6% annual economic growth, in the year 2000, repair costs could have fallen between $12.6 and $18.8 million for a single levee breach.

Deriving costs from previous projects without detailed engineering and management data is challenging. Unit cost information available through a wide variety of source also varies: $2.8 million per mile for increasing the height of a levee (Rogers, no date; Suddeth et al., 2008), between $21.12 and $42.24 million per mile for the construction of a clay levee (Scandaliato, 2010), and $45 million per mile for a seismically-resistant levee (Suddeth et al., 2008). Based on this information, it is estimated that moderate investment may fall between $2.5 million and $20 million, and major investment between $20 million and $300 million. Figure 35 shows the variables of the levee infrastructure management module.

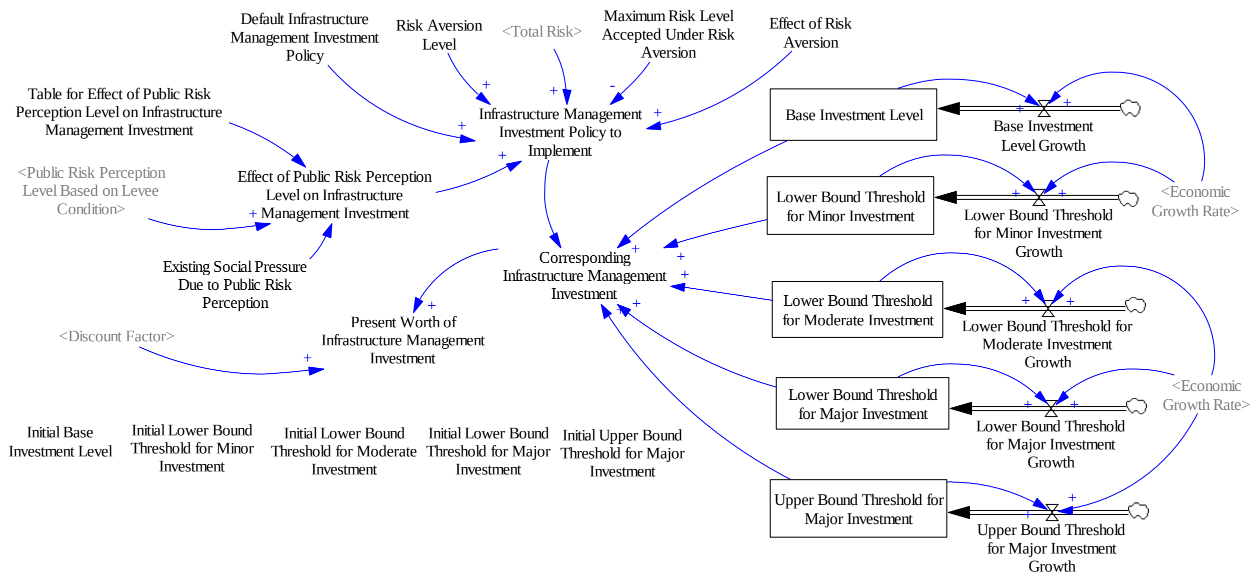

Figure 35 - Infrastructure Management Module

The Risk Construct

This module leverages the definition of infrastructure failure risk by assessing the risk due to high, medium and low intensity hazards given the likelihood of such events, corresponding system vulnerability and consequences. As suggested before, vulnerability and consequence values for these intensities are analyzed assuming 500-year, 100-year and 50-year flood events. The exceedance probability of a 500-year event was used as the annual probability of occurrence of a high intensity hazard. The exceedance probability of a 50-year event minus the exceedance probability of a 500-year event was used as the annual probability of occurrence of a moderate intensity hazard. Finally, the annual probability of occurrence of a low intensity hazard is simply the remaining probability in the cumulative density function, or in other words, one minus the annual probability of occurrence of a moderate intensity hazard, minus the annual probability of occurrence of a high intensity hazard.

High and medium intensity hazard events are subject to climate change effects (Figure 36). Low intensity hazard events are also subject to climate change effects by its dependent definition on high and medium intensity hazard events. The intensity and frequency of extreme precipitation events, as known today, are likely to increase over time (van Aalst, 2006; IPCC, 2007). The IPCC (2012), using three different special report emission scenarios (A1B, A2, B1) and 14 GMCs, estimates significant changes in return periods for a 20-year precipitation event for years 2046-2065 and 2081-2100 for the southern region of the United States, where Jefferson East is located. On average, the return periods decrease to approximately 12.5 and 9.5 years for the discussed timeframes. Lower return periods imply higher frequencies. Knowing this information, an annual climate change effect of 0.83% growth that reflects this change in return periods assuming a steady impact is applied to the probabilities of occurrence belonging to high and medium intensity hazards. Executing the actual models available and scenarios, and precisely applying them to the region of study, will be an important step towards refining climate change impact.

The three scenarios modeled by IPCC are described next (IPCC, 2011a), where scenario B1 generates less impact on the climate at a global scale, and scenario A1B outperforms scenario A2 in the long-run.

1. **A1B**: A future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality.
2. **A2**: A very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development.
3. **B1**: A convergent world with the same global population as in the A1B storyline but with rapid changes in economic structures toward a service and information economy, with reductions in materials intensity, and the introduction of clean and resource-efficient technologies.

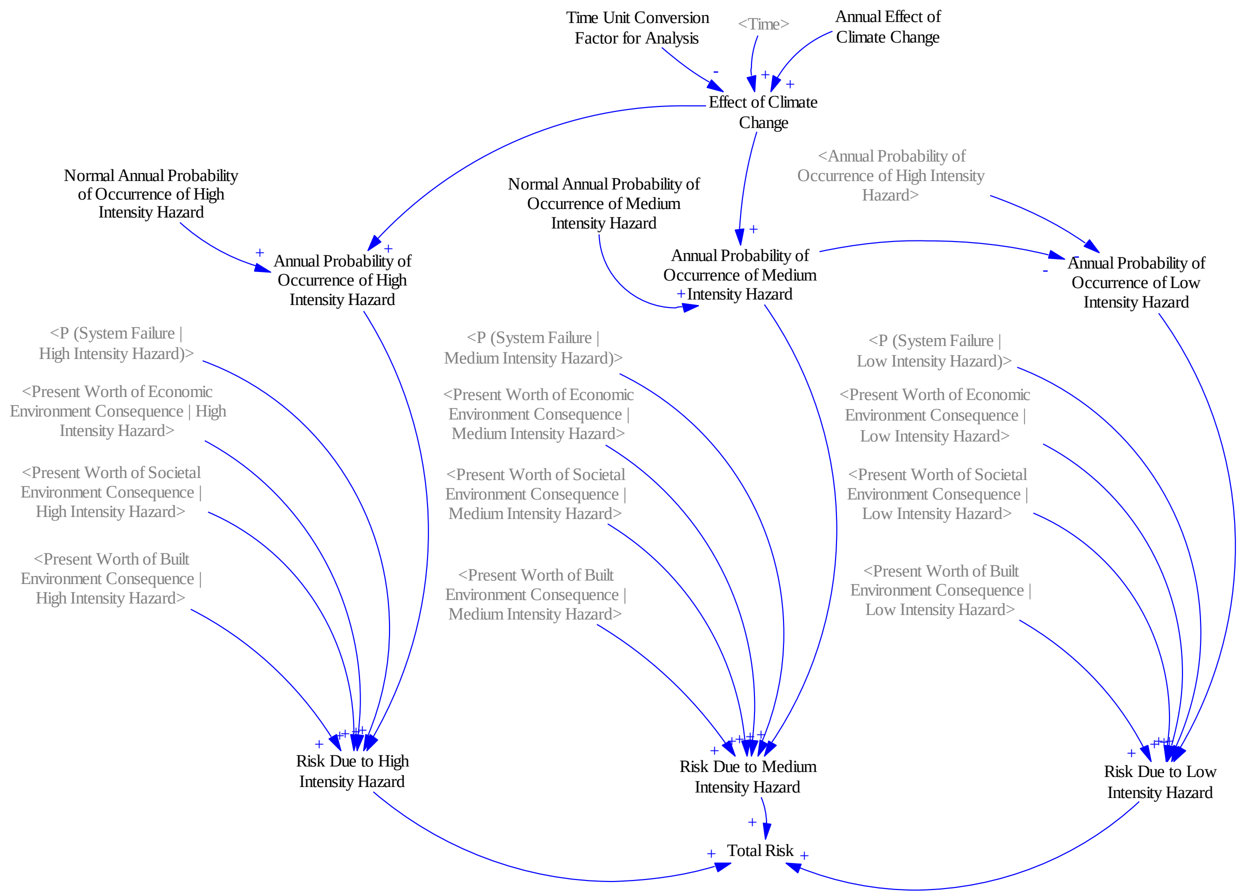

Figure 36 - Risk Construct Module

Model Results

The results of the sixteen scenarios modeled (Table 11) are discussed here. This section seeks to understand the behavior of risk as a result of specific investments, and not quantify risk.

Table 11 - Modeled Infrastructure Management Investment Scenarios

Scenario Name	Investment Level				Risk Aversion (RA)		Social Pressure (SP)	
	No	Minor	Moderate	Major	Not Included	Included	Not Included	Included
No Investment without RA or SP	●				●		●	
Minor Investment without RA or SP		●			●		●	
Moderate Investment without RA or SP			●		●		●	
Major Investment without RA or SP				●	●		●	
No Investment without RA with SP	●				●			●
Minor Investment without RA with SP		●			●			●
Moderate Investment without RA with SP			●		●			●
Major Investment without RA with SP				●	●			●
No Investment with RA without SP	●					●	●	
Minor Investment with RA without SP		●				●	●	
Moderate Investment with RA without SP			●			●	●	
Major Investment with RA without SP				●		●	●	
No Investment with RA and SP	●					●		●
Minor Investment with RA and SP		●				●		●
Moderate Investment with RA and SP			●			●		●
Major Investment with RA and SP				●		●		●

It is important to understand that RiskDIMS offers a different risk analysis framework, where the number of policies under evaluation is likely to be large given the possible combination of MR&R actions for individual levee sections driven by physical condition, functional performance, and/or budget thresholds. Modeling of public risk perception should also differ and need to be founded on field evaluation results. Risk aversion in the proof-of-concept SD model attempts to recreate decision making. In RiskDIMS, provision for designing risk-averse MR&R policies that decrease levee system vulnerability are granted by the DSS, and thus need not to be modeled.

According to Table 12, similar risk patterns are exhibited by modeled scenarios. The nine distinctive risk patterns observed conclude that social pressure only affects risk behavior in the baseline scenarios (no investment). The lack of attention to infrastructure condition under this scenario increases risk perception. Another conclusion that may be reached is the fact that risk aversion of decision makers plays a role when no, minor and moderate investments are made. The threshold for acceptable risk determines when larger investments are expected to be needed (e.g., when actual risk exceeds maximum acceptable risk). For all the analyses, a risk threshold of $13 billion is used. Finally, it is also observed that neither social pressure nor risk aversion have an effect on major investments. This is expected given that this level of investment drives the condition of the entire levee network to "good," eliminating public risk perception and significantly reducing vulnerability.

Table 12 – Groups of Scenarios by Similar Risk Behavior

<table>
<tr><th>Pattern</th><th>Scenario Name</th><th>Pattern</th><th>Scenario Name</th></tr>
<tr><td>A</td><td>• No Investment without RA or SP</td><td rowspan="2">G</td><td rowspan="2">• Moderate Investment without RA or SP
• Moderate Investment without RA with SP</td></tr>
<tr><td>B</td><td>• No Investment without RA with SP</td></tr>
<tr><td>C</td><td>• No Investment with RA without SP</td><td rowspan="2">H</td><td rowspan="2">• Moderate Investment with RA without SP
• Moderate Investment with RA and SP</td></tr>
<tr><td>D</td><td>• No Investment with RA and SP</td></tr>
<tr><td>E</td><td>• Minor Investment without RA or SP
• Minor Investment without RA with SP</td><td rowspan="2">I</td><td rowspan="2">• Major Investment without RA or SP
• Major Investment without RA with SP
• Major Investment with RA without SP
• Major Investment with RA and SP</td></tr>
<tr><td>F</td><td>• Minor Investment with RA without SP
• Minor Investment with RA and SP</td></tr>
</table>

The following sub-sections present the results of the modeling exercise grouped by active/inactive risk aversion and social pressure. One of the main challenges faced by this analysis is the inability to relate model elements in space, as RiskDIMS proposes. The integration of temporal and geospatial dimensions would enable the attainment of more accurate results. After all, factors that define risk do interact in time and space.

Without Risk Aversion or Social Pressure

The small-scale Vensim proof-of-concept model indicates that major investments for infrastructure management result in lower risk than the baseline option in the first 32 years (Figure 37). In the long run, the baseline option outperforms all levels of investments as the population moves away from highly-exposed areas of Jefferson East due to high risk perception, resulting in lower consequence (e.g., less people, lower economic output, devalued properties) and risk. Minor and moderate investments are outperformed in years 5 and 15, respectively.

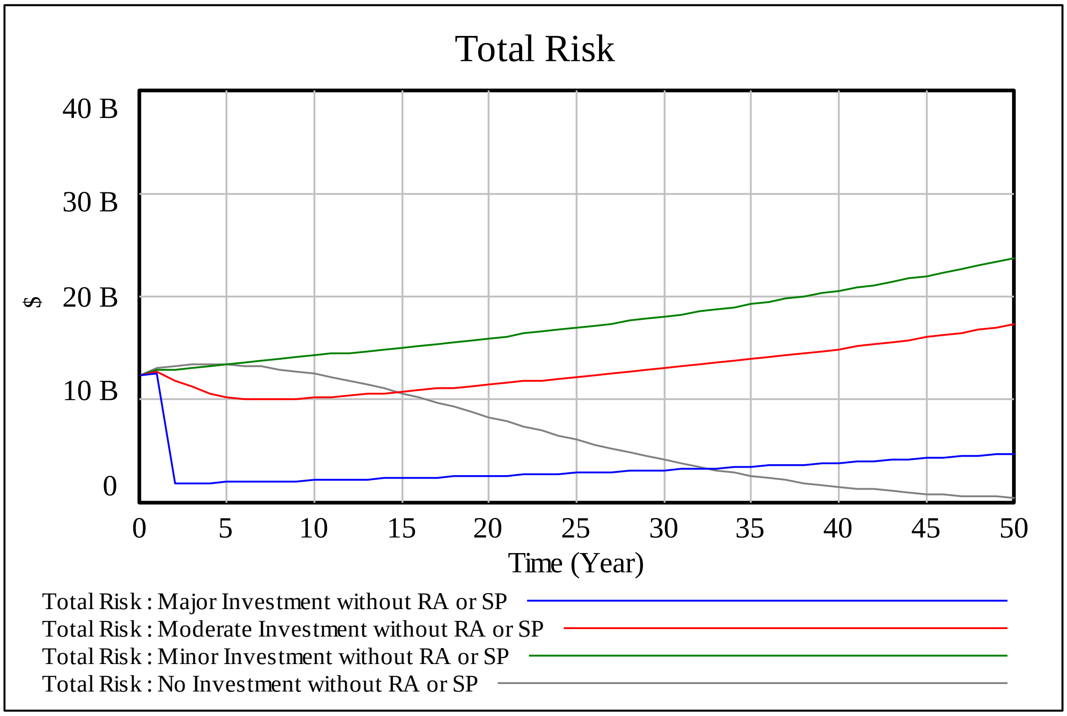

Figure 37 – Present Worth Risk Resulting from Investments without Risk-Averse Decision Making or Social Pressure

This figure also shows that risk increases despite mitigation efforts due to the dynamic behavior of population, urbanization and economic development. This is indicated by the upward slope of risk associated with minor, moderate and major investments. Even under major investments, risk inevitably rises over time after a sharp decrease. This result suggests reconsidering the use of floodplains and other highly hazardous areas, where population, assets, and part of the economy may be at risk despite flood protection mechanisms.

Table 13 summarizes the results obtained through the simulation understanding that a lag of two periods exists between investment decisions and the attainment of actual benefits. As a result, TPWB is measured from year 2 to year 50, and TPWC, from year 0 to year 48. Total Present Worth Risk (TPWR) is measured from year 2 to year 50 since risk values for the first two years were not impacted by investments made within the period of analysis due to system delays. Risk, benefits and costs data are presented in Appendix D.

Table 13 – Summary Output of Investments without Risk-Averse Decision Making or Social Pressure

Model Indicator	Major Investment without RA or SP	Moderate Investment without RA or SP	Minor Investment without RA or SP	No Investment without RA or SP
TPWR	$149,602,463,744	$627,244,615,680	$860,867,773,440	$314,925,766,560
TPWB	$165,323,302,816	$(312,318,849,120)	$(545,942,006,880)	Not Applicable; No Investment Used as Baseline
TPWC	$10,313,711,946	$723,874,184	$96,317,140	$6,666,873
TNPW	$155,009,590,870	$(313,042,723,304)	$(546,038,324,020)	Not Applicable; No Investment Used as Baseline
BCR	16.0	-431.5	-5668.2	Not Applicable; No Investment Used as Baseline

Table 13 shows that major investments made throughout the period of analysis produce less risk and more benefits than other investment levels. In fact, moderate and minor investments produce negative benefits as they are eventually outperformed by the baseline scenario. The TPWC of major investments, nonetheless, is significantly higher. Despite the large cost, major investments produce the largest Total Net Present Worth (TNPW), which is the difference between TPWB and TPWC, and the highest BCR. The success of such investment level is contingent to the length of the period of analysis, however. TNPW and BCR results for different lengths of analysis periods based on cumulative benefit and cost data are presented in Appendix E. If the decision maker uses BCR as the preferred indicator, it is observed the minor investments are preferred for periods of analysis of 3 years or less, considering the 2-year time gap between investments and results. Moderate investments would potentially be selected when the period of analysis is between 4 and 21 years. On the other hand, major investments become the preferred option when the analysis period lasts 22 years or more.

Without Risk Aversion, with Social Pressure

As discussed before, social pressure arising from public risk perception only influences the baseline scenario because the majority of the levee network reaches a poor condition state. When this happens, social pressure pushes for the next level of investment until the majority of the levee is no longer in poor condition. Then social pressure relaxes until the condition falls again. This ongoing pattern alters population growth, including emigration due to high public risk perception, and all associated variables, generating a slightly different level of risk over time. No investment option starts producing less risk than minor, moderate and major investments at years 5, 17, and 37, respectively (Figure 38).

Table 14 shows that social pressure drives the cost of the no investment policy upwards. Also, the estimated TPWR increases by 15%. Risk, benefits and costs data for all the investments are presented in Appendix F. Major investments continue to be the preferred option for the defined period of analysis. Using BCR as the indicator for investment decisions, minor investments are expected to become the preferred selection for periods of analysis of 3 years or less. Moderate investments would be selected for analysis periods of between 4 and 23 years, and major investments, thereafter. TNPW and BCR results for different lengths of analysis periods based on cumulative benefit and cost data are presented in Appendix G.

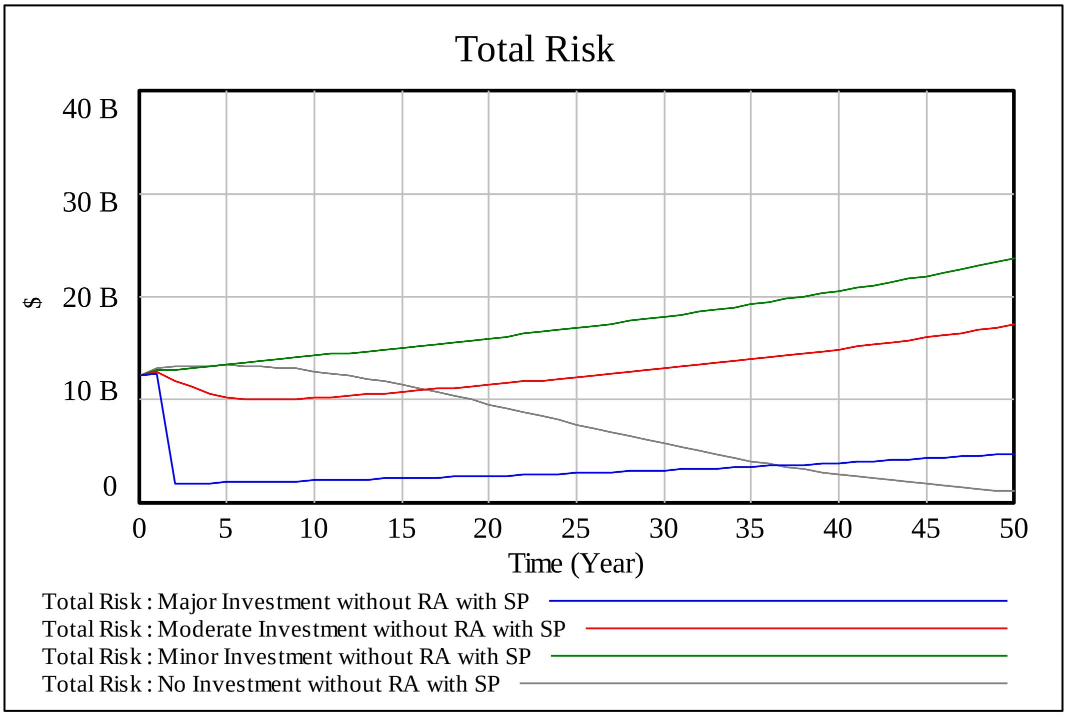

Figure 38 - Present Worth Risk Resulting from Investments with Social Pressure Only

Table 14 - Summary Output of Investments with Social Pressure Only

Model Indicator	Major Investment without RA with SP	Moderate Investment without RA with SP	Minor Investment without RA with SP	No Investment without RA with SP
TPWR	$149,602,463,744	$627,244,615,680	$860,867,773,440	$362,060,036,736
TPWB	$212,457,572,992	$(265,184,578,944)	$(498,807,736,704)	Not Applicable; No Investment Used as Baseline
TPWC	$10,313,711,946	$723,874,184	$96,317,140	$34,472,527
TNPW	$202,143,861,046	$(265,908,453,128)	$(498,904,053,844)	Not Applicable; No Investment Used as Baseline
BCR	20.6	-366.3	-5178.8	Not Applicable; No Investment Used as Baseline

With Risk Aversion, without Social Pressure

Risk aversion changes the behavior of risk completely at all investment levels, except under major investments, which are effective at reducing risk immediately (Figure 39). Under risk aversion, the no investment policy calls for an increased level of investment between years 2 and 7 when the present worth of risk surpasses the $13 billion specified threshold risk level. Nonetheless, this segmented risk behavior is not significantly different from the one exhibited under risk-neutral decision making. Minor and moderate investments seek higher investment levels as risk increases above the maximum acceptable risk threshold. Despite higher investments, risk continues to increase. In the long run, risk-averse minor investment only reduces risk as moderate investments would under risk neutrality –notice the similarity between the green line’s slope after year 32 and the slope of the moderate investment’s red line before risk-averse behavior demands higher investments. Moderate investments exhibit larger decreases in risk than minor investments due to the effectiveness of additional investments at that funding level.

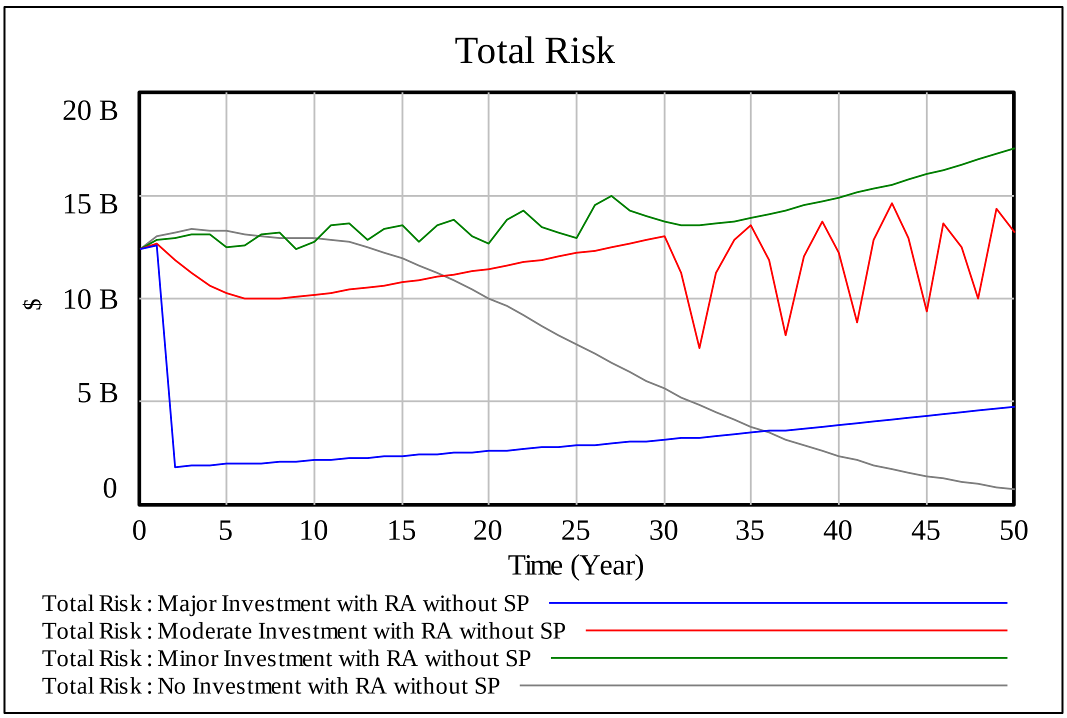

Figure 39 - Present Worth Risk Resulting from Investments with Risk-Averse Decision Making Only

Table 15 shows that despite changes in risk patterns as a result of risk-averse minor and moderate investments, relative shifts in terms of preference do not occur. Major investments are still preferred over moderate and minor investments according to TNPW and BCR indicators. Risk, benefits and costs data are presented in Appendix H. Infrastructure investment decisions are again sensitive to the period of analysis selected. Minor investments output a larger BCR when the period of analysis is less than 3 years, moderate, when the period ranges between 4 and 25 years, and major, when the period is above 26 years. TNPW and BCR results for different lengths of analysis periods based on cumulative benefit and cost data are presented in Appendix I.

Table 15 - Summary Output of Investments with Risk-Averse Decision Making Only

Model Indicator	Major Investment with RA without SP	Moderate Investment with RA without SP	Minor Investment with RA without SP	No Investment with RA without SP
TPWR	$149,602,463,744	$562,503,434,240	$690,088,381,440	$361,567,204,672
TPWB	$211,964,740,928	$(200,936,229,568)	$(328,521,176,768)	Not Applicable; No Investment Used as Baseline
TPWC	$10,313,711,946	$2,280,566,089	$610,682,808	$14,679,998
TNPW	$201,651,028,982	$(203,216,795,657)	$(329,131,859,576)	Not Applicable; No Investment Used as Baseline
BCR	20.6	-88.1	-538.0	Not Applicable; No Investment Used as Baseline

With Risk Aversion and Social Pressure

Under this new scenario, the no investment policy is the only strategy that significantly changes risk pattern (Figure 40) since this policy is sensitive by both, risk aversion and social pressure. Even though risk aversion attempts to reduce risk below the threshold by decreasing the vulnerability of the system, risk continues to rise. Under the last three scenarios, risk resulting from no investment continuously drops as people move away from unprotected areas. This time, however, infrastructure is under maintenance and repair, which encourages population growth in the floodplain. Risk, benefits and costs data are presented in Appendix J.

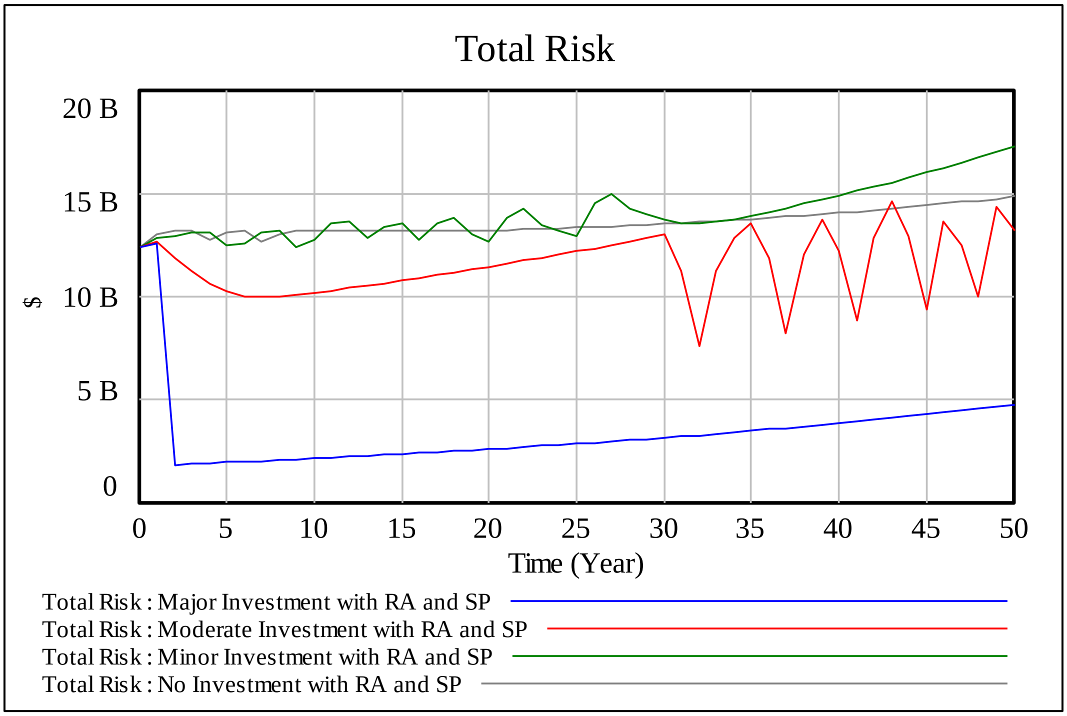

Figure 40 - Present Worth Risk Resulting from Investments with Risk-Averse Decision Making and Social Pressure

Due to this change in behavior, moderate investments have an improved BCR and positive TNPW (Table 16). Moderate investments have now become an attractive option if large funding streams are not available. In fact, using BCR as the preferred indicator, moderate investments become the preferred options for periods of analysis from 3 to 44 years. Shorter periods favor minor investments and larger periods, major investments. TNPW and BCR results for different lengths of analysis periods based on cumulative benefit and cost data are presented in Appendix K.

Table 16 - Summary Output of Investments with Risk-Averse Decision Making and Social Pressure

Model Indicator	Major Investment with RA and SP	Moderate Investment with RA and SP	Minor Investment with RA and SP	No Investment with RA and SP
TPWR	$149,602,463,744	$562,503,434,240	$690,088,381,440	$665,631,502,336
TPWB	$516,029,038,592	$103,128,068,096	$(24,456,879,104)	Not Applicable; No Investment Used as Baseline
TPWC	$10,313,711,946	$2,280,566,089	$610,682,808	$84,261,643
TNPW	$505,715,326,646	$100,847,502,008	$(25,067,561,912)	Not Applicable; No Investment Used as Baseline
BCR	50.0	45.2	-40.0	Not Applicable; No Investment Used as Baseline

Effects of Social Pressure and Risk Aversion

As mentioned previously, social pressure only has an effect on the baseline scenario. This effect may be observed by comparing the behavior of risk in the cases presented in Figure 37 and Figure 38. In the baseline scenario, where the lack of attention to infrastructure condition increases risk perception, risk is higher when social pressure occurs –a total of approximately $47 billion in probabilistic risk more over the period of analysis. Despite social pressure's efforts to increase infrastructure management investment, and hence decrease system vulnerability, the impact of the next investment level (minor investment) increases risk. Risk is higher when social pressure occurs because the population remains larger due to erratic confidence in the protection system when investments are augmented.

To determine the impact of risk aversion, results displayed in Figure 37 and Figure 39 need to be compared. First, it is observed that risk aversion increases risk in the baseline scenario. In fact, its effect is very similar to the effect that social pressure has when no risk aversion occurs. When no investment occurs, risk aversion increases investments between years 2 and 7. During these years, risk is above the threshold. The difference in risk behavior is attributed to additional investments at the beginning of the period of analysis, which changes risk perception. On the other hand, risk-averse decision making has an impact when selecting minor and moderate investment strategies. The condition of the infrastructure does not affect risk perception to a point where population decides to migrate. Despite not having an impact on population, and associated variables such as housing and economic output, larger investments reduce the vulnerability of the levee network. This is characterized by the fluctuation of risk. Increasing investments from moderate to major levels has a larger impact on risk than increasing investments from minor to moderate. Finally, risk aversion doesn't have an effect on major investments given the impact of such investment on the condition of the entire levee network to "good."

Summary

Although the scope of this model is limited to illustrating the value of temporal analysis, it is important to acknowledge that, as a result of the use of assumptions and synthetic data in the proof-of-concept SD model definition, results obtained need to be carefully considered. The results obtained, including the behavior of risk over time, are likely to change after model verification and validation. Model verification may involve working closely with the EJLD and USACE to derive model requirements and determine dynamic processes to include. This is also true for RiskDIMS. This step will be critical in transitioning the model from concept to application. Future research should also validate the model by using historical data to calibrate the relationships. The use of actual data has the potential to impact the level of risk and other endogenous parameters associated with the model.

The proof-of-concept SD model, nonetheless, demonstrates the potential of temporal analysis in infrastructure management and validates the need to account for risk variability over time in modern risk assessment. Non-linear temporal analysis is extremely powerful, and can provide answers not often reached through static linear analyses. The potential of this method may reach its peak when combined with geospatial analysis. In fact, risk is very dynamic and sensitive to changes in the surrounding environment and context, whose characteristics vary in time and over a geographic area.

Discussion of Results

The results exhibited here by the 16 modeled scenarios can help derive a number of conclusions.

1. The length of the period of analysis matters and influences investment selection. Therefore, long periods of analysis are encouraged to be used. Decision makers should also be conscious of system delays and lag times between investments and results.
2. Additionally, the selection of the baseline scenario is critical to the modeling exercise outcome as this scenario serves as the foundation for deriving benefit information, and eventually BCRs. Decision makers should carefully define the baseline scenario for analyses.
3. Other indicators should be used in decision making. In this example, no investments, with the exception of the no investments with risk aversion and social pressure, result in lower risk, but also in smaller economic output (Figure 41). All of the other investment levels returned higher GDPs.

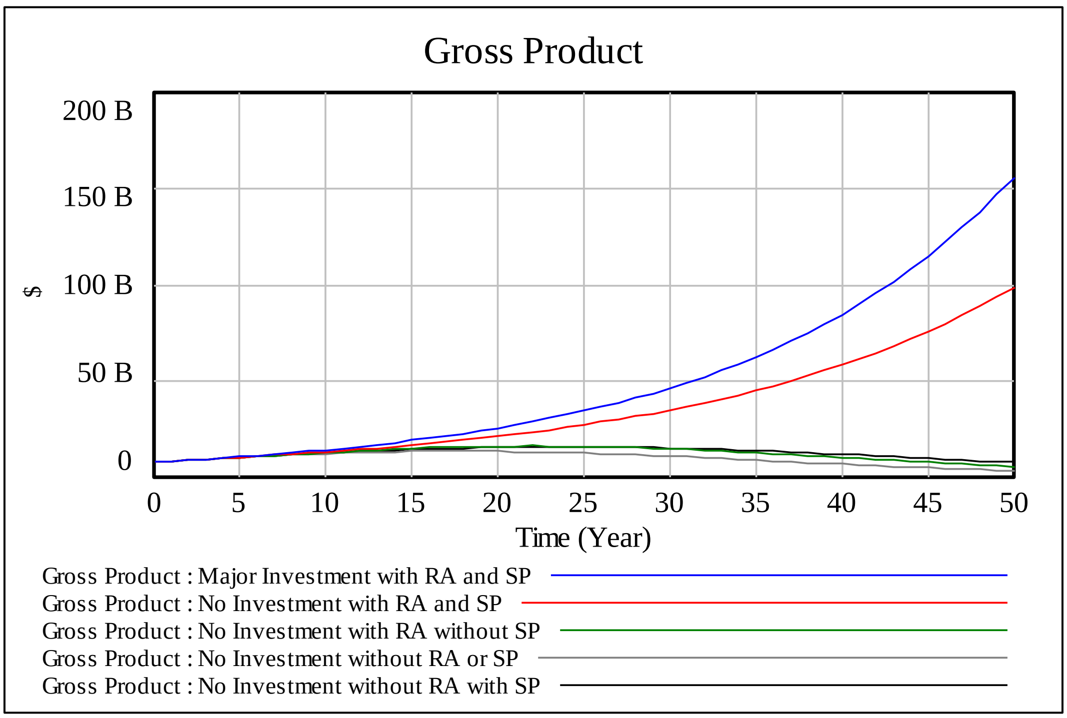

Figure 41 - Gross Product of Selected Infrastructure Management Investments

4. Unconventional model parameters, such as public risk perception and risk-averse decision making, have important effects on risk. The study of overlooked but important human-related processes will enable a deeper understanding of risk dynamics, and the unintended results of infrastructure management decisions.
5. As the economy expands, population grows and other factors change, risk will inevitably vary over time. In order to mitigate dynamic risk, it is necessary to provide a mix of structural and non-structural mitigation measures.

Chapter 7 : Summary, Conclusions and Closing Remarks

Summary and Conclusions

The proposed framework, implemented through RiskDIMS, challenges conventional linear and static risk assessment methods by accounting for the temporal and spatial characteristics of factors that define infrastructure failure risk. The emergence of systems able to adapt to our changing environment and evolving risk are needed to address 21st century critical infrastructure management challenges, including properly evaluating the effects of MR&R decisions throughout the lifecycle of assets. The application of the framework to the national levee system is timely given the unfortunate state of this infrastructure sector, its key role in our society and economic development, and its traditionally-low perceived societal value. The principal findings from this study are:

1. Current infrastructure failure risk assessment models neither account for the non-linear relationships of parameters that define risk nor allow for the dynamic assessment of risk. New critical infrastructure management frameworks, risk assessment models and DSSs suitable for non-linear dynamic environments are needed. The estimation of risk using non-linear dynamic relationships among parameters is deemed to generate more accurate results than those obtained through traditional linear risk assessment models.
2. Systems engineering methods and analogs created to address non-linear complex problems may be used to capture the non-linearity and dynamism of infrastructure failure risk and associated parameters. Systems engineering can handle increasingly complex situations (e.g., risk analysis) that involve deep multidisciplinary consideration of technical, environmental, socioeconomic and managerial factors (Chang, 2011).
3. System interdependencies, interconnectivity, urbanization, unsustainable development and climate variability are some of the critical dynamic processes and characteristics that affect the

estimation of risk variability associated with infrastructure failure. These processes need to be carefully integrated into risk assessment models.

4. Previous and current research projects have limited the use of GIS to a visualization tool and kept temporal and geospatial models in separate logical frameworks. This effort marks an important milestone in the assessment and management of dynamic risk by incorporating time and space in an integrated environment, a unified geospatiotemporal model of significant value.
5. Modeling results may be evaluated through the DSS, enabling well-informed decision making. RiskDIMS users, including federal, state and local government officials, will have a better understanding of risk and other indicators of interest such as economic growth. Users will be empowered by the evaluation of multiple infrastructure management policies and their short and long-term impacts, allowing for new insights valuable to decision makers and stakeholders.
6. Sustainable risk-based decision making requires sensing, geospatiotemporal modeling, and risk-based decision support algorithms, in conjunction with advanced computer architectures able to integrate all the physical and logical components required to successfully deliver highly-reliable information to decision makers.
7. The proof-of-concept SD model, using data from the east region of the Jefferson Parish in the Greater New Orleans area, illustrates the significant role of temporal analysis in infrastructure management and risk assessment. This exercise demonstrates that risk varies over time, and that more accurate results may be attained if model parameters are geographically-referenced.
8. This work will make important contributions to the realization of a non-linear dynamic risk-based framework for the way critical infrastructure systems are designed, built, and managed by fostering the integration of advanced sensing, modeling, and decision support.
9. The research presented here offers an interdisciplinary approach leading to an increased understanding of both the anatomy of risk and of the definition of sustainable risk mitigation policies, or policies able to meet present demands without compromising the needs of future generations.

Implications for Policy and Practice

This research provides a platform for collaboration between various fields, including but not limited to civil and systems engineering. Integrated and innovative interdisciplinary research is needed for and can be effective at addressing problems posed by changing environments. In fact, the development of RiskDIMS relies on the logical integration of advances from different fields, attempting to simulate dynamic phenomena from the built, natural and socio-economic domains. The implementation of RiskDIMS will succeed if diverse thematic expertise is combined with technological skills. Research funding should continue to target interdisciplinary research efforts aiming to solve complex and highly-coupled problems such as the management of critical infrastructure systems.

Success will also depend on the level of interagency collaboration. As discussed before, the federal government has ventured to create the Geospatial Platform and other complementary initiatives. Ultimately, RiskDIMS needs to be the result of a joint interagency effort, where data collection and management as well as domain-specific model development are decentralized but synchronized at the same time. An integrated infrastructure management framework must also provide a certain level of process standardization as means to reach a common point of comparison for decision analysis. This is of particular importance when aggregating data at the state or national level. While this type of collaboration may at first be viewed as an immediate financial burden, the long-term benefits accrued through sustainable risk-based decision making are expected to far offset the costs.

Raising awareness about the non-linearity and dynamic nature of risk is critical to the effective development and implementation of RiskDIMS. Most decision makers think in a linear fashion, and thus do not often consider the potential unintended long-term effects of policies and decisions. Decisions are made using static snapshots of data, without considering what the potential conditions in the field are expected to be by the time the solution is implemented. It is important to understand that risk evolves over time due to the numerous feedback effects and delays in the environment.

Recommendations for Future Research

The next step is to implement the proof-of-concept of RiskDIMS based on the framework and specifications developed as part of this study. It is expected that a large portion of the development will focus on (A) developing the public risk perception model and collecting expert data on MR&R activities and their impact on physical and functional performance as these efforts involve surveys, (B) logically integrating the suggested urbanization models into a single model for application to floodplain dynamics, (C) reviewing USACE systems and engineering documents listed in Chapter 5 and applicable to levee infrastructure management, if the implementation team is not already familiar with these systems, (D) assessing the use of GCMs for climate variability integration, (E) precisely defining the mathematical relationships among factors to include in the proof-of-concept and implementing domain-specific models that can leverage available GIS services and the use of ArcObjects, (F) designing and implementing the orchestrating entity for model execution –the use of the LDSME or similar system for the proof-of-concept should be explored, (G) developing the logic behind the DSS and creating the GUI, (H) collecting data to use for a case study and actual proof of concept, (I) understanding and analyzing output results and deriving conclusions.

While data will help reach some conclusions, data may also drive the development of the proof-of-concept geospatiotemporal model. In fact, some mathematical relationships will greatly depend on regression analysis and historical data belonging to the region of interest. The recommendation is to focus data collection efforts in a particular region where large quantity of data is expected to be found, and authorities and society are willing to collaborate. For instance, most districts within the Greater New Orleans area would be excellent and suitable localities to study. When a particular dataset is not readily-available, in addition to collecting that data, efforts to advocate for the collection of such data, as long as the data are of significant relevance to the framework for critical infrastructure management, should occur.

Beyond the initial implementation of the RiskDIMS proof-of-concept, four critical activities are to take place to increase the reliability of results: (A) the integration of sensing technologies to resemble actual final implementation, (B) the addition of supplementary dimensions to decision making, which may include additional evaluation indicators and the inclusion of the diverse priorities and values of stakeholders involved, (C) the incorporation of uncertainty, which, if not properly controlled, will have a significant impact in the ultimate model output, and (D) the implementation of network interdependencies.

This research introduces a new critical infrastructure paradigm that is also applicable to other sustainability and infrastructure challenges, such as monitoring the compliance of building codes in earthquake-prone megacities around the world. Lessons learned will directly inform future integration efforts in different infrastructure management contexts and at different scales, including other large-scale infrastructure sectors exposed to extreme events, whose human-system interaction is closely coupled and operational environment is complex and dynamic. Extending the framework to other critical infrastructure sectors will lead to disaster-resilient and sustainable communities.

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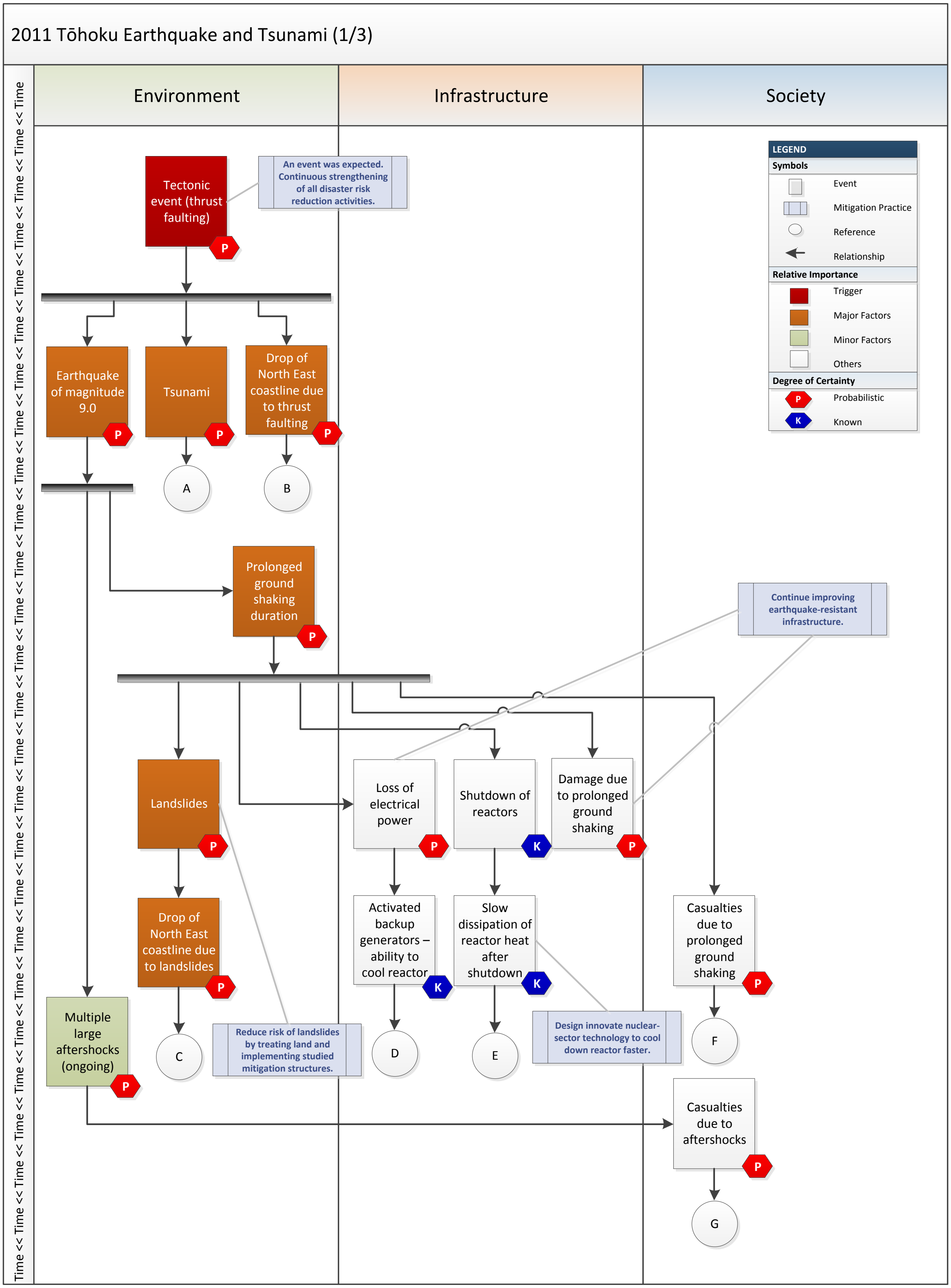
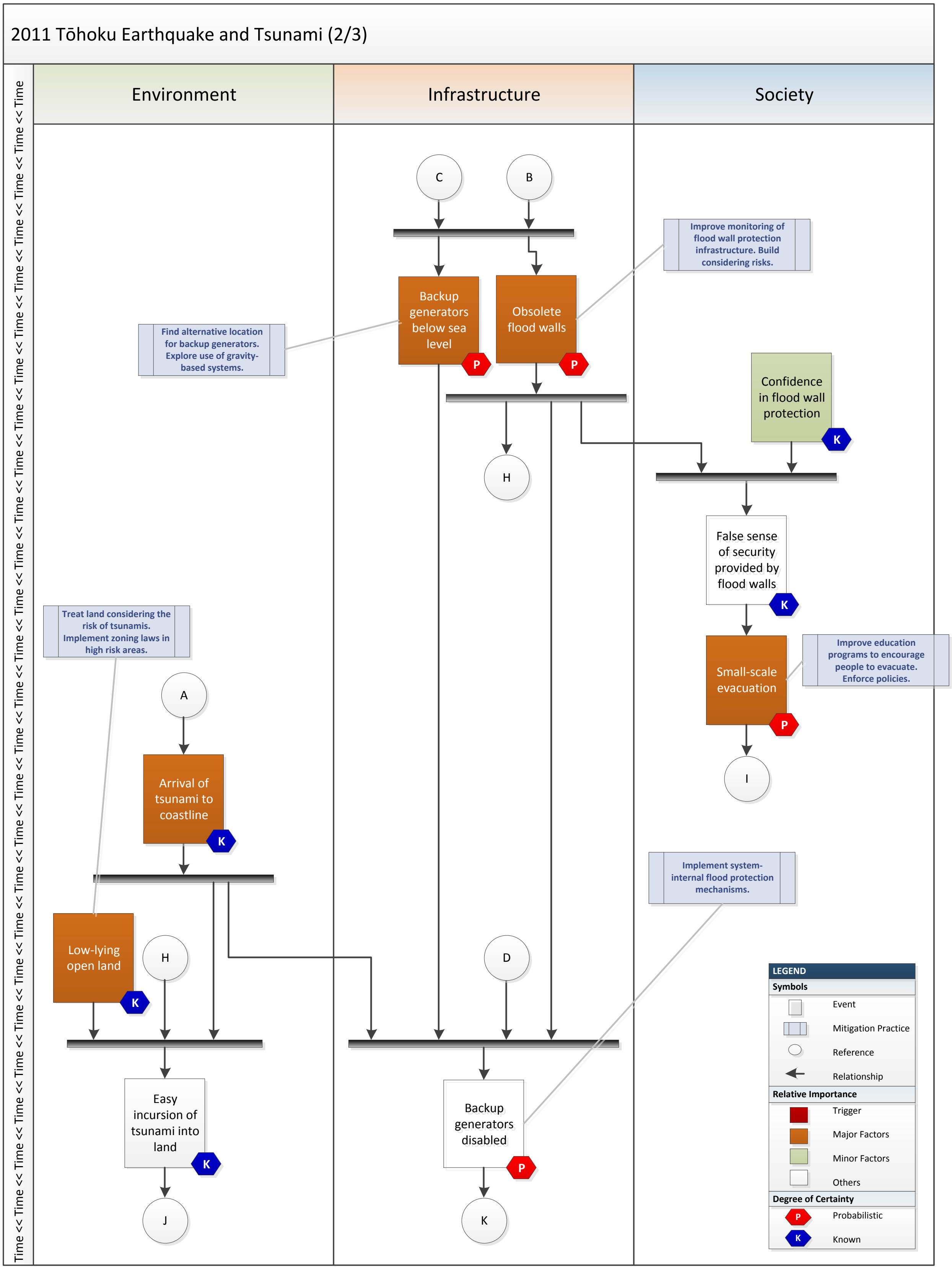
Appendix A – Dynamic Process of Tōhoku Earthquake and Tsunami

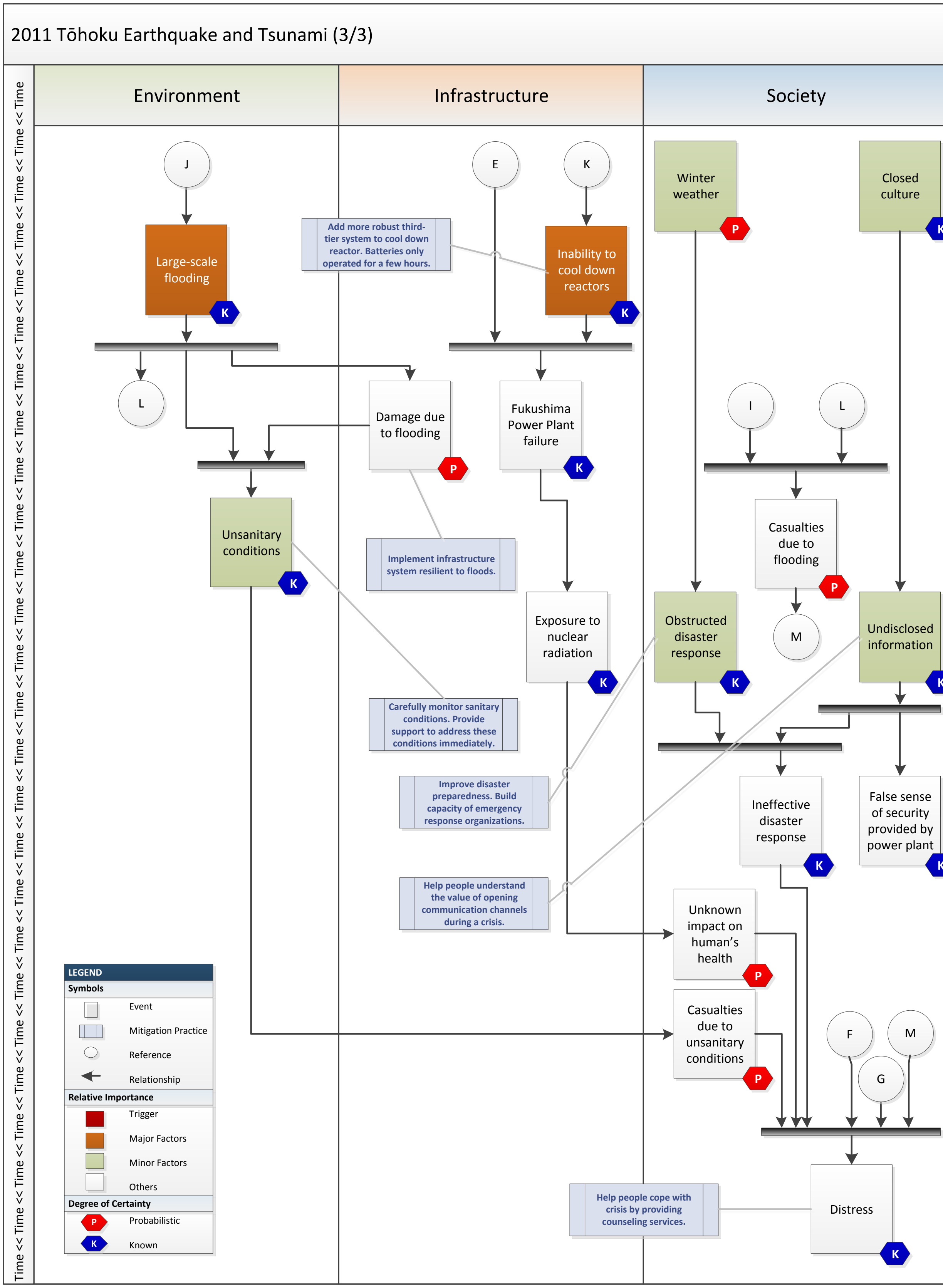
Attached is a flowchart that describes the evolution of the unfortunate disaster in Japan. The diagram includes a legend that explains the symbols and colors used. The events are presented in three domains – environment, infrastructure and society– and organized in sequence of occurrence. In terms of relative importance, events have been arranged in four categories: (A) TRIGGER (triggering event), (B) MAJOR FACTORS (natural phenomena originated by trigger, land condition, primary resulting events), (C) MINOR FACTORS (other contributing external factors, secondary resulting events), and (D) OTHERS (remaining resulting events, consequences, operational processes). In terms of degree of certainty, events were either classified as (A) PROBABILISTIC (P), which are events governed by uncertainty and risk even when conditional prior events are known, and (B) KNOWN (K), which are events known when conditional prior events are known –using Bayesian theorem where pre-conditions have probability of 1. Illustrative risk reduction activities are proposed and linked to each opportunity.



2011 Tōhoku Earthquake and Tsunami (1/3)
Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time
Environment
Infrastructure
Society
LEGEND
Symbols
Event
Mitigation Practice
Reference
Relationship
Relative Importance
Trigger
Major Factors
Minor Factors
Others
Degree of Certainty
Probabilistic
Known
Tectonic event (thrust faulting)
An event was expected. Continuous strengthening of all disaster risk reduction activities.
Earthquake of magnitude 9.0
Tsunami
Drop of North East coastline due to thrust faulting
A
B
Prolonged ground shaking duration
Continue improving earthquake-resistant infrastructure.
Landslides
Loss of electrical power
Shutdown of reactors
Damage due to prolonged ground shaking
Drop of North East coastline due to landslides
Activated backup generators – ability to cool reactor
Slow dissipation of reactor heat after shutdown
Casualties due to prolonged ground shaking
Multiple large aftershocks (ongoing)
C
Reduce risk of landslides by treating land and implementing studied mitigation structures.
D
E
Design innovate nuclear-sector technology to cool down reactor faster.
F
Casualties due to aftershocks
G
P
K



2011 Tōhoku Earthquake and Tsunami (2/3)
Environment
Infrastructure
Society
Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time
C
B
Improve monitoring of flood wall protection infrastructure. Build considering risks.
Backup generators below sea level
P
Obsolete flood walls
P
Find alternative location for backup generators. Explore use of gravity-based systems.
Confidence in flood wall protection
K
H
False sense of security provided by flood walls
K
Treat land considering the risk of tsunamis. Implement zoning laws in high risk areas.
Small-scale evacuation
P
Improve education programs to encourage people to evacuate. Enforce policies.
A
Arrival of tsunami to coastline
K
I
Implement system-internal flood protection mechanisms.
Low-lying open land
K
H
D
Easy incursion of tsunami into land
K
Backup generators disabled
P
J
K
LEGEND
Symbols
Event
Mitigation Practice
Reference
Relationship
Relative Importance
Trigger
Major Factors
Minor Factors
Others
Degree of Certainty
P Probabilistic
K Known


2011 Tōhoku Earthquake and Tsunami (3/3)
Environment
Infrastructure
Society
Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time << Time
J
E
K
Winter weather
P
Closed culture
K
Add more robust third-tier system to cool down reactor. Batteries only operated for a few hours.
Large-scale flooding
K
Inability to cool down reactors
K
L
Damage due to flooding
P
Fukushima Power Plant failure
K
I
L
Unsanitary conditions
K
Implement infrastructure system resilient to floods.
Casualties due to flooding
P
Exposure to nuclear radiation
K
Obstructed disaster response
K
M
Undisclosed information
K
Carefully monitor sanitary conditions. Provide support to address these conditions immediately.
Improve disaster preparedness. Build capacity of emergency response organizations.
Ineffective disaster response
K
False sense of security provided by power plant
K
Help people understand the value of opening communication channels during a crisis.
Unknown impact on human's health
P
Casualties due to unsanitary conditions
P
F
M
G
Help people cope with crisis by providing counseling services.
Distress
K
LEGEND
Symbols
Event
Mitigation Practice
Reference
Relationship
Relative Importance
Trigger
Major Factors
Minor Factors
Others
Degree of Certainty
P
Probabilistic
K
Known

Appendix B – International Resources

This research has identified successful applications of asset management frameworks and systems in relevant hazard-specific areas. For example, the Netherlands is today's world leader in managing flood protection infrastructure. The Dutch Ministry of Infrastructure and the Environment has asset-management-related information available in its Helpdesk Water and Inspection of Flood Defense System websites. In addition to this, The Netherlands has several organizations working together towards the enhancement of the Dutch entire flood management system, and the dissemination of best practices. One of these organizations is the Dutch Floodplanning Initiative, which is a consortium of government agencies, universities, water research institutes, private engineering firms and financial institutions formed to help people prevent flood-related disasters. Other organizations include the Netherlands Water Partnership and the Dutch Delta Design 2012.

Dutch Delta Design 2012

http://www.ddd2012.nl/

Dutch Floodplanning Initiative

http://www.dutchfloodplanninginitiative.com/

Netherlands' Helpdesk Water

http://www.helpdeskwater.nl/algemene-onderdelen/serviceblok/english/

Netherlands' Inspection of Flood Defense System

http://www.inspectiewaterkeringen.nl/content.asp?page=46

Netherlands Water Partnership

http://www.nwp.nl/en/

Appendix C – Cloud Computing Advantages and Disadvantages

Lewis (2010) states some of the benefits and shortcomings of cloud computing. These are presented in the tables below.

Attribute	Why It Can Draw an Organization Toward Cloud Computing
Availability	Users have the ability to access their resources at any time through a standard internet connection.
Collaboration	Users begin to see the cloud as a way to work simultaneously on common data and information.
Elasticity	The provider transparently manages a user's resource utilization based on dynamically changing needs.
Lower Infrastructure Costs	The pay-per-usage model allows an organization to only pay for the resources they need with basically no investment in the physical resources available in the cloud. There are no infrastructure maintenance or upgrade costs.
Mobility	Users have the ability to access data and applications from around the globe.
Risk Reduction	Organizations can use the cloud to test ideas and concepts before making major investments in technology.
Scalability	Users have access to a large amount of resources that scale based on their demand.
Virtualization	Each user has a single view of the available resources, independently of how they are arranged in terms of physical devices. Therefore, there is potential from a provider perspective to serve a greater number of users with fewer physical resources.

Concern	Why It Can Act as a Barrier to Cloud Computing Adoption
Interoperability	A universal set of standards and/or interfaces have not yet been defined, resulting in a significant risk of vendor lock-in.
Latency	All access to the cloud is done via the internet, introducing latency into every communication between the user and the provider.
Platform or Language Constraints	Some cloud providers support specific platforms and languages only.
Regulations	There are concerns in the cloud computing community over jurisdiction, data protection, fair information practices, and international data transfer—mainly for organizations that manage sensitive data.
Reliability	Many existing cloud infrastructures leverage commodity hardware that is known to fail unexpectedly.
Resource Control	The amount of control that the user has over the cloud provider and its resources varies greatly between providers.
Security	The main concern is data privacy: users do not have control or knowledge of where their data is being stored.

Appendix D – Present Worth Risk, Benefit and Cost of Investments without Risk-Averse Decision Making or Social Pressure

Time (Year)	Present Worth Risk			
	Major Investment without RA or SP	Moderate Investment without RA or SP	Minor Investment without RA or SP	No Investment without RA or SP
0	$12,435,153,920	$12,435,153,920	$12,435,153,920	$12,435,153,920
1	$12,568,590,336	$12,668,358,656	$12,830,967,808	$12,980,767,744
2	$1,864,920,832	$11,896,647,680	$12,945,357,824	$13,238,302,720
3	$1,898,909,312	$11,247,315,968	$13,097,738,240	$13,362,799,616
4	$1,933,596,928	$10,648,981,504	$13,262,459,904	$13,402,706,944
5	$1,969,025,792	$10,237,846,528	$13,428,623,360	$13,376,163,840
6	$2,005,191,680	$10,031,638,528	$13,593,543,680	$13,291,231,232
7	$2,042,115,200	$9,972,889,600	$13,756,958,720	$13,152,886,784
8	$2,079,816,704	$10,001,087,488	$13,919,392,768	$12,965,135,360
9	$2,118,316,544	$10,075,736,064	$14,081,590,272	$12,731,786,240
10	$2,157,634,560	$10,174,234,624	$14,244,257,792	$12,456,714,240
11	$2,197,790,976	$10,285,086,720	$14,407,991,296	$12,143,941,632
12	$2,238,806,528	$10,402,748,416	$14,573,264,896	$11,797,633,024
13	$2,280,727,296	$10,524,756,992	$14,740,601,856	$11,422,060,544
14	$2,323,558,656	$10,649,876,480	$14,910,181,376	$11,021,556,736
15	$2,367,321,088	$10,777,613,312	$15,082,226,688	$10,600,445,952
16	$2,412,043,264	$10,907,789,312	$15,256,936,448	$10,162,989,056
17	$2,457,752,064	$11,040,352,256	$15,434,468,352	$9,713,331,200
18	$2,504,470,016	$11,175,313,408	$15,614,945,280	$9,255,446,528
19	$2,552,228,096	$11,312,715,776	$15,798,483,968	$8,792,927,232
20	$2,601,049,600	$11,452,594,176	$15,985,175,552	$8,328,909,824
21	$2,650,996,224	$11,595,132,928	$16,175,278,080	$7,866,288,640
22	$2,702,071,296	$11,740,295,168	$16,368,752,640	$7,407,768,064
23	$2,754,309,888	$11,888,152,576	$16,565,694,464	$6,955,836,416
24	$2,807,740,672	$12,038,771,712	$16,766,199,808	$6,512,759,808
25	$2,862,403,840	$12,192,239,616	$16,970,376,192	$6,080,562,688
26	$2,918,323,712	$12,348,604,416	$17,178,292,224	$5,661,021,696
27	$2,975,576,064	$12,508,080,128	$17,390,229,504	$5,255,667,712
28	$3,034,170,368	$12,670,644,224	$17,606,156,288	$4,865,785,344
29	$3,094,140,416	$12,836,372,480	$17,826,162,688	$4,492,412,928
30	$3,155,532,544	$13,005,361,152	$18,050,373,632	$4,136,356,864
31	$3,218,387,456	$13,177,702,400	$18,278,907,904	$3,798,204,160
32	$3,282,747,392	$13,353,476,096	$18,511,867,904	$3,478,331,648
33	$3,348,693,504	$13,532,919,808	$18,749,566,976	$3,176,923,136
34	$3,416,243,968	$13,716,022,272	$18,991,980,544	$2,893,983,232
35	$3,485,446,144	$13,902,886,912	$19,239,239,680	$2,629,359,360
36	$3,556,346,880	$14,093,607,936	$19,491,467,264	$2,382,754,304
37	$3,629,037,824	$14,288,441,344	$19,749,003,264	$2,153,748,480
38	$3,703,541,760	$14,487,386,112	$20,011,827,200	$1,941,817,344
39	$3,779,915,776	$14,690,562,048	$20,280,098,816	$1,746,347,008
40	$3,858,221,056	$14,898,104,320	$20,553,986,048	$1,566,652,416
41	$3,938,510,336	$15,110,117,376	$20,833,624,064	$1,402,000,384
42	$4,020,896,256	$15,326,904,320	$21,119,412,224	$1,251,642,624
43	$4,105,404,416	$15,548,465,152	$21,411,336,192	$1,114,814,720
44	$4,192,111,104	$15,774,958,592	$21,709,602,816	$990,712,768
45	$4,281,075,712	$16,006,510,592	$22,014,365,696	$878,512,320
46	$4,372,423,680	$16,243,448,832	$22,326,056,960	$777,382,144
47	$4,466,196,480	$16,485,805,056	$22,644,705,280	$686,496,512
48	$4,562,471,936	$16,733,744,128	$22,970,523,648	$605,046,976
49	$4,661,332,992	$16,987,437,056	$23,303,720,960	$532,250,944
50	$4,762,918,912	$17,247,236,096	$23,644,766,208	$467,357,216

Time (Year)	Present Worth Benefit		
	Major Investment without RA or SP	Moderate Investment without RA or SP	Minor Investment without RA or SP
0	$-	$-	$-
1	$412,177,408	$312,409,088	$149,799,936
2	$11,373,381,888	$1,341,655,040	$292,944,896
3	$11,463,890,304	$2,115,483,648	$265,061,376
4	$11,469,110,016	$2,753,725,440	$140,247,040
5	$11,407,138,048	$3,138,317,312	$(52,459,520)
6	$11,286,039,552	$3,259,592,704	$(302,312,448)
7	$11,110,771,584	$3,179,997,184	$(604,071,936)
8	$10,885,318,656	$2,964,047,872	$(954,257,408)
9	$10,613,469,696	$2,656,050,176	$(1,349,804,032)
10	$10,299,079,680	$2,282,479,616	$(1,787,543,552)
11	$9,946,150,656	$1,858,854,912	$(2,264,049,664)
12	$9,558,826,496	$1,394,884,608	$(2,775,631,872)
13	$9,141,333,248	$897,303,552	$(3,318,541,312)
14	$8,697,998,080	$371,680,256	$(3,888,624,640)
15	$8,233,124,864	$(177,167,360)	$(4,481,780,736)
16	$7,750,945,792	$(744,800,256)	$(5,093,947,392)
17	$7,255,579,136	$(1,327,021,056)	$(5,721,137,152)
18	$6,750,976,512	$(1,919,866,880)	$(6,359,498,752)
19	$6,240,699,136	$(2,519,788,544)	$(7,005,556,736)
20	$5,727,860,224	$(3,123,684,352)	$(7,656,265,728)
21	$5,215,292,416	$(3,728,844,288)	$(8,308,989,440)
22	$4,705,696,768	$(4,332,527,104)	$(8,960,984,576)
23	$4,201,526,528	$(4,932,316,160)	$(9,609,858,048)
24	$3,705,019,136	$(5,526,011,904)	$(10,253,440,000)
25	$3,218,158,848	$(6,111,676,928)	$(10,889,813,504)
26	$2,742,697,984	$(6,687,582,720)	$(11,517,270,528)
27	$2,280,091,648	$(7,252,412,416)	$(12,134,561,792)
28	$1,831,614,976	$(7,804,858,880)	$(12,740,370,944)
29	$1,398,272,512	$(8,343,959,552)	$(13,333,749,760)
30	$980,824,320	$(8,869,004,288)	$(13,914,016,768)
31	$579,816,704	$(9,379,498,240)	$(14,480,703,744)
32	$195,584,256	$(9,875,144,448)	$(15,033,536,256)
33	$(171,770,368)	$(10,355,996,672)	$(15,572,643,840)
34	$(522,260,736)	$(10,822,039,040)	$(16,097,997,312)
35	$(856,086,784)	$(11,273,527,552)	$(16,609,880,320)
36	$(1,173,592,576)	$(11,710,853,632)	$(17,108,712,960)
37	$(1,475,289,344)	$(12,134,692,864)	$(17,595,254,784)
38	$(1,761,724,416)	$(12,545,568,768)	$(18,070,009,856)
39	$(2,033,568,768)	$(12,944,215,040)	$(18,533,751,808)
40	$(2,291,568,640)	$(13,331,451,904)	$(18,987,333,632)
41	$(2,536,509,952)	$(13,708,116,992)	$(19,431,623,680)
42	$(2,769,253,632)	$(14,075,261,696)	$(19,867,769,600)
43	$(2,990,589,696)	$(14,433,650,432)	$(20,296,521,472)
44	$(3,201,398,336)	$(14,784,245,824)	$(20,718,890,048)
45	$(3,402,563,392)	$(15,127,998,272)	$(21,135,853,376)
46	$(3,595,041,536)	$(15,466,066,688)	$(21,548,674,816)
47	$(3,779,699,968)	$(15,799,308,544)	$(21,958,208,768)
48	$(3,957,424,960)	$(16,128,697,152)	$(22,365,476,672)
49	$(4,129,082,048)	$(16,455,186,112)	$(22,771,470,016)
50	$(4,295,561,696)	$(16,779,878,880)	$(23,177,408,992)

Time (Year)	Present Worth Cost		
	Major Investment without RA or SP	Moderate Investment without RA or SP	Minor Investment without RA or SP
0	$157,977,984	$11,123,624	$1,485,557
1	$180,363,632	$12,534,632	$1,648,856
2	$40,821,128	$3,825,293	$655,572
3	$208,154,864	$14,295,885	$1,854,308
4	$130,550,736	$9,458,029	$1,303,536
5	$136,026,384	$9,812,833	$1,346,241
6	$168,677,664	$11,866,291	$1,583,108
7	$215,031,888	$14,776,366	$1,917,906
8	$233,205,760	$15,925,353	$2,051,468
9	$131,426,008	$9,577,427	$1,328,272
10	$154,804,064	$11,052,059	$1,499,116
11	$109,851,032	$8,256,197	$1,181,938
12	$306,153,248	$20,538,988	$2,588,069
13	$306,892,352	$20,599,294	$2,597,381
14	$67,034,080	$5,622,479	$888,200
15	$249,758,336	$17,057,290	$2,197,529
16	$178,061,776	$12,591,020	$1,689,630
17	$237,099,744	$16,295,890	$2,115,614
18	$225,938,096	$15,613,517	$2,040,239
19	$213,470,112	$14,849,737	$1,955,602
20	$146,061,792	$10,652,434	$1,478,605
21	$223,051,440	$15,480,256	$2,033,094
22	$269,582,240	$18,404,660	$2,370,093
23	$167,900,368	$12,066,036	$1,648,506
24	$79,700,968	$6,570,340	$1,023,301
25	$247,874,256	$17,098,214	$2,229,409
26	$87,693,088	$7,104,225	$1,090,210
27	$284,682,528	$19,433,690	$2,502,313
28	$207,542,512	$14,630,367	$1,956,435
29	$256,969,648	$17,737,802	$2,314,697
30	$392,101,472	$26,202,098	$3,285,227
31	$197,984,992	$14,088,702	$1,904,076
32	$336,611,296	$22,772,066	$2,899,755
33	$228,367,984	$16,026,424	$2,132,179
34	$115,107,544	$8,967,566	$1,328,867
35	$355,432,416	$24,008,156	$3,051,269
36	$30,474,946	$3,718,975	$736,047
37	$174,304,624	$12,729,374	$1,769,415
38	$347,432,736	$23,571,324	$3,012,171
39	$348,736,864	$23,674,684	$3,027,730
40	$229,286,192	$16,231,292	$2,180,874
41	$376,361,280	$25,446,190	$3,237,898
42	$135,590,176	$10,421,146	$1,524,718
43	$413,471,360	$27,812,328	$3,516,329
44	$151,785,712	$11,481,055	$1,654,026
45	$476,340,544	$31,790,300	$3,979,294
46	$160,737,216	$12,090,157	$1,732,146
47	$151,407,072	$11,532,606	$1,672,812
48	$69,819,792	$6,459,515	$1,097,506
49	$429,465,184	$28,964,016	$3,674,020
50	$406,524,992	$27,557,480	$3,517,941

Appendix E – TNPW and BCR Based on Cumulative Benefits and Cost of Investments without Risk-Averse Decision Making or Social Pressure

Time (Year)	TNPW Based on Cumulative Benefit and Cost			Investment Level Selection
	Major Investment without RA or SP	Moderate Investment without RA or SP	Minor Investment without RA or SP	
0	$11,627,581,312	$1,642,940,504	$441,259,275	Major
1	$22,911,107,984	$3,745,889,520	$704,671,795	Major
2	$34,339,396,872	$6,495,789,667	$844,263,263	Major
3	$45,538,380,056	$9,619,811,094	$789,949,436	Major
4	$56,693,868,872	$12,869,945,769	$486,333,452	Major
5	$67,668,614,072	$16,040,130,120	$(119,084,726)	Major
6	$78,385,255,064	$18,992,311,701	$(1,074,925,242)	Major
7	$88,783,692,872	$21,633,585,511	$(2,426,647,179)	Major
8	$98,849,566,792	$23,900,139,774	$(4,216,242,199)	Major
9	$108,664,291,440	$25,749,417,259	$(6,481,620,135)	Major
10	$118,068,313,872	$27,133,249,808	$(9,258,751,123)	Major
11	$127,099,796,088	$28,022,297,164	$(12,578,474,373)	Major
12	$135,491,640,920	$28,373,438,432	$(16,469,687,082)	Major
13	$143,417,873,432	$28,175,671,778	$(20,954,065,198)	Major
14	$151,101,785,144	$27,425,249,043	$(26,048,900,790)	Major
15	$158,107,605,944	$26,081,170,697	$(31,772,235,471)	Major
16	$164,680,520,680	$24,148,712,797	$(38,133,423,853)	Major
17	$170,684,120,072	$21,612,628,363	$(45,141,096,203)	Major
18	$176,186,042,200	$18,473,330,494	$(52,799,402,170)	Major
19	$181,187,864,504	$14,729,636,469	$(61,110,347,213)	Major
20	$185,747,499,480	$10,386,456,931	$(70,072,810,394)	Major
21	$189,725,974,568	$5,438,660,515	$(79,684,701,535)	Major
22	$193,161,411,464	$(105,756,049)	$(89,940,511,628)	Major
23	$196,211,669,944	$(6,229,499,013)	$(100,831,973,639)	Major
24	$198,874,666,960	$(12,923,652,073)	$(112,350,267,468)	Major
25	$200,906,884,352	$(20,193,162,703)	$(124,487,058,668)	Major
26	$202,650,806,240	$(28,005,125,807)	$(137,228,519,822)	Major
27	$203,764,396,224	$(36,368,519,049)	$(150,564,771,895)	Major
28	$204,537,678,032	$(45,252,153,704)	$(164,480,745,098)	Major
29	$204,860,525,088	$(54,649,389,746)	$(178,963,763,540)	Major
30	$204,664,007,872	$(64,550,736,292)	$(194,000,585,022)	Major
31	$204,294,252,512	$(74,920,821,666)	$(209,575,132,938)	Major
32	$203,435,380,480	$(85,765,632,772)	$(225,676,030,005)	Major
33	$202,350,925,712	$(97,055,186,748)	$(242,288,042,504)	Major
34	$201,062,225,592	$(108,775,007,946)	$(259,398,084,330)	Major
35	$199,231,503,832	$(120,933,708,966)	$(276,996,390,383)	Major
36	$197,439,304,470	$(133,482,996,709)	$(295,067,136,286)	Major
37	$195,231,431,078	$(146,439,941,123)	$(313,602,657,509)	Major
38	$192,592,429,702	$(159,794,964,351)	$(332,593,003,311)	Major
39	$189,707,182,886	$(173,526,756,027)	$(352,027,654,721)	Major
40	$186,708,643,062	$(187,618,249,015)	$(371,897,605,195)	Major
41	$183,341,692,086	$(202,077,345,637)	$(392,197,364,565)	Major
42	$180,004,703,574	$(216,872,012,607)	$(412,917,779,331)	Major
43	$176,188,668,822	$(232,027,823,207)	$(434,057,149,036)	Major
44	$172,441,841,574	$(247,505,370,950)	$(455,607,477,878)	Major
45	$168,185,801,062	$(263,336,469,794)	$(477,569,665,940)	Major
46	$164,067,638,886	$(279,477,257,103)	$(499,936,874,758)	Major
47	$159,787,149,766	$(295,943,975,821)	$(522,710,017,585)	Major
48	$155,421,768,278	$(312,730,314,216)	$(545,888,524,084)	Major

Time (Year)	BCR Based on Cumulative Benefit and Cost			Investment Level Selection
	Major Investment without RA or SP	Moderate Investment without RA or SP	Minor Investment without RA or SP	
0	74.6	148.7	298.0	Minor
1	68.7	159.3	225.8	Minor
2	91.6	237.4	223.8	Moderate
3	78.5	231.3	141.0	Moderate
4	80.0	252.2	71.0	Moderate
5	80.2	263.7	-13.4	Moderate
6	77.7	261.5	-107.8	Moderate
7	72.7	247.7	-204.7	Moderate
8	68.2	231.7	-303.5	Moderate
9	68.8	228.5	-426.1	Moderate
10	68.2	219.4	-554.3	Moderate
11	69.1	212.5	-703.4	Moderate
12	63.4	186.4	-804.6	Moderate
13	58.8	163.3	-908.4	Moderate
14	60.3	154.0	-1087.6	Moderate
15	57.5	133.8	-1215.1	Moderate
16	56.4	116.6	-1369.9	Moderate
17	54.1	97.0	-1507.1	Moderate
18	52.2	77.7	-1650.4	Moderate
19	50.6	58.6	-1800.2	Moderate
20	49.9	40.0	-1978.1	Major
21	48.2	20.3	-2127.3	Major
22	46.0	0.6	-2258.2	Major
23	45.0	-18.9	-2431.1	Major
24	44.8	-39.5	-2643.7	Major
25	43.0	-59.1	-2783.3	Major
26	42.6	-80.6	-2995.2	Major
27	40.5	-99.3	-3116.0	Major
28	39.1	-119.0	-3271.6	Major
29	37.4	-137.4	-3403.0	Major
30	35.0	-152.3	-3472.0	Major
31	33.9	-171.2	-3627.1	Major
32	32.1	-186.3	-3719.1	Major
33	30.9	-203.8	-3857.3	Major
34	30.2	-224.3	-4044.2	Major
35	28.5	-237.6	-4122.4	Major
36	28.1	-260.4	-4343.8	Major
37	27.2	-278.8	-4499.5	Major
38	25.7	-291.2	-4574.3	Major
39	24.3	-303.1	-4648.0	Major
40	23.3	-318.7	-4772.9	Major
41	21.9	-329.0	-4832.6	Major
42	21.2	-347.3	-4994.1	Major
43	19.9	-355.7	-5035.6	Major
44	19.2	-372.9	-5186.1	Major
45	17.9	-378.6	-5200.5	Major
46	17.3	-394.9	-5343.2	Major
47	16.6	-411.5	-5488.5	Major
48	16.1	-431.0	-5666.6	Major

Appendix F – Present Worth Risk, Benefit and Cost of Investments without Risk-Averse Decision Making but with Social Pressure

Time (Year)	Present Worth Risk			
	Major Investment without RA with SP	Moderate Investment without RA with SP	Minor Investment without RA with SP	No Investment without RA with SP
0	$12,435,153,920	$12,435,153,920	$12,435,153,920	$12,435,153,920
1	$12,568,590,336	$12,668,358,656	$12,830,967,808	$12,980,767,744
2	$1,864,920,832	$11,896,647,680	$12,945,357,824	$13,181,326,336
3	$1,898,909,312	$11,247,315,968	$13,097,738,240	$13,208,216,576
4	$1,933,596,928	$10,648,981,504	$13,262,459,904	$13,288,133,632
5	$1,969,025,792	$10,237,846,528	$13,428,623,360	$13,351,915,520
6	$2,005,191,680	$10,031,638,528	$13,593,543,680	$13,276,923,904
7	$2,042,115,200	$9,972,889,600	$13,756,958,720	$13,165,357,056
8	$2,079,816,704	$10,001,087,488	$13,919,392,768	$13,076,142,080
9	$2,118,316,544	$10,075,736,064	$14,081,590,272	$12,980,229,120
10	$2,157,634,560	$10,174,234,624	$14,244,257,792	$12,761,363,456
11	$2,197,790,976	$10,285,086,720	$14,407,991,296	$12,512,595,968
12	$2,238,806,528	$10,402,748,416	$14,573,264,896	$12,288,438,272
13	$2,280,727,296	$10,524,756,992	$14,740,601,856	$12,064,855,040
14	$2,323,558,656	$10,649,876,480	$14,910,181,376	$11,736,330,240
15	$2,367,321,088	$10,777,613,312	$15,082,226,688	$11,388,124,160
16	$2,412,043,264	$10,907,789,312	$15,256,936,448	$11,069,018,112
17	$2,457,752,064	$11,040,352,256	$15,434,468,352	$10,757,483,520
18	$2,504,470,016	$11,175,313,408	$15,614,945,280	$10,361,715,712
19	$2,552,228,096	$11,312,715,776	$15,798,483,968	$9,957,259,264
20	$2,601,049,600	$11,452,594,176	$15,985,175,552	$9,586,067,456
21	$2,650,996,224	$11,595,132,928	$16,175,278,080	$9,228,716,032
22	$2,702,071,296	$11,740,295,168	$16,368,752,640	$8,808,030,208
23	$2,754,309,888	$11,888,152,576	$16,565,694,464	$8,388,528,128
24	$2,807,740,672	$12,038,771,712	$16,766,199,808	$8,004,621,824
25	$2,862,403,840	$12,192,239,616	$16,970,376,192	$7,639,040,512
26	$2,918,323,712	$12,348,604,416	$17,178,292,224	$7,228,795,904
27	$2,975,576,064	$12,508,080,128	$17,390,229,504	$6,826,661,888
28	$3,034,170,368	$12,670,644,224	$17,606,156,288	$6,459,504,128
29	$3,094,140,416	$12,836,372,480	$17,826,162,688	$6,112,454,656
30	$3,155,532,544	$13,005,361,152	$18,050,373,632	$5,735,595,008
31	$3,218,387,456	$13,177,702,400	$18,278,907,904	$5,371,499,008
32	$3,282,747,392	$13,353,476,096	$18,511,867,904	$5,040,259,072
33	$3,348,693,504	$13,532,919,808	$18,749,566,976	$4,729,536,512
34	$3,416,243,968	$13,716,022,272	$18,991,980,544	$4,400,978,944
35	$3,485,446,144	$13,902,886,912	$19,239,239,680	$4,087,660,800
36	$3,556,346,880	$14,093,607,936	$19,491,467,264	$3,803,933,440
37	$3,629,037,824	$14,288,441,344	$19,749,003,264	$3,539,822,080
38	$3,703,541,760	$14,487,386,112	$20,011,827,200	$3,266,745,856
39	$3,779,915,776	$14,690,562,048	$20,280,098,816	$3,009,450,240
40	$3,858,221,056	$14,898,104,320	$20,553,986,048	$2,777,689,856
41	$3,938,510,336	$15,110,117,376	$20,833,624,064	$2,563,621,888
42	$4,020,896,256	$15,326,904,320	$21,119,412,224	$2,346,538,496
43	$4,105,404,416	$15,548,465,152	$21,411,336,192	$2,144,313,088
44	$4,192,111,104	$15,774,958,592	$21,709,602,816	$1,963,207,808
45	$4,281,075,712	$16,006,510,592	$22,014,365,696	$1,797,210,368
46	$4,372,423,680	$16,243,448,832	$22,326,056,960	$1,631,839,360
47	$4,466,196,480	$16,485,805,056	$22,644,705,280	$1,479,357,696
48	$4,562,471,936	$16,733,744,128	$22,970,523,648	$1,343,626,752
49	$4,661,332,992	$16,987,437,056	$23,303,720,960	$1,220,167,680
50	$4,762,918,912	$17,247,236,096	$23,644,766,208	$1,099,134,080

Time (Year)	Present Worth Benefit		
	Major Investment without RA with SP	Moderate Investment without RA with SP	Minor Investment without RA with SP
0	$-	$-	$-
1	$412,177,408	$312,409,088	$149,799,936
2	$11,316,405,504	$1,284,678,656	$235,968,512
3	$11,309,307,264	$1,960,900,608	$110,478,336
4	$11,354,536,704	$2,639,152,128	$25,673,728
5	$11,382,889,728	$3,114,068,992	$(76,707,840)
6	$11,271,732,224	$3,245,285,376	$(316,619,776)
7	$11,123,241,856	$3,192,467,456	$(591,601,664)
8	$10,996,325,376	$3,075,054,592	$(843,250,688)
9	$10,861,912,576	$2,904,493,056	$(1,101,361,152)
10	$10,603,728,896	$2,587,128,832	$(1,482,894,336)
11	$10,314,804,992	$2,227,509,248	$(1,895,395,328)
12	$10,049,631,744	$1,885,689,856	$(2,284,826,624)
13	$9,784,127,744	$1,540,098,048	$(2,675,746,816)
14	$9,412,771,584	$1,086,453,760	$(3,173,851,136)
15	$9,020,803,072	$610,510,848	$(3,694,102,528)
16	$8,656,974,848	$161,228,800	$(4,187,918,336)
17	$8,299,731,456	$(282,868,736)	$(4,676,984,832)
18	$7,857,245,696	$(813,597,696)	$(5,253,229,568)
19	$7,405,031,168	$(1,355,456,512)	$(5,841,224,704)
20	$6,985,017,856	$(1,866,526,720)	$(6,399,108,096)
21	$6,577,719,808	$(2,366,416,896)	$(6,946,562,048)
22	$6,105,958,912	$(2,932,264,960)	$(7,560,722,432)
23	$5,634,218,240	$(3,499,624,448)	$(8,177,166,336)
24	$5,196,881,152	$(4,034,149,888)	$(8,761,577,984)
25	$4,776,636,672	$(4,553,199,104)	$(9,331,335,680)
26	$4,310,472,192	$(5,119,808,512)	$(9,949,496,320)
27	$3,851,085,824	$(5,681,418,240)	$(10,563,567,616)
28	$3,425,333,760	$(6,211,140,096)	$(11,146,652,160)
29	$3,018,314,240	$(6,723,917,824)	$(11,713,708,032)
30	$2,580,062,464	$(7,269,766,144)	$(12,314,778,624)
31	$2,153,111,552	$(7,806,203,392)	$(12,907,408,896)
32	$1,757,511,680	$(8,313,217,024)	$(13,471,608,832)
33	$1,380,843,008	$(8,803,383,296)	$(14,020,030,464)
34	$984,734,976	$(9,315,043,328)	$(14,591,001,600)
35	$602,214,656	$(9,815,226,112)	$(15,151,578,880)
36	$247,586,560	$(10,289,674,496)	$(15,687,533,824)
37	$(89,215,744)	$(10,748,619,264)	$(16,209,181,184)
38	$(436,795,904)	$(11,220,640,256)	$(16,745,081,344)
39	$(770,465,536)	$(11,681,111,808)	$(17,270,648,576)
40	$(1,080,531,200)	$(12,120,414,464)	$(17,776,296,192)
41	$(1,374,888,448)	$(12,546,495,488)	$(18,270,002,176)
42	$(1,674,357,760)	$(12,980,365,824)	$(18,772,873,728)
43	$(1,961,091,328)	$(13,404,152,064)	$(19,267,023,104)
44	$(2,228,903,296)	$(13,811,750,784)	$(19,746,395,008)
45	$(2,483,865,344)	$(14,209,300,224)	$(20,217,155,328)
46	$(2,740,584,320)	$(14,611,609,472)	$(20,694,217,600)
47	$(2,986,838,784)	$(15,006,447,360)	$(21,165,347,584)
48	$(3,218,845,184)	$(15,390,117,376)	$(21,626,896,896)
49	$(3,441,165,312)	$(15,767,269,376)	$(22,083,553,280)
50	$(3,663,784,832)	$(16,148,102,016)	$(22,545,632,128)

Time (Year)	Present Worth Cost			
	Major Investment without RA with SP	Moderate Investment without RA with SP	Minor Investment without RA with SP	No Investment without RA with SP
0	$157,977,984	$11,123,624	$1,485,557	$246,389
1	$180,363,632	$12,534,632	$1,648,856	$1,648,856
2	$40,821,128	$3,825,293	$655,572	$655,572
3	$208,154,864	$14,295,885	$1,854,308	$333,593
4	$130,550,736	$9,458,029	$1,303,536	$1,287,662
5	$136,026,384	$9,812,833	$1,346,241	$1,319,173
6	$168,677,664	$11,866,291	$1,583,108	$1,532,624
7	$215,031,888	$14,776,366	$1,917,906	$329,425
8	$233,205,760	$15,925,353	$2,051,468	$1,915,726
9	$131,426,008	$9,577,427	$1,328,272	$1,216,062
10	$154,804,064	$11,052,059	$1,499,116	$1,340,399
11	$109,851,032	$8,256,197	$1,181,938	$136,088
12	$306,153,248	$20,538,988	$2,588,069	$2,182,455
13	$306,892,352	$20,599,294	$2,597,381	$2,123,677
14	$67,034,080	$5,622,479	$888,200	$701,561
15	$249,758,336	$17,057,290	$2,197,529	$307,664
16	$178,061,776	$12,591,020	$1,689,630	$1,232,330
17	$237,099,744	$16,295,890	$2,115,614	$1,480,576
18	$225,938,096	$15,613,517	$2,040,239	$1,365,344
19	$213,470,112	$14,849,737	$1,955,602	$215,642
20	$146,061,792	$10,652,434	$1,478,605	$895,774
21	$223,051,440	$15,480,256	$2,033,094	$1,170,404
22	$269,582,240	$18,404,660	$2,370,093	$1,292,333
23	$167,900,368	$12,066,036	$1,648,506	$131,232
24	$79,700,968	$6,570,340	$1,023,301	$495,903
25	$247,874,256	$17,098,214	$2,229,409	$1,017,359
26	$87,693,088	$7,104,225	$1,090,210	$467,056
27	$284,682,528	$19,433,690	$2,502,313	$185,043
28	$207,542,512	$14,630,367	$1,956,435	$732,069
29	$256,969,648	$17,737,802	$2,314,697	$808,473
30	$392,101,472	$26,202,098	$3,285,227	$1,067,889
31	$197,984,992	$14,088,702	$1,904,076	$91,861
32	$336,611,296	$22,772,066	$2,899,755	$809,187
33	$228,367,984	$16,026,424	$2,132,179	$550,566
34	$115,107,544	$8,967,566	$1,328,867	$316,587
35	$355,432,416	$24,008,156	$3,051,269	$127,874
36	$30,474,946	$3,718,975	$736,047	$147,975
37	$174,304,624	$12,729,374	$1,769,415	$326,322
38	$347,432,736	$23,571,324	$3,012,171	$508,138
39	$348,736,864	$23,674,684	$3,027,730	$87,562
40	$229,286,192	$16,231,292	$2,180,874	$305,212
41	$376,361,280	$25,446,190	$3,237,898	$412,123
42	$135,590,176	$10,421,146	$1,524,718	$176,006
43	$413,471,360	$27,812,328	$3,516,329	$71,206
44	$151,785,712	$11,481,055	$1,654,026	$155,742
45	$476,340,544	$31,790,300	$3,979,294	$337,873
46	$160,737,216	$12,090,157	$1,732,146	$132,259
47	$151,407,072	$11,532,606	$1,672,812	$14,465
48	$69,819,792	$6,459,515	$1,097,506	$67,220
49	$429,465,184	$28,964,016	$3,674,020	$201,204
50	$406,524,992	$27,557,480	$3,517,941	$171,802

Appendix G – TNPW and BCR Based on Cumulative Benefits and Cost of Investments without Risk-Averse Decision Making but with Social Pressure

Time (Year)	TNPW Based on Cumulative Benefit and Cost			Investment Level Selection
	Major Investment without RA with SP	Moderate Investment without RA with SP	Minor Investment without RA with SP	
0	$11,570,604,928	$1,585,964,120	$384,282,891	Major
1	$22,699,548,560	$3,534,330,096	$493,112,371	Major
2	$34,013,264,136	$6,169,656,931	$518,130,527	Major
3	$45,187,999,000	$9,269,430,038	$439,568,380	Major
4	$56,329,180,488	$12,505,257,385	$121,645,068	Major
5	$67,316,395,960	$15,687,912,008	$(471,302,838)	Major
6	$78,144,043,672	$18,751,100,309	$(1,316,136,634)	Major
7	$88,790,924,360	$21,640,816,999	$(2,419,415,691)	Major
8	$99,161,447,496	$24,212,020,478	$(3,904,361,495)	Major
9	$109,344,826,480	$26,429,952,299	$(5,801,085,095)	Major
10	$119,239,654,160	$28,304,590,096	$(8,087,410,835)	Major
11	$128,913,930,872	$29,836,431,948	$(10,764,339,589)	Major
12	$138,020,549,208	$30,902,346,720	$(13,940,778,794)	Major
13	$146,734,459,928	$31,492,258,274	$(17,637,478,702)	Major
14	$155,324,400,696	$31,647,864,595	$(21,826,285,238)	Major
15	$163,374,373,816	$31,347,938,569	$(26,505,467,599)	Major
16	$171,053,557,736	$30,521,749,853	$(31,760,386,797)	Major
17	$178,221,489,160	$29,149,997,451	$(37,603,727,115)	Major
18	$184,980,568,920	$27,267,857,214	$(44,004,875,450)	Major
19	$191,344,818,616	$24,886,590,581	$(50,953,393,101)	Major
20	$197,304,715,736	$21,943,673,187	$(58,515,594,138)	Major
21	$202,715,882,536	$18,428,568,483	$(66,694,793,567)	Major
22	$207,643,181,448	$14,376,013,935	$(75,458,741,644)	Major
23	$212,251,917,752	$9,810,748,795	$(84,791,725,831)	Major
24	$216,482,688,976	$4,684,369,943	$(94,742,245,452)	Major
25	$220,085,900,544	$(1,014,146,511)	$(105,308,042,476)	Major
26	$223,423,541,216	$(7,232,390,831)	$(116,455,784,846)	Major
27	$226,157,172,928	$(13,975,742,345)	$(128,171,995,191)	Major
28	$228,529,692,880	$(21,260,138,856)	$(140,488,730,250)	Major
29	$230,425,834,784	$(29,084,080,050)	$(153,398,453,844)	Major
30	$231,791,244,992	$(37,423,499,172)	$(166,873,347,902)	Major
31	$232,974,103,008	$(46,240,971,170)	$(180,895,282,442)	Major
32	$233,622,226,688	$(55,578,786,564)	$(195,489,183,797)	Major
33	$233,996,073,360	$(65,410,039,100)	$(210,642,894,856)	Major
34	$234,128,552,376	$(75,708,681,162)	$(226,331,757,546)	Major
35	$233,683,904,216	$(86,481,308,582)	$(242,543,989,999)	Major
36	$233,216,633,366	$(97,705,667,813)	$(259,289,807,390)	Major
37	$232,271,863,206	$(109,399,508,995)	$(276,562,225,381)	Major
38	$230,843,899,270	$(121,543,494,783)	$(294,341,533,743)	Major
39	$229,120,273,958	$(134,113,664,955)	$(312,614,563,649)	Major
40	$227,216,630,006	$(147,110,262,071)	$(331,389,618,251)	Major
41	$224,879,177,398	$(160,539,860,325)	$(350,659,879,253)	Major
42	$222,514,683,926	$(174,362,032,255)	$(370,407,798,979)	Major
43	$219,617,347,222	$(188,599,144,807)	$(390,628,470,636)	Major
44	$216,724,977,190	$(203,222,235,334)	$(411,324,342,262)	Major
45	$213,261,797,862	$(218,260,472,994)	$(432,493,669,140)	Major
46	$209,882,215,462	$(233,662,680,527)	$(454,122,298,182)	Major
47	$206,289,643,078	$(249,441,482,509)	$(476,207,524,273)	Major
48	$202,556,038,454	$(265,596,044,040)	$(498,754,253,908)	Major

Time (Year)	BCR Based on Cumulative Benefit and Cost			Investment Level Selection
	Major Investment without RA with SP	Moderate Investment without RA with SP	Minor Investment without RA with SP	
0	74.2	143.6	259.7	Minor
1	68.1	150.4	158.3	Minor
2	90.7	225.5	137.7	Moderate
3	77.9	222.9	78.9	Moderate
4	79.5	245.1	18.5	Moderate
5	79.8	258.0	-55.8	Moderate
6	77.4	258.2	-132.3	Moderate
7	72.7	247.8	-204.1	Moderate
8	68.4	234.7	-281.0	Moderate
9	69.2	234.5	-381.3	Moderate
10	68.9	228.8	-484.0	Moderate
11	70.1	226.2	-601.8	Moderate
12	64.5	202.9	-680.9	Moderate
13	60.2	182.4	-764.5	Moderate
14	62.0	177.5	-911.1	Moderate
15	59.4	160.7	-1013.5	Moderate
16	58.5	147.1	-1140.8	Moderate
17	56.5	130.4	-1255.3	Moderate
18	54.8	114.2	-1375.3	Moderate
19	53.4	98.3	-1500.8	Moderate
20	53.0	83.4	-1651.7	Moderate
21	51.4	66.4	-1780.4	Moderate
22	49.4	48.9	-1894.5	Major
23	48.6	32.4	-2044.2	Major
24	48.7	15.7	-2229.2	Major
25	47.0	-2.0	-2354.3	Major
26	46.8	-20.1	-2541.6	Major
27	44.8	-37.6	-2652.5	Major
28	43.6	-55.4	-2794.2	Major
29	42.0	-72.7	-2916.7	Major
30	39.5	-87.9	-2986.3	Major
31	38.5	-105.3	-3130.6	Major
32	36.7	-120.4	-3221.5	Major
33	35.5	-137.0	-3353.4	Major
34	35.0	-155.8	-3528.5	Major
35	33.2	-169.6	-3609.6	Major
36	33.0	-190.3	-3817.0	Major
37	32.2	-208.0	-3967.9	Major
38	30.6	-221.2	-4048.1	Major
39	29.1	-234.0	-4127.5	Major
40	28.1	-249.7	-4252.9	Major
41	26.7	-261.2	-4320.6	Major
42	26.0	-279.0	-4479.8	Major
43	24.6	-288.9	-4531.6	Major
44	23.9	-306.0	-4681.9	Major
45	22.5	-313.6	-4709.5	Major
46	21.8	-330.0	-4853.5	Major
47	21.1	-346.7	-5000.1	Major
48	20.6	-365.9	-5177.3	Major

Appendix H – Present Worth Risk, Benefit and Cost of Investments with Risk-Averse Decision Making but without Social Pressure

Time (Year)	Present Worth Risk			
	Major Investment with RA without SP	Moderate Investment with RA without SP	Minor Investment with RA without SP	No Investment with RA without SP
0	$12,435,153,920	$12,435,153,920	$12,435,153,920	$12,435,153,920
1	$12,568,590,336	$12,668,358,656	$12,830,967,808	$12,980,767,744
2	$1,864,920,832	$11,896,647,680	$12,945,357,824	$13,238,302,720
3	$1,898,909,312	$11,247,315,968	$13,097,738,240	$13,337,103,360
4	$1,933,596,928	$10,648,981,504	$13,132,152,832	$13,314,571,264
5	$1,969,025,792	$10,237,846,528	$12,523,642,880	$13,251,200,000
6	$2,005,191,680	$10,031,638,528	$12,569,835,520	$13,153,148,928
7	$2,042,115,200	$9,972,889,600	$13,108,971,520	$13,056,141,312
8	$2,079,816,704	$10,001,087,488	$13,154,006,016	$12,965,226,496
9	$2,118,316,544	$10,075,736,064	$12,402,819,072	$12,949,987,328
10	$2,157,634,560	$10,174,234,624	$12,782,343,168	$12,961,474,560
11	$2,197,790,976	$10,285,086,720	$13,546,416,128	$12,872,865,792
12	$2,238,806,528	$10,402,748,416	$13,636,450,304	$12,716,036,096
13	$2,280,727,296	$10,524,756,992	$12,877,097,984	$12,505,768,960
14	$2,323,558,656	$10,649,876,480	$13,345,623,040	$12,249,901,056
15	$2,367,321,088	$10,777,613,312	$13,538,471,936	$11,954,165,760
16	$2,412,043,264	$10,907,789,312	$12,742,096,896	$11,623,529,472
17	$2,457,752,064	$11,040,352,256	$13,524,921,344	$11,262,639,104
18	$2,504,470,016	$11,175,313,408	$13,801,303,040	$10,876,002,304
19	$2,552,228,096	$11,312,715,776	$13,038,235,648	$10,468,024,320
20	$2,601,049,600	$11,452,594,176	$12,666,742,784	$10,042,995,712
21	$2,650,996,224	$11,595,132,928	$13,855,608,832	$9,605,066,752
22	$2,702,071,296	$11,740,295,168	$14,232,488,960	$9,158,200,320
23	$2,754,309,888	$11,888,152,576	$13,508,411,392	$8,706,031,616
24	$2,807,740,672	$12,038,771,712	$13,194,421,248	$8,251,741,696
25	$2,862,403,840	$12,192,239,616	$12,907,155,456	$7,798,215,680
26	$2,918,323,712	$12,348,604,416	$14,524,325,888	$7,348,148,736
27	$2,975,576,064	$12,508,080,128	$14,997,352,448	$6,904,034,304
28	$3,034,170,368	$12,670,644,224	$14,287,655,936	$6,468,140,544
29	$3,094,140,416	$12,836,372,480	$14,004,889,600	$6,042,502,144
30	$3,155,532,544	$13,005,361,152	$13,733,103,616	$5,628,915,712
31	$3,218,387,456	$11,280,494,592	$13,581,680,640	$5,228,929,024
32	$3,282,747,392	$7,606,870,016	$13,561,432,064	$4,843,848,192
33	$3,348,693,504	$11,226,310,656	$13,634,840,576	$4,474,742,272
34	$3,416,243,968	$12,837,768,192	$13,764,355,072	$4,122,448,640
35	$3,485,446,144	$13,558,956,032	$13,925,283,840	$3,787,583,744
36	$3,556,346,880	$11,856,076,800	$14,103,812,096	$3,470,559,744
37	$3,629,037,824	$8,240,394,240	$14,293,032,960	$3,171,595,776
38	$3,703,541,760	$12,066,800,640	$14,489,427,968	$2,890,731,776
39	$3,779,915,776	$13,768,480,768	$14,691,464,192	$2,627,846,656
40	$3,858,221,056	$12,186,843,136	$14,898,497,536	$2,382,676,992
41	$3,938,510,336	$8,824,357,888	$15,110,289,408	$2,154,838,528
42	$4,020,896,256	$12,822,648,832	$15,326,976,000	$1,943,835,392
43	$4,105,404,416	$14,594,101,248	$15,548,494,848	$1,749,084,288
44	$4,192,111,104	$12,938,567,680	$15,774,969,856	$1,569,928,960
45	$4,281,075,712	$9,407,930,368	$16,006,516,736	$1,405,654,528
46	$4,372,423,680	$13,613,267,968	$16,243,449,856	$1,255,531,392
47	$4,466,196,480	$12,501,426,176	$16,485,804,032	$1,118,820,224
48	$4,562,471,936	$10,023,151,616	$16,733,743,104	$994,739,328
49	$4,661,332,992	$14,344,607,744	$16,987,435,008	$882,484,864
50	$4,762,918,912	$13,165,500,416	$17,247,236,096	$781,242,304

Time (Year)	Present Worth Benefit		
	Major Investment with RA without SP	Moderate Investment with RA without SP	Minor Investment with RA without SP
0	$-	$-	$-
1	$412,177,408	$312,409,088	$149,799,936
2	$11,373,381,888	$1,341,655,040	$292,944,896
3	$11,438,194,048	$2,089,787,392	$239,365,120
4	$11,380,974,336	$2,665,589,760	$182,418,432
5	$11,282,174,208	$3,013,353,472	$727,557,120
6	$11,147,957,248	$3,121,510,400	$583,313,408
7	$11,014,026,112	$3,083,251,712	$(52,830,208)
8	$10,885,409,792	$2,964,139,008	$(188,779,520)
9	$10,831,670,784	$2,874,251,264	$547,168,256
10	$10,803,840,000	$2,787,239,936	$179,131,392
11	$10,675,074,816	$2,587,779,072	$(673,550,336)
12	$10,477,229,568	$2,313,287,680	$(920,414,208)
13	$10,225,041,664	$1,981,011,968	$(371,329,024)
14	$9,926,342,400	$1,600,024,576	$(1,095,721,984)
15	$9,586,844,672	$1,176,552,448	$(1,584,306,176)
16	$9,211,486,208	$715,740,160	$(1,118,567,424)
17	$8,804,887,040	$222,286,848	$(2,262,282,240)
18	$8,371,532,288	$(299,311,104)	$(2,925,300,736)
19	$7,915,796,224	$(844,691,456)	$(2,570,211,328)
20	$7,441,946,112	$(1,409,598,464)	$(2,623,747,072)
21	$6,954,070,528	$(1,990,066,176)	$(4,250,542,080)
22	$6,456,129,024	$(2,582,094,848)	$(5,074,288,640)
23	$5,951,721,728	$(3,182,120,960)	$(4,802,379,776)
24	$5,444,001,024	$(3,787,030,016)	$(4,942,679,552)
25	$4,935,811,840	$(4,394,023,936)	$(5,108,939,776)
26	$4,429,825,024	$(5,000,455,680)	$(7,176,177,152)
27	$3,928,458,240	$(5,604,045,824)	$(8,093,318,144)
28	$3,433,970,176	$(6,202,503,680)	$(7,819,515,392)
29	$2,948,361,728	$(6,793,870,336)	$(7,962,387,456)
30	$2,473,383,168	$(7,376,445,440)	$(8,104,187,904)
31	$2,010,541,568	$(6,051,565,568)	$(8,352,751,616)
32	$1,561,100,800	$(2,763,021,824)	$(8,717,583,872)
33	$1,126,048,768	$(6,751,568,384)	$(9,160,098,304)
34	$706,204,672	$(8,715,319,552)	$(9,641,906,432)
35	$302,137,600	$(9,771,372,288)	$(10,137,700,096)
36	$(85,787,136)	$(8,385,517,056)	$(10,633,252,352)
37	$(457,442,048)	$(5,068,798,464)	$(11,121,437,184)
38	$(812,809,984)	$(9,176,068,864)	$(11,598,696,192)
39	$(1,152,069,120)	$(11,140,634,112)	$(12,063,617,536)
40	$(1,475,544,064)	$(9,804,166,144)	$(12,515,820,544)
41	$(1,783,671,808)	$(6,669,519,360)	$(12,955,450,880)
42	$(2,077,060,864)	$(10,878,813,440)	$(13,383,140,608)
43	$(2,356,320,128)	$(12,845,016,960)	$(13,799,410,560)
44	$(2,622,182,144)	$(11,368,638,720)	$(14,205,040,896)
45	$(2,875,421,184)	$(8,002,275,840)	$(14,600,862,208)
46	$(3,116,892,288)	$(12,357,736,576)	$(14,987,918,464)
47	$(3,347,376,256)	$(11,382,605,952)	$(15,366,983,808)
48	$(3,567,732,608)	$(9,028,412,288)	$(15,739,003,776)
49	$(3,778,848,128)	$(13,462,122,880)	$(16,104,950,144)
50	$(3,981,676,608)	$(12,384,258,112)	$(16,465,993,792)

Time (Year)	Present Worth Cost			
	Major Investment with RA without SP	Moderate Investment with RA without SP	Minor Investment with RA without SP	No Investment with RA without SP
0	$157,977,984	$11,123,624	$1,485,557	$246,389
1	$180,363,632	$12,534,632	$1,648,856	$286,024
2	$40,821,128	$3,825,293	$655,572	$655,572
3	$208,154,864	$14,295,885	$14,295,885	$1,846,762
4	$130,550,736	$9,458,029	$9,458,029	$1,287,662
5	$136,026,384	$9,812,833	$1,346,241	$1,313,709
6	$168,677,664	$11,866,291	$1,583,108	$1,520,057
7	$215,031,888	$14,776,366	$14,776,366	$1,812,250
8	$233,205,760	$15,925,353	$15,925,353	$351,431
9	$131,426,008	$9,577,427	$1,328,272	$179,205
10	$154,804,064	$11,052,059	$1,499,116	$213,721
11	$109,851,032	$8,256,197	$8,256,197	$138,289
12	$306,153,248	$20,538,988	$20,538,988	$437,488
13	$306,892,352	$20,599,294	$2,597,381	$426,552
14	$67,034,080	$5,622,479	$5,622,479	$64,192
15	$249,758,336	$17,057,290	$17,057,290	$318,599
16	$178,061,776	$12,591,020	$1,689,630	$209,341
17	$237,099,744	$16,295,890	$16,295,890	$277,162
18	$225,938,096	$15,613,517	$15,613,517	$250,812
19	$213,470,112	$14,849,737	$14,849,737	$223,936
20	$146,061,792	$10,652,434	$1,478,605	$136,673
21	$223,051,440	$15,480,256	$15,480,256	$210,966
22	$269,582,240	$18,404,660	$18,404,660	$245,509
23	$167,900,368	$12,066,036	$12,066,036	$134,741
24	$79,700,968	$6,570,340	$6,570,340	$48,054
25	$247,874,256	$17,098,214	$2,229,409	$183,945
26	$87,693,088	$7,104,225	$7,104,225	$47,641
27	$284,682,528	$19,433,690	$19,433,690	$185,431
28	$207,542,512	$14,630,367	$14,630,367	$120,372
29	$256,969,648	$17,737,802	$17,737,802	$141,436
30	$392,101,472	$392,101,472	$26,202,098	$206,682
31	$197,984,992	$14,088,702	$14,088,702	$88,738
32	$336,611,296	$22,772,066	$22,772,066	$147,231
33	$228,367,984	$16,026,424	$16,026,424	$87,229
34	$115,107,544	$8,967,566	$8,967,566	$34,407
35	$355,432,416	$355,432,416	$24,008,156	$117,742
36	$30,474,946	$3,718,975	$3,718,975	$472
37	$174,304,624	$12,729,374	$12,729,374	$42,744
38	$347,432,736	$23,571,324	$23,571,324	$84,415
39	$348,736,864	$348,736,864	$23,674,684	$76,073
40	$229,286,192	$16,231,292	$16,231,292	$42,539
41	$376,361,280	$25,446,190	$25,446,190	$66,061
42	$135,590,176	$10,421,146	$10,421,146	$17,795
43	$413,471,360	$413,471,360	$27,812,328	$57,852
44	$151,785,712	$11,481,055	$11,481,055	$16,099
45	$476,340,544	$31,790,300	$31,790,300	$52,741
46	$160,737,216	$160,737,216	$12,090,157	$13,415
47	$151,407,072	$11,532,606	$11,532,606	$10,907
48	$69,819,792	$6,459,515	$6,459,515	$2,937
49	$429,465,184	$429,465,184	$28,964,016	$28,037
50	$406,524,992	$406,524,992	$27,557,480	$23,052

Appendix I – TNPW and BCR Based on Cumulative Benefits and Cost of Policies

Investments Risk-Averse Decision Making but without Social Pressure

Time (Year)	TNPW Based on Cumulative Benefit and Cost			Investment Level Selection
	Major Investment with RA without SP	Moderate Investment with RA without SP	Minor Investment with RA without SP	
0	$11,627,581,312	$1,642,940,504	$441,259,275	Major
1	$22,885,411,728	$3,720,193,264	$678,975,539	Major
2	$34,225,564,936	$6,381,957,731	$860,738,399	Major
3	$45,299,584,280	$9,381,015,318	$1,573,999,634	Major
4	$56,316,990,792	$12,493,067,689	$2,147,855,013	Major
5	$67,194,990,520	$15,566,506,568	$2,093,678,564	Major
6	$77,911,722,648	$18,518,779,285	$1,903,315,936	Major
7	$88,528,361,544	$21,378,254,183	$2,435,707,826	Major
8	$99,098,995,784	$24,149,568,766	$2,598,913,865	Major
9	$109,642,644,592	$26,727,770,411	$1,924,035,257	Major
10	$119,965,070,096	$29,030,006,032	$1,002,121,933	Major
11	$130,080,260,728	$31,002,761,804	$622,536,713	Major
12	$139,700,449,880	$32,582,247,392	$(493,724,259)	Major
13	$148,980,402,200	$33,738,200,546	$(2,080,627,816)	Major
14	$158,124,854,328	$34,448,318,227	$(3,204,817,719)	Major
15	$166,679,983,032	$34,653,547,785	$(5,484,157,249)	Major
16	$174,873,453,544	$34,341,645,661	$(8,411,147,614)	Major
17	$182,552,150,024	$33,480,658,315	$(10,997,654,832)	Major
18	$189,768,158,040	$32,055,446,334	$(13,637,015,421)	Major
19	$196,508,758,456	$30,050,530,421	$(17,902,407,238)	Major
20	$202,818,825,688	$27,457,783,139	$(22,978,174,483)	Major
21	$208,547,495,976	$24,260,181,923	$(27,796,034,515)	Major
22	$213,721,914,760	$20,454,747,247	$(32,757,118,727)	Major
23	$218,489,826,232	$16,048,657,275	$(37,878,124,539)	Major
24	$222,839,950,288	$11,041,631,255	$(45,060,872,031)	Major
25	$226,520,534,272	$5,420,487,217	$(53,156,419,584)	Major
26	$229,866,811,360	$(789,120,687)	$(60,983,039,200)	Major
27	$232,530,490,560	$(7,602,424,713)	$(68,964,860,346)	Major
28	$234,796,331,216	$(14,993,500,520)	$(77,083,678,617)	Major
29	$236,549,903,136	$(21,062,803,890)	$(85,454,168,035)	Major
30	$237,718,902,464	$(24,217,927,186)	$(94,197,954,005)	Major
31	$238,646,966,240	$(30,983,584,272)	$(103,372,141,011)	Major
32	$239,016,559,616	$(39,721,675,890)	$(113,036,819,509)	Major
33	$239,090,329,232	$(49,509,074,602)	$(123,190,546,029)	Major
34	$238,889,434,552	$(57,903,559,224)	$(133,832,765,947)	Major
35	$238,076,560,088	$(63,327,790,104)	$(144,978,211,287)	Major
36	$237,233,275,158	$(72,507,577,943)	$(156,580,626,454)	Major
37	$235,906,901,414	$(83,660,941,429)	$(168,656,973,364)	Major
38	$234,083,924,614	$(93,488,678,897)	$(181,196,365,232)	Major
39	$231,951,515,942	$(100,506,935,121)	$(194,175,490,796)	Major
40	$229,645,168,886	$(111,401,979,853)	$(207,574,862,696)	Major
41	$226,912,487,478	$(124,272,443,003)	$(221,399,719,446)	Major
42	$224,154,715,158	$(135,651,502,869)	$(235,615,181,488)	Major
43	$220,865,822,614	$(144,067,250,069)	$(250,243,856,024)	Major
44	$217,597,144,614	$(156,436,467,700)	$(265,243,255,543)	Major
45	$213,773,427,814	$(167,850,863,952)	$(280,642,029,651)	Major
46	$210,044,957,990	$(177,040,013,456)	$(296,393,123,584)	Major
47	$206,114,702,790	$(190,513,668,942)	$(312,509,606,334)	Major
48	$202,063,206,390	$(202,904,386,569)	$(328,982,059,640)	Major

Time (Year)	BCR Based on Cumulative Benefit and Cost			Investment Level Selection
	Major Investment with RA without SP	Moderate Investment with RA without SP	Minor Investment with RA without SP	
0	74.6	148.7	298.0	Minor
1	68.6	158.2	217.6	Minor
2	91.3	233.2	228.1	Moderate
3	78.1	225.5	88.0	Moderate
4	79.5	244.8	79.0	Moderate
5	79.7	256.0	73.5	Moderate
6	77.2	255.0	63.5	Moderate
7	72.5	244.8	54.8	Moderate
8	68.4	234.1	43.5	Moderate
9	69.4	237.1	31.8	Moderate
10	69.3	234.6	16.7	Moderate
11	70.7	235.0	9.6	Moderate
12	65.3	213.9	-4.3	Moderate
13	61.1	195.3	-20.8	Moderate
14	63.1	193.2	-30.7	Moderate
15	60.6	177.5	-45.4	Moderate
16	59.8	165.4	-69.2	Moderate
17	57.8	149.7	-79.8	Moderate
18	56.2	134.1	-88.9	Moderate
19	54.8	118.5	-106.5	Moderate
20	54.4	104.1	-135.8	Moderate
21	52.9	87.1	-150.5	Moderate
22	50.8	69.1	-161.3	Moderate
23	50.0	52.4	-176.0	Moderate
24	50.1	35.6	-203.3	Major
25	48.3	17.1	-237.6	Major
26	48.2	-1.3	-264.3	Major
27	46.1	-20.0	-275.6	Major
28	44.8	-38.8	-291.1	Major
29	43.1	-52.3	-302.4	Major
30	40.5	-29.8	-305.0	Major
31	39.4	-37.7	-320.1	Major
32	37.5	-47.2	-326.9	Major
33	36.3	-58.0	-340.5	Major
34	35.7	-67.2	-361.0	Major
35	33.8	-51.6	-367.2	Major
36	33.6	-59.0	-393.0	Major
37	32.7	-67.5	-410.2	Major
38	31.0	-74.1	-416.8	Major
39	29.5	-62.1	-423.5	Major
40	28.4	-68.2	-437.2	Major
41	26.9	-75.0	-442.6	Major
42	26.2	-81.5	-461.4	Major
43	24.7	-69.0	-464.7	Major
44	24.0	-74.6	-482.3	Major
45	22.5	-78.9	-482.4	Major
46	21.8	-77.2	-499.1	Major
47	21.1	-82.8	-516.2	Major
48	20.6	-88.0	-537.7	Major

Appendix J – Present Worth Risk, Benefit and Cost of Investments with Risk-Averse Decision Making and Social Pressure

Time (Year)	Present Worth Risk			
	Major Investment with RA and SP	Moderate Investment with RA and SP	Minor Investment with RA and SP	No Investment with RA and SP
0	$12,435,153,920	$12,435,153,920	$12,435,153,920	$12,435,153,920
1	$12,568,590,336	$12,668,358,656	$12,830,967,808	$12,980,767,744
2	$1,864,920,832	$11,896,647,680	$12,945,357,824	$13,181,326,336
3	$1,898,909,312	$11,247,315,968	$13,097,738,240	$13,158,607,872
4	$1,933,596,928	$10,648,981,504	$13,132,152,832	$12,789,192,704
5	$1,969,025,792	$10,237,846,528	$12,523,642,880	$13,124,833,280
6	$2,005,191,680	$10,031,638,528	$12,569,835,520	$13,190,258,688
7	$2,042,115,200	$9,972,889,600	$13,108,971,520	$12,680,916,992
8	$2,079,816,704	$10,001,087,488	$13,154,006,016	$13,063,204,864
9	$2,118,316,544	$10,075,736,064	$12,402,819,072	$13,207,767,040
10	$2,157,634,560	$10,174,234,624	$12,782,343,168	$13,184,290,816
11	$2,197,790,976	$10,285,086,720	$13,546,416,128	$13,181,518,848
12	$2,238,806,528	$10,402,748,416	$13,636,450,304	$13,176,639,488
13	$2,280,727,296	$10,524,756,992	$12,877,097,984	$13,171,537,920
14	$2,323,558,656	$10,649,876,480	$13,345,623,040	$13,168,592,896
15	$2,367,321,088	$10,777,613,312	$13,538,471,936	$13,168,769,024
16	$2,412,043,264	$10,907,789,312	$12,742,096,896	$13,172,353,024
17	$2,457,752,064	$11,040,352,256	$13,524,921,344	$13,179,319,296
18	$2,504,470,016	$11,175,313,408	$13,801,303,040	$13,189,523,456
19	$2,552,228,096	$11,312,715,776	$13,038,235,648	$13,202,788,352
20	$2,601,049,600	$11,452,594,176	$12,666,742,784	$13,218,800,640
21	$2,650,996,224	$11,595,132,928	$13,855,608,832	$13,237,529,600
22	$2,702,071,296	$11,740,295,168	$14,232,488,960	$13,258,854,400
23	$2,754,309,888	$11,888,152,576	$13,508,411,392	$13,282,693,120
24	$2,807,740,672	$12,038,771,712	$13,194,421,248	$13,308,985,344
25	$2,862,403,840	$12,192,239,616	$12,907,155,456	$13,337,688,064
26	$2,918,323,712	$12,348,604,416	$14,524,325,888	$13,368,772,608
27	$2,975,576,064	$12,508,080,128	$14,997,352,448	$13,402,220,544
28	$3,034,170,368	$12,670,644,224	$14,287,655,936	$13,438,025,728
29	$3,094,140,416	$12,836,372,480	$14,004,889,600	$13,476,186,112
30	$3,155,532,544	$13,005,361,152	$13,733,103,616	$13,516,697,600
31	$3,218,387,456	$11,280,494,592	$13,581,680,640	$13,559,582,720
32	$3,282,747,392	$7,606,870,016	$13,561,432,064	$13,604,838,400
33	$3,348,693,504	$11,226,310,656	$13,634,840,576	$13,652,486,144
34	$3,416,243,968	$12,837,768,192	$13,764,355,072	$13,702,534,144
35	$3,485,446,144	$13,558,956,032	$13,925,283,840	$13,755,000,832
36	$3,556,346,880	$11,856,076,800	$14,103,812,096	$13,809,892,352
37	$3,629,037,824	$8,240,394,240	$14,293,032,960	$13,867,227,136
38	$3,703,541,760	$12,066,800,640	$14,489,427,968	$13,927,020,544
39	$3,779,915,776	$13,768,480,768	$14,691,464,192	$13,989,300,224
40	$3,858,221,056	$12,186,843,136	$14,898,497,536	$14,054,081,536
41	$3,938,510,336	$8,824,357,888	$15,110,289,408	$14,121,393,152
42	$4,020,896,256	$12,822,648,832	$15,326,976,000	$14,191,254,528
43	$4,105,404,416	$14,594,101,248	$15,548,494,848	$14,263,683,072
44	$4,192,111,104	$12,938,567,680	$15,774,969,856	$14,338,705,408
45	$4,281,075,712	$9,407,930,368	$16,006,516,736	$14,416,353,280
46	$4,372,423,680	$13,613,267,968	$16,243,449,856	$14,496,650,240
47	$4,466,196,480	$12,501,426,176	$16,485,804,032	$14,579,630,080
48	$4,562,471,936	$10,023,151,616	$16,733,743,104	$14,665,318,400
49	$4,661,332,992	$14,344,607,744	$16,987,435,008	$14,753,776,640
50	$4,762,918,912	$13,165,500,416	$17,247,236,096	$14,844,878,848

Time (Year)	Present Worth Benefit		
	Major Investment with RA and SP	Moderate Investment with RA and SP	Minor Investment with RA and SP
0	$-	$-	$-
1	$412,177,408	$312,409,088	$149,799,936
2	$11,316,405,504	$1,284,678,656	$235,968,512
3	$11,259,698,560	$1,911,291,904	$60,869,632
4	$10,855,595,776	$2,140,211,200	$(342,960,128)
5	$11,155,807,488	$2,886,986,752	$601,190,400
6	$11,185,067,008	$3,158,620,160	$620,423,168
7	$10,638,801,792	$2,708,027,392	$(428,054,528)
8	$10,983,388,160	$3,062,117,376	$(90,801,152)
9	$11,089,450,496	$3,132,030,976	$804,947,968
10	$11,026,656,256	$3,010,056,192	$401,947,648
11	$10,983,727,872	$2,896,432,128	$(364,897,280)
12	$10,937,832,960	$2,773,891,072	$(459,810,816)
13	$10,890,810,624	$2,646,780,928	$294,439,936
14	$10,845,034,240	$2,518,716,416	$(177,030,144)
15	$10,801,447,936	$2,391,155,712	$(369,702,912)
16	$10,760,309,760	$2,264,563,712	$430,256,128
17	$10,721,567,232	$2,138,967,040	$(345,602,048)
18	$10,685,053,440	$2,014,210,048	$(611,779,584)
19	$10,650,560,256	$1,890,072,576	$164,552,704
20	$10,617,751,040	$1,766,206,464	$552,057,856
21	$10,586,533,376	$1,642,396,672	$(618,079,232)
22	$10,556,783,104	$1,518,559,232	$(973,634,560)
23	$10,528,383,232	$1,394,540,544	$(225,718,272)
24	$10,501,244,672	$1,270,213,632	$114,564,096
25	$10,475,284,224	$1,145,448,448	$430,532,608
26	$10,450,448,896	$1,020,168,192	$(1,155,553,280)
27	$10,426,644,480	$894,140,416	$(1,595,131,904)
28	$10,403,855,360	$767,381,504	$(849,630,208)
29	$10,382,045,696	$639,813,632	$(528,703,488)
30	$10,361,165,056	$511,336,448	$(216,406,016)
31	$10,341,195,264	$2,279,088,128	$(22,097,920)
32	$10,322,091,008	$5,997,968,384	$43,406,336
33	$10,303,792,640	$2,426,175,488	$17,645,568
34	$10,286,290,176	$864,765,952	$(61,820,928)
35	$10,269,554,688	$196,044,800	$(170,283,008)
36	$10,253,545,472	$1,953,815,552	$(293,919,744)
37	$10,238,189,312	$5,626,832,896	$(425,805,824)
38	$10,223,478,784	$1,860,219,904	$(562,407,424)
39	$10,209,384,448	$220,819,456	$(702,163,968)
40	$10,195,860,480	$1,867,238,400	$(844,416,000)
41	$10,182,882,816	$5,297,035,264	$(988,896,256)
42	$10,170,358,272	$1,368,605,696	$(1,135,721,472)
43	$10,158,278,656	$(330,418,176)	$(1,284,811,776)
44	$10,146,594,304	$1,400,137,728	$(1,436,264,448)
45	$10,135,277,568	$5,008,422,912	$(1,590,163,456)
46	$10,124,226,560	$883,382,272	$(1,746,799,616)
47	$10,113,433,600	$2,078,203,904	$(1,906,173,952)
48	$10,102,846,464	$4,642,166,784	$(2,068,424,704)
49	$10,092,443,648	$409,168,896	$(2,233,658,368)
50	$10,081,959,936	$1,679,378,432	$(2,402,357,248)

Time (Year)	Present Worth Cost			
	Major Investment with RA and SP	Moderate Investment with RA and SP	Minor Investment with RA and SP	No Investment with RA and SP
0	$157,977,984	$11,123,624	$1,485,557	$246,389
1	$180,363,632	$12,534,632	$1,648,856	$1,648,856
2	$40,821,128	$3,825,293	$655,572	$3,825,293
3	$208,154,864	$14,295,885	$14,295,885	$1,846,762
4	$130,550,736	$9,458,029	$9,458,029	$193,636
5	$136,026,384	$9,812,833	$1,346,241	$9,615,530
6	$168,677,664	$11,866,291	$1,583,108	$1,539,001
7	$215,031,888	$14,776,366	$14,776,366	$332,150
8	$233,205,760	$15,925,353	$15,925,353	$1,947,330
9	$131,426,008	$9,577,427	$1,328,272	$1,246,152
10	$154,804,064	$11,052,059	$1,499,116	$1,390,222
11	$109,851,032	$8,256,197	$8,256,197	$1,083,587
12	$306,153,248	$20,538,988	$20,538,988	$2,345,954
13	$306,892,352	$20,599,294	$2,597,381	$2,328,132
14	$67,034,080	$5,622,479	$5,622,479	$787,343
15	$249,758,336	$17,057,290	$17,057,290	$1,926,730
16	$178,061,776	$12,591,020	$1,689,630	$1,465,420
17	$237,099,744	$16,295,890	$16,295,890	$1,815,269
18	$225,938,096	$15,613,517	$15,613,517	$1,732,084
19	$213,470,112	$14,849,737	$14,849,737	$1,642,860
20	$146,061,792	$10,652,434	$1,478,605	$1,229,283
21	$223,051,440	$15,480,256	$15,480,256	$1,672,953
22	$269,582,240	$18,404,660	$18,404,660	$1,930,473
23	$167,900,368	$12,066,036	$12,066,036	$1,329,248
24	$79,700,968	$6,570,340	$6,570,340	$816,920
25	$247,874,256	$17,098,214	$2,229,409	$1,762,260
26	$87,693,088	$7,104,225	$7,104,225	$853,367
27	$284,682,528	$19,433,690	$19,433,690	$1,939,789
28	$207,542,512	$14,630,367	$14,630,367	$1,502,121
29	$256,969,648	$17,737,802	$17,737,802	$1,760,350
30	$392,101,472	$392,101,472	$26,202,098	$2,474,991
31	$197,984,992	$14,088,702	$14,088,702	$1,421,127
32	$336,611,296	$22,772,066	$22,772,066	$2,144,304
33	$228,367,984	$16,026,424	$16,026,424	$1,562,284
34	$115,107,544	$8,967,566	$8,967,566	$964,858
35	$355,432,416	$355,432,416	$24,008,156	$2,195,537
36	$30,474,946	$3,718,975	$3,718,975	$524,899
37	$174,304,624	$12,729,374	$12,729,374	$1,250,666
38	$347,432,736	$23,571,324	$23,571,324	$2,110,384
39	$348,736,864	$348,736,864	$23,674,684	$2,102,801
40	$229,286,192	$16,231,292	$16,231,292	$1,501,545
41	$376,361,280	$25,446,190	$25,446,190	$2,210,160
42	$135,590,176	$10,421,146	$10,421,146	$1,031,878
43	$413,471,360	$413,471,360	$27,812,328	$2,359,558
44	$151,785,712	$11,481,055	$11,481,055	$1,100,547
45	$476,340,544	$31,790,300	$31,790,300	$2,625,543
46	$160,737,216	$160,737,216	$12,090,157	$1,133,353
47	$151,407,072	$11,532,606	$11,532,606	$1,085,462
48	$69,819,792	$6,459,515	$6,459,515	$706,285
49	$429,465,184	$429,465,184	$28,964,016	$2,344,965
50	$406,524,992	$406,524,992	$27,557,480	$2,227,006

Appendix K – TNPW and BCR Based on Cumulative Benefits and Cost of Investments with Risk-Averse Decision Making and Social Pressure

Time (Year)	TNPW Based on Cumulative Benefit and Cost			Investment Level Selection
	Major Investment with RA and SP	Moderate Investment with RA and SP	Minor Investment with RA and SP	
0	$11,570,604,928	$1,585,964,120	$384,282,891	Major
1	$22,649,939,856	$3,484,721,392	$443,503,667	Major
2	$33,464,714,504	$5,621,107,299	$99,887,967	Major
3	$44,412,367,128	$8,493,798,166	$686,782,482	Major
4	$55,466,883,400	$11,642,960,297	$1,297,747,621	Major
5	$65,969,658,808	$14,341,174,856	$868,346,852	Major
6	$76,784,369,304	$17,391,425,941	$775,962,592	Major
7	$87,658,787,912	$20,508,680,551	$1,566,134,194	Major
8	$98,452,238,408	$23,502,811,390	$1,952,156,489	Major
9	$109,304,540,272	$26,389,666,091	$1,585,930,937	Major
10	$120,087,569,168	$29,152,505,104	$1,124,621,005	Major
11	$130,868,528,760	$31,791,029,836	$1,410,804,745	Major
12	$141,407,409,752	$34,289,207,264	$1,213,235,613	Major
13	$151,901,965,336	$36,659,763,682	$840,935,320	Major
14	$162,595,241,016	$38,918,704,915	$1,265,568,969	Major
15	$173,067,049,912	$41,040,614,665	$902,909,631	Major
16	$183,574,041,576	$43,042,233,693	$289,440,418	Major
17	$193,987,502,088	$44,916,010,379	$437,697,232	Major
18	$204,379,315,032	$46,666,603,326	$974,141,571	Major
19	$214,752,378,296	$48,294,150,261	$341,212,602	Major
20	$225,163,099,608	$49,802,057,059	$(633,900,563)	Major
21	$235,468,431,400	$51,181,117,347	$(875,099,091)	Major
22	$245,700,093,832	$52,432,926,319	$(778,939,655)	Major
23	$256,007,477,688	$53,566,308,731	$(360,473,083)	Major
24	$266,378,225,616	$54,579,906,583	$(1,522,596,703)	Major
25	$276,556,995,840	$55,456,948,785	$(3,119,958,016)	Major
26	$286,873,158,112	$56,217,226,065	$(3,976,692,448)	Major
27	$296,970,521,280	$56,837,606,007	$(4,524,829,626)	Major
28	$307,124,143,824	$57,334,312,088	$(4,755,866,009)	Major
29	$317,208,369,440	$59,595,662,414	$(4,795,701,731)	Major
30	$327,138,358,976	$65,201,529,326	$(4,778,497,493)	Major
31	$337,244,166,624	$67,613,616,112	$(4,774,940,627)	Major
32	$347,193,845,504	$68,455,609,998	$(4,859,533,621)	Major
33	$357,235,032,208	$68,635,628,374	$(5,045,843,053)	Major
34	$367,373,470,136	$70,580,476,360	$(5,348,730,363)	Major
35	$377,256,227,032	$75,851,876,840	$(5,798,544,343)	Major
36	$387,449,230,870	$77,708,377,769	$(6,364,670,742)	Major
37	$397,484,310,694	$77,916,467,851	$(7,079,564,084)	Major
38	$407,332,738,438	$79,760,134,927	$(7,947,551,408)	Major
39	$417,166,884,390	$84,708,433,327	$(8,960,122,348)	Major
40	$427,107,956,470	$86,060,807,731	$(10,112,075,112)	Major
41	$436,889,873,846	$85,704,943,365	$(11,422,333,078)	Major
42	$446,900,877,974	$87,094,659,947	$(12,869,018,672)	Major
43	$456,622,684,182	$91,689,611,499	$(14,486,994,456)	Major
44	$466,595,125,030	$92,561,512,716	$(16,245,275,127)	Major
45	$476,232,218,086	$94,607,926,320	$(18,183,239,379)	Major
46	$486,174,327,334	$99,089,355,888	$(20,263,754,240)	Major
47	$496,115,363,910	$99,486,992,178	$(22,508,945,214)	Major
48	$506,127,504,054	$101,159,911,096	$(24,917,761,976)	Major

Time (Year)	BCR Based on Cumulative Benefit and Cost			Investment Level Selection
	Major Investment with RA and SP	Moderate Investment with RA and SP	Minor Investment with RA and SP	
0	74.2	143.6	259.7	Minor
1	67.9	148.3	142.5	Moderate
2	89.3	205.5	27.4	Moderate
3	76.6	204.3	39.0	Moderate
4	78.3	228.2	48.1	Moderate
5	78.3	235.9	31.1	Moderate
6	76.1	239.5	26.5	Moderate
7	71.8	234.9	35.6	Moderate
8	67.9	227.8	32.9	Moderate
9	69.2	234.1	26.4	Moderate
10	69.3	235.6	18.6	Moderate
11	71.1	240.9	20.5	Moderate
12	66.1	225.0	14.1	Moderate
13	62.3	212.1	9.8	Moderate
14	64.8	218.1	13.5	Moderate
15	62.9	210.0	8.6	Moderate
16	62.7	207.0	3.4	Moderate
17	61.4	200.4	4.2	Moderate
18	60.5	194.8	7.4	Moderate
19	59.8	189.9	3.0	Moderate
20	60.3	188.0	-2.8	Moderate
21	59.6	182.6	-3.8	Moderate
22	58.3	175.7	-2.9	Moderate
23	58.4	172.5	-0.7	Moderate
24	59.7	172.2	-5.9	Moderate
25	58.8	166.1	-13.0	Moderate
26	59.9	164.9	-16.3	Moderate
27	58.6	157.8	-17.2	Moderate
28	58.2	153.0	-17.0	Moderate
29	57.4	151.9	-16.0	Moderate
30	55.4	83.9	-14.5	Moderate
31	55.3	85.4	-13.8	Moderate
32	54.0	84.1	-13.1	Moderate
33	53.7	82.7	-13.0	Moderate
34	54.3	84.2	-13.5	Moderate
35	53.0	64.0	-13.7	Moderate
36	54.2	65.3	-15.0	Moderate
37	54.3	64.8	-16.3	Moderate
38	53.2	65.1	-17.3	Moderate
39	52.2	54.2	-18.6	Moderate
40	52.0	54.5	-20.3	Moderate
41	50.9	53.4	-21.9	Moderate
42	51.3	53.9	-24.3	Moderate
43	50.1	45.5	-26.0	Major
44	50.3	45.7	-28.6	Major
45	49.0	46.0	-30.3	Major
46	49.2	44.8	-33.2	Major
47	49.4	44.7	-36.3	Major
48	50.1	45.4	-39.8	Major

Appendix L – Vensim Model Definition

Variable	Category	Definition	Unit	Comment	Data Source
Amount Society Willing to Invest to Prevent Casualties	Variable	Population*Amount Society Willing to Invest to Prevent One Casualty	$	Amount represents what society would be willing to invest to save all lives throughout the analysis period.	N/A
Amount Society Willing to Invest to Prevent Injuries	Variable	Amount Society Willing to Invest to Prevent One Injury*Population	$	Amount represents what society would be willing to invest to prevent everyone from getting injured throughout the analysis period.	N/A
Amount Society Willing to Invest to Prevent One Casualty	Stock	INTEG (Net Change of Amount Value to Prevent One Casualty, Initial Amount Society Willing to Invest to Prevent One Casualty)	$/people	Amount represents what society would be willing to invest to save one life throughout the analysis period.	N/A
Amount Society Willing to Invest to Prevent One Injury	Stock	INTEG (Net Change of Amount Value to Prevent One Injury, Initial Amount Society Willing to Invest to Prevent One Injury)	$/people	Amount represents what society would be willing to invest to prevent an injury throughout the analysis period.	N/A
Annual Effect of Climate Change	Variable	0.0083	Dmnl	This is the estimated annual effect of climate change.	Derived from IPCC (2012)
Annual Probability of Occurrence of High Intensity Hazard	Variable	Normal Annual Probability of Occurrence of High Intensity Hazard*Effect of Climate Change	Dmnl	This is the annual probability of occurrence of a high intensity hazard throughout the analysis period.	N/A
Annual Probability of Occurrence of Low Intensity Hazard	Variable	1-Annual Probability of Occurrence of High Intensity Hazard-Annual Probability of Occurrence of Medium Intensity Hazard	Dmnl	This is the annual probability of occurrence of a low intensity hazard throughout the analysis period. Probability is defined as the remaining probability in the cumulative density function.	N/A
Annual Probability of Occurrence of Medium Intensity Hazard	Variable	Normal Annual Probability of Occurrence of Medium Intensity Hazard*Effect of Climate Change	Dmnl	This is the annual probability of occurrence of a medium intensity hazard throughout the analysis period.	N/A
Average Number of Apartments in a Building	Variable	15	apartment/ building	Variable estimates the number of apartments in a building.	Derived from US Census 2000
Average Size of Building	Variable	2287*8	(foot*foot)/ building	Variable is the average size of a building.	User Selection - Needs Further Research
Average Size of Household	Variable	2.4	people/house hold	Variable represents the average size of a household in the studied geographic area.	US Census 2000

Variable	Category	Definition	Unit	Comment	Data Source
Average Size of Residential Home	Variable	2287	foot*foot/ home	Variable represents the average size of a residential home.	Estimated from US Census 2000
Average Value of Building	Stock	INTEG (Net Change of Building Value, Initial Average Value of Building)	$/building	Stock represents the average value of a single residential building for the analysis period.	N/A
Average Value of Residential Home	Stock	INTEG (Net Change of Residential Home Value, Initial Average Value of Residential Home)	$/home	Stock represents the average value of a single residential home for the analysis period.	N/A
Base Investment Level	Stock	INTEG (Base Investment Level Net Growth, Initial Base Investment Level)	$	This is the floor amount for the no investment policy after economic growth adjustment.	N/A
Base Investment Level Net Growth	Flow	Base Investment Level*Economic Growth Rate	$/Year	This is the annual adjustment threshold level (floor amount for no investment) given the economic growth rate.	N/A
Birth Rate	Flow	INTEGER(Population*Fractional Birth Rate)	people/Year	Rate represents the actual change in population due to births.	N/A
Building Construction Time Delay	Variable	1	Year	This is the time period required between the construction of a building and its commission.	User Selection - Needs Further Research
Buildings	Stock	INTEG (Buildings Commissioned, Initial Number of Buildings)	building	Stock represents the number of residential buildings in the studied geographic area.	N/A
Buildings Being Constructed	Stock	INTEG (Buildings to Construct-Buildings Commissioned, Initial Number of Buildings Being Constructed)	building	Stock represents the number of residential buildings under construction in the studied geographic area.	N/A
Buildings Commissioned	Flow	INTEGER(Buildings Being Constructed/Building Construction Time Delay)	building/ Year	Rate represents the number of buildings to be commissioned in a given year.	N/A
Buildings to Construct	Flow	INTEGER(MIN(Number of New Buildings Needed/Transaction Time Period, Land Available for Building Construction/Average Size of Building*Square Feet to Square Mile Conversion Factor/Transaction Time Period))	building/ Year	Rate represents the number of buildings to be constructed on a yearly basis.	N/A
Conversion Rate of Residential Homes into Buildings	Flow	INTEGER(MIN(Number of New Buildings Needed*Number of Residential Homes to Convert into Buildings/Demolition Time Period, Residential Homes/Demolition Time Period))	home/Year	Rate represents the annual number of homes that are demolished to be converted into buildings.	N/A

Variable	Category	Definition	Unit	Comment	Data Source
Corresponding Infrastructure Management Investment	Variable	Base Investment Level+(IF THEN ELSE(Infrastructure Management Investment Policy to Implement=1,RANDOM UNIFORM(Base Investment Level, Lower Bound Threshold for Minor Investment,0),IF THEN ELSE(Infrastructure Management Investment Policy to Implement=2,RANDOM UNIFORM(Lower Bound Threshold for Minor Investment, Lower Bound Threshold for Moderate Investment,0),IF THEN ELSE(Infrastructure Management Investment Policy to Implement=3,RANDOM UNIFORM(Lower Bound Threshold for Moderate Investment, Lower Bound Threshold for Major Investment,0),RANDOM UNIFORM(Lower Bound Threshold for Major Investment, Upper Bound Threshold for Major Investment,0)))))	$	Variable is the level of investment that corresponds to the selected policy according to uniform distribution between appropriate threshold levels.	N/A
Currency Unit Conversion Factor for Analysis	Variable	1	1/$	Factor converts currency units into dimensionless units for economic recovery analysis.	Default
Death Rate	Flow	INTEGER(Population*Fractional Death Rate)	people/Year	Rate represents the actual change in population due to deaths.	N/A
Default Infrastructure Management Investment Policy	Variable	**<USER SELECTION>**	Dmnl [1,4,1]	This variable sets the default/initial (before social pressure and risk aversion) infrastructure management investment policy: no investment = 1, minor investment = 2, moderate investment = 3, and major investment = 4.	User Preference
Demolition Time Period	Variable	1	Year	This is the estimated time needed to demolish a home from the time the decision is made.	User Selection - Needs Further Research
Discount Factor	Variable	1/(1+Discount Rate*Time Unit Conversion Factor for Analysis)^(Time/Time Unit Conversion Factor for Analysis)	Dmnl	The discount factor is applied to amounts adjusted to economic growth to determine present values.	N/A
Discount Rate	Variable	0.05	1/Year	Constant is the discount rate used to determine the present value of amounts.	User Selection - Needs Further Research

Variable	Category	Definition	Unit	Comment	Data Source
Economic Environment Consequence | High Intensity Hazard	Variable	(((Gross Product Level Before Disaster*Currency Unit Conversion Factor for Analysis)*("Expected Economic Recovery Time | High Intensity Hazard"/Time Unit Conversion Factor for Analysis))-(EXP("Exponential Constant Function | High Intensity Hazard"*("Expected Economic Recovery Time | High Intensity Hazard"/Time Unit Conversion Factor for Analysis))/"Exponential Constant Function | High Intensity Hazard"^2*("Exponential Constant Function | High Intensity Hazard"*("Expected Economic Recovery Time | High Intensity Hazard"/Time Unit Conversion Factor for Analysis)-1)-EXP("Exponential Constant Function | High Intensity Hazard"*0)/"Exponential Constant Function | High Intensity Hazard"^2*("Exponential Constant Function | High Intensity Hazard"*0-1)))/Currency Unit Conversion Factor for Analysis	$	This is the economic consequence of a high intensity hazard under the assumption of an exponential economic recovery.	N/A
Economic Environment Consequence | Low Intensity Hazard	Variable	(((Gross Product Level Before Disaster*Currency Unit Conversion Factor for Analysis)*("Expected Economic Recovery Time | Low Intensity Hazard"/Time Unit Conversion Factor for Analysis))-(EXP("Exponential Constant Function | Low Intensity Hazard"*("Expected Economic Recovery Time | Low Intensity Hazard"/Time Unit Conversion Factor for Analysis))/"Exponential Constant Function | Low Intensity Hazard"^2*("Exponential Constant Function | Low Intensity Hazard"*("Expected Economic Recovery Time | Low Intensity Hazard"/Time Unit Conversion Factor for Analysis)-1)-EXP("Exponential Constant Function | Low Intensity Hazard"*0)/"Exponential Constant Function | Low Intensity Hazard"^2*("Exponential Constant Function | Low Intensity Hazard"*0-1)))/Currency Unit Conversion Factor for Analysis	$	This is the economic consequence of a low intensity hazard under the assumption of an exponential economic recovery.	N/A

Variable	Category	Definition	Unit	Comment	Data Source
Economic Environment Consequence | Medium Intensity Hazard	Variable	(((Gross Product Level Before Disaster*Currency Unit Conversion Factor for Analysis)*("Expected Economic Recovery Time | Medium Intensity Hazard"/Time Unit Conversion Factor for Analysis))-(EXP("Exponential Constant Function | Medium Intensity Hazard"*("Expected Economic Recovery Time | Medium Intensity Hazard"/Time Unit Conversion Factor for Analysis))/"Exponential Constant Function | Medium Intensity Hazard"^2*("Exponential Constant Function | Medium Intensity Hazard"*("Expected Economic Recovery Time | Medium Intensity Hazard"/Time Unit Conversion Factor for Analysis)-1)-EXP("Exponential Constant Function | Medium Intensity Hazard"*0)/"Exponential Constant Function | Medium Intensity Hazard"^2*("Exponential Constant Function | Medium Intensity Hazard"*0-1)))/Currency Unit Conversion Factor for Analysis	$	This is the economic consequence of a medium intensity hazard under the assumption of an exponential economic recovery.	N/A
Economic Growth Rate	Variable	Normal Economic Growth Rate*Effect of Population on Economic Growth Rate	1/Year	Variable represents the rate at which the economy grows.	N/A
Effect of Climate Change	Variable	(1+Annual Effect of Climate Change)^(Time/Time Unit Conversion Factor for Analysis)	Dmnl	This is the estimated effect of climate change at every year in the time period of analysis.	N/A
Effect of Economy on Immigration Rate	Variable	Table for Effect of Economy on Immigration Rate((Economic Growth Rate-Normal Economic Growth Rate)/Normal Economic Growth Rate)	Dmnl	Variable estimates the effect of the state of the economy on immigration rate.	N/A
Effect of Population on Economic Growth Rate	Variable	Table for Effect of Population on Economic Growth Rate((Population-Normal Population)/Normal Population)	Dmnl	Variable estimates the effect of population on the state of the economy.	N/A
Effect of Public Risk Perception Level on Emigration Rate	Variable	Table for Effect of Public Risk Perception Level on Emigration Rate(Public Risk Perception Level Based on Levee Condition)	Dmnl	This is the effect of public risk perception on the emigration rate.	N/A
Effect of Public Risk Perception Level on Infrastructure Management Investment	Variable	Table for Effect of Public Risk Perception Level on Infrastructure Management Investment(Public Risk Perception Level Based on Levee Condition)*Existing Social Pressure Due to Public Risk Perception	Dmnl	This is the effect of public risk perception on investment policy to implement.	N/A
Effect of Risk Aversion	Variable	IF THEN ELSE(Risk Aversion Level=0,0,IF THEN ELSE(Total Risk>Maximum Risk Level Accepted Under Risk Aversion,1,0))	Dmnl	This is the effect of risk aversion on investment policy to implement.	N/A

Variable	Category	Definition	Unit	Comment	Data Source
Emigration Rate	Flow	INTEGER(MIN(Population*Fractional Emigration Rate*Effect of Public Risk Perception Level on Emigration Rate, Population/Emigration Time Period))	people/Year	Rate represents the actual change in population due to emigration.	N/A
Emigration Time Period	Variable	1	Year	Variable represents the time period for someone to emigrate from the studied area.	User Selection - Needs Further Research
Estimated Percentage of Property Losses | High Intensity Hazard	Variable	0.9125	Dmnl	Given a hazard of high intensity, this factor represents the estimated percentage of property losses.	IPET (2009a)
Estimated Percentage of Property Losses | Low Intensity Hazard	Variable	0.05	Dmnl	Given a hazard of low intensity, this factor represents the estimated percentage of property losses.	IPET (2009a)
Estimated Percentage of Property Losses | Medium Intensity Hazard	Variable	0.4	Dmnl	Given a hazard of medium intensity, this factor represents the estimated percentage of property losses.	IPET (2009a)
Existing Social Pressure Due to Public Risk Perception	Variable	**<USER SELECTION>**	Dmnl [0,1,1]	This variable activates social pressure based on risk perception: social pressure does not exist = 0, and social pressure exist = 1.	User Preference
Expected Economic Recovery Time | High Intensity Hazard	Variable	10	Year	This is the expected recovery time of the economy given a high intensity hazard.	User Selection - Needs Further Research
Expected Economic Recovery Time | Low Intensity Hazard	Variable	1	Year	This is the expected recovery time of the economy given a low intensity hazard.	User Selection - Needs Further Research
Expected Economic Recovery Time | Medium Intensity Hazard	Variable	5	Year	This is the expected recovery time of the economy given a medium intensity hazard.	User Selection - Needs Further Research

Variable	Category	Definition	Unit	Comment	Data Source
Expected Net Change in Population	Flow	Birth Rate+Immigration Rate-Death Rate-Emigration Rate	people/Year	Rate captures the yearly net change in population.	N/A
Exponential Constant Function | High Intensity Hazard	Variable	(LN(Gross Product Level Before Disaster*Currency Unit Conversion Factor for Analysis)-LN("Expected Economic Recovery Time | High Intensity Hazard"/Time Unit Conversion Factor for Analysis))/("Expected Economic Recovery Time | High Intensity Hazard"/Time Unit Conversion Factor for Analysis)	Dmnl	Variable is the exponential constant to determine the economic impact of a high intensity hazard.	N/A
Exponential Constant Function | Low Intensity Hazard	Variable	(LN(Gross Product Level Before Disaster*Currency Unit Conversion Factor for Analysis)-LN("Expected Economic Recovery Time | Low Intensity Hazard"/Time Unit Conversion Factor for Analysis))/("Expected Economic Recovery Time | Low Intensity Hazard"/Time Unit Conversion Factor for Analysis)	Dmnl	Variable is the exponential constant to determine the economic impact of a low intensity hazard.	N/A
Exponential Constant Function | Medium Intensity Hazard	Variable	(LN(Gross Product Level Before Disaster*Currency Unit Conversion Factor for Analysis)-LN("Expected Economic Recovery Time | Medium Intensity Hazard"/Time Unit Conversion Factor for Analysis))/("Expected Economic Recovery Time | Medium Intensity Hazard"/Time Unit Conversion Factor for Analysis)	Dmnl	Variable is the exponential constant to determine the economic impact of a medium intensity hazard.	N/A
Fractional Birth Rate	Variable	Normal Fractional Birth Rate*(1-Population Density/Maximum Population Density)	1/Year	Variable is the fractional birth rate of the population given population density and the capacity of the environment.	N/A
Fractional Death Rate	Variable	Normal Fractional Death Rate*(1-Population Density/Maximum Population Density)	1/Year	Variable is the fractional death rate of the population given population density and the capacity of the environment.	N/A
Fractional Emigration Rate	Variable	Normal Fractional Emigration Rate*(1-Population Density/Maximum Population Density)	1/Year	Variable is the fractional emigration rate of the population given population density and the capacity of the environment.	N/A
Gross Product	Stock	INTEG (Net Change in Gross Product, Initial Gross Product)	$	This is the gross product of the region under analysis.	N/A
Gross Product Level Before Disaster	Variable	Gross Product	$	Variable represents the gross product level before disaster scenario and serves to calculate economic impact.	N/A
Immigration Rate	Flow	INTEGER(Normal Immigration Rate*(1-Population Density/Maximum Population Density)*Effect of Economy on Immigration Rate)	people/Year	Rate represents the actual change in population due to immigration.	N/A

Variable	Category	Definition	Unit	Comment	Data Source
Infrastructure Management Investment Policy to Implement	Variable	MIN(4,Default Infrastructure Management Investment Policy+Effect of Public Risk Perception Level on Infrastructure Management Investment+Effect of Risk Aversion)	Dmnl [1,4,1]	This variable sets the infrastructure management investment policy to implement. The output is as follow: no investment = 1, minor investment = 2, moderate investment = 3, and major investment = 4.	N/A
Initial Amount Society Willing to Invest to Prevent One Casualty	Variable	5500000	$/people	Amount represents what society would be willing to invest to save one life at the beginning of the analysis period.	Robinson (2007)
Initial Amount Society Willing to Invest to Prevent One Injury	Variable	1000000	$/people	Amount represents what society would be willing to invest to prevent an injury at the beginning of the analysis period.	Derived from Robinson (2007)
Initial Average Value of Building	Variable	133117*15	$/building	Variable represents the initial average value of a single residential building.	User Selection - Needs Further Research
Initial Average Value of Residential Home	Variable	133117	$/home	Variable represents the initial average value of a single residential home.	Derived from US Census 2000
Initial Base Investment Level	Variable	0	$	This is the floor amount for the no investment policy.	Default
Initial Gross Product	Variable	7914350000	$	This variable represents the gross product of the region under analysis at the beginning of the analysis period.	Derived from Barreca et al. (2012)
Initial Lower Bound Threshold for Major Investment	Variable	20000000	$	This is the ceiling amount for the moderate investment policy, and the floor amount for the major investment policy.	USACE Project Database
Initial Lower Bound Threshold for Minor Investment	Variable	500000	$	This is the ceiling amount for the no investment policy, and the floor amount for the minor investment policy.	EJLD (no date)
Initial Lower Bound Threshold for Moderate Investment	Variable	2500000	$	This is the ceiling amount for the minor investment policy, and the floor amount for the moderate investment policy.	USACE Project Database
Initial Number of Buildings	Variable	26891	building	Variable represents the initial number of residential buildings in the studied geographic area.	US Census 2000

Variable	Category	Definition	Unit	Comment	Data Source
Initial Number of Buildings Being Constructed	Variable	1	building	Variable represents the initial number of residential buildings under construction in the studied geographic area.	User Selection - Needs Further Research
Initial Number of Levees in Fair Condition	Variable	5.12	section	This is the initial number of levee "sections" in fair condition. In this case, levee crown height compliance was used to determine functional state.	Derived from IPET (2009a)
Initial Number of Levees in Good Condition	Variable	4.43	section	This is the initial number of levee "sections" in good condition. In this case, levee crown height compliance was used to determine functional state.	Derived from IPET (2009a)
Initial Number of Levees in Poor Condition	Variable	2.05	section	This is the initial number of levee "sections" in poor condition. In this case, levee crown height compliance was used to determine functional state.	Derived from IPET (2009a)
Initial Number of Residential Homes	Variable	107331	home	Variable represents the initial number of residential homes in the studied geographic area.	US Census 2000
Initial Percentage of Available Land for Development	Variable	0.093	Dmnl	This is the initial percentage of land that is available for real estate development.	Pagano and Bowman (2000)
Initial Population	Variable	257501	people	This is the population at the beginning of the analysis period.	US Census 2000
Initial Size of Land Available for Building Construction	Variable	Territorial Capacity*Initial Percentage of Available Land for Development	mile*mile	This is the initial size of land that is available for real estate development.	N/A
Initial Upper Bound Threshold for Major Investment	Variable	300000000	$	This is the ceiling amount for the major investment policy.	USACE Project Database
Land Available for Building Construction	Stock	INTEG (New Land Available for Building Construction-Land Designated for Building Construction, Initial Size of Land Available for Building Construction)	(mile*mile)	Stock represents the amount of land available for real estate development, specifically building construction.	N/A
Land Designated for Building Construction	Flow	Buildings to Construct*Average Size of Building/Square Feet to Square Mile Conversion Factor	(mile*mile)/ Year	Rate represents the available land designated for building conversion based on building demand.	N/A
Levee in Fair Condition	Stock	INTEG (Levee Repair Rate from Poor to Fair+Transition from Good to Fair-Transition from Fair to Good-Transition from Fair to Poor, Initial Number of Levees in Fair Condition)	section	Stock represents the number of "sections" in fair condition.	N/A

Variable	Category	Definition	Unit	Comment	Data Source
Levee in Good Condition	Stock	INTEG (Levee Repair Rate from Fair to Good+Levee Rehabilitation Rate from Poor to Good-Transition from Good to Fair-Transition from Good to Poor, Initial Number of Levees in Good Condition)	section	Stock represents the number of "sections" in good condition.	N/A
Levee in Poor Condition	Stock	INTEG (Transition from Fair to Poor+Transition from Good to Poor-Transition from Poor to Fair-Transition from Poor to Good, Initial Number of Levees in Poor Condition)	section	Stock represents the number of "sections" in poor condition.	N/A
Levee Rehabilitation Rate from Poor to Good	Flow	Levee under Rehabilitation from Poor Condition to Good Condition/Repair and Rehabilitation Time Duration	section/Year	Flow represents the rate at which levee "sections" are rehabilitated.	N/A
Levee Repair Rate from Fair to Good	Flow	Levee under Repair from Fair Condition to Good Condition/Repair and Rehabilitation Time Duration	section/Year	Flow represents the rate at which levee "sections" are repaired.	N/A
Levee Repair Rate from Poor to Fair	Flow	Levee under Repair from Poor Condition to Fair Condition/Repair and Rehabilitation Time Duration	section/Year	Flow represents the rate at which levee "sections" are repaired.	N/A
Levee Section Unit Conversion Factor for Analysis	Variable	1	1/section	Factor is used to convert section units into dimensionless units for the analysis of system failure.	Default
Levee under Rehabilitation from Poor Condition to Good Condition	Stock	INTEG (Transition from Poor to Good-Levee Rehabilitation Rate from Poor to Good,0)	section	Stock represents the number of "sections" transitioning from poor to good condition given an infrastructure management investment strategy.	N/A
Levee under Repair from Fair Condition to Good Condition	Stock	INTEG (Transition from Fair to Good-Levee Repair Rate from Fair to Good,0)	section	Stock represents the number of "sections" transitioning from fair to good condition given an infrastructure management investment strategy.	N/A
Levee under Repair from Poor Condition to Fair Condition	Stock	INTEG (Transition from Poor to Fair-Levee Repair Rate from Poor to Fair,0)	section	Stock represents the number of "sections" transitioning from poor to fair condition given an infrastructure management investment strategy.	N/A
Lower Bound Threshold for Major Investment	Stock	INTEG (Lower Bound Threshold for Major Investment Net Growth, Initial Lower Bound Threshold for Major Investment)	$	This is the ceiling amount for the moderate investment policy and the floor amount for the major investment policy after economic growth adjustment.	N/A
Lower Bound Threshold for Major Investment Net Growth	Flow	Lower Bound Threshold for Major Investment*Economic Growth Rate	$/Year	This is the annual adjustment to threshold levels (ceiling amount for moderate investment, floor amount for major investment) given the economic growth rate.	N/A
Lower Bound Threshold for Minor Investment	Stock	INTEG (Lower Bound Threshold for Minor Investment Net Growth, Initial Lower Bound Threshold for Minor Investment)	$	This is the ceiling amount for the no investment policy and the floor amount for the minor investment policy after economic growth adjustment.	N/A

Variable	Category	Definition	Unit	Comment	Data Source
Lower Bound Threshold for Minor Investment Net Growth	Flow	Lower Bound Threshold for Minor Investment*Economic Growth Rate	$/Year	This is the annual adjustment to threshold levels (ceiling amount for no investment, floor amount for minor investment) given the economic growth rate.	N/A
Lower Bound Threshold for Moderate Investment	Stock	INTEG (Lower Bound Threshold for Moderate Investment Net Growth, Initial Lower Bound Threshold for Moderate Investment)	$	This is the ceiling amount for the minor investment policy and the floor amount for the moderate investment policy after economic growth adjustment.	N/A
Lower Bound Threshold for Moderate Investment Net Growth	Flow	Lower Bound Threshold for Moderate Investment*Economic Growth Rate	$/Year	This is the annual adjustment to threshold levels (ceiling amount for minor investment, floor amount for moderate investment) given the economic growth rate.	N/A
Maximum Population Density	Variable	16784	people/(mile *mile)	This is the carrying capacity of the environment.	Census Tract 202.02
Maximum Risk Level Accepted Under Risk Aversion	Variable	**<USER SELECTION>**	$	This threshold represents the largest acceptable risk to the decision maker.	User Preference
Moderately to Severely Vulnerable Ratio	Variable	2	Dmnl	This is the estimated ratio between moderately and severely vulnerable populations.	User Selection - Needs Further Research
Net Change in Gross Product	Flow	Gross Product*Economic Growth Rate	$/Year	Rate presents the annual change of gross product.	N/A
Net Change of Amount Value to Prevent One Casualty	Flow	Amount Society Willing to Invest to Prevent One Casualty*Economic Growth Rate	$/(people*Y ear)	This is the rate at which the amount society is willing to invest to save a life changes due to economic growth.	N/A
Net Change of Amount Value to Prevent One Injury	Flow	Amount Society Willing to Invest to Prevent One Injury*Economic Growth Rate	$/(people*Y ear)	This is the rate at which the amount society is willing to invest to prevent an injury changes due to economic growth.	N/A
Net Change of Building Value	Flow	Average Value of Building*Economic Growth Rate	$/(building* Year)	Rate represents the change in average value of a single residential building.	N/A
Net Change of Residential Home Value	Flow	Average Value of Residential Home*Economic Growth Rate	$/(home* Year)	Rate represents the change in average value of a single residential home.	N/A
New Land Available for Building Construction	Flow	(Average Size of Residential Home*Conversion Rate of Residential Homes into Buildings)/Square Feet to Square Mile Conversion Factor	mile*mile/ Year	Based on the number of homes demolished, rate represents the annual amount of new land available for development.	N/A

Variable	Category	Definition	Unit	Comment	Data Source
Normal Annual Probability of Occurrence of High Intensity Hazard	Variable	1/500	Dmnl	This is the annual probability of occurrence of a high intensity hazard based on an initial assessment at the beginning of the year of analysis.	High Intensity Level Defined by User
Normal Annual Probability of Occurrence of Medium Intensity Hazard	Variable	1/50-1/500	Dmnl	This is the annual probability of occurrence of a medium intensity hazard based on an initial assessment at the beginning of the year of analysis.	Medium Intensity Level Defined by User
Normal Economic Growth Rate	Variable	0.06	1/Year	Variable is the normal economic growth of the region.	Derived from Barreca et al. (2012)
Normal Fractional Birth Rate	Variable	15.2/1000	1/Year	Variable is the normal fractional birth rate of the population.	Jindal et al. (2004)
Normal Fractional Death Rate	Variable	9.158/1000	1/Year	Variable is the normal fractional death rate of the population.	Jindal et al. (2004)
Normal Fractional Emigration Rate	Variable	36/1000	1/Year	Variable is the normal fractional emigration rate from the studied area.	Derived from Population Dynamics Data
Normal Immigration Rate	Variable	7967	people/Year	Variable is the normal immigration rate into the studied area.	Derived from US Census Data 2000 and 1995
Normal Population	Variable	257501	people	Variable is the normal population for the studied geographic area.	US Census 2000
Number of Households per Apartment	Variable	1	household/ apartment	Variable represents the number of households living in an apartment.	User Selection - Needs Further Research
Number of New Buildings Needed	Variable	MAX(0,INTEGER(Population Growth/(Average Size of Household*Number of Households per Apartment*Average Number of Apartments in a Building)))	building	Based on population growth, variable estimates the number of new buildings needed.	N/A

Variable	Category	Definition	Unit	Comment	Data Source
Number of Residential Homes to Convert into Buildings	Variable	2	home/ building	Homes may be converted into buildings. On average, in addition to using land available for development, every building needs a number of homes to be demolished.	User Selection - Needs Further Research
P (Failure of Levee in Fair Condition | High Intensity Hazard)	Variable	0.776667	Dmnl	Variable represents the probability that a levee "section" in fair condition will fail given a high intensity hazard.	Derived from IPET (2009b)
P (Failure of Levee in Fair Condition | Low Intensity Hazard)	Variable	0.288733	Dmnl	Variable represents the probability that a levee "section" in fair condition will fail given a low intensity hazard.	Derived from IPET (2009b)
P (Failure of Levee in Fair Condition | Medium Intensity Hazard)	Variable	0.396067	Dmnl	Variable represents the probability that a levee "section" in fair condition will fail given a medium intensity hazard.	Derived from IPET (2009b)
P (Failure of Levee in Good Condition | High Intensity Hazard)	Variable	0.5542	Dmnl	Variable represents the probability that a levee "section" in good condition will fail given a high intensity hazard.	Derived from IPET (2009b)
P (Failure of Levee in Good Condition | Low Intensity Hazard)	Variable	1E-12	Dmnl	Variable represents the probability that a levee "section" in good condition will fail given a low intensity hazard.	Derived from IPET (2009b)
P (Failure of Levee in Good Condition | Medium Intensity Hazard)	Variable	0.288733	Dmnl	Variable represents the probability that a levee "section" in good condition will fail given a medium intensity hazard.	Derived from IPET (2009b)
P (Failure of Levee in Poor Condition | High Intensity Hazard)	Variable	1	Dmnl	Variable represents the probability that a levee "section" in poor condition will fail given a high intensity hazard.	Derived from IPET (2009b)
P (Failure of Levee in Poor Condition | Low Intensity Hazard)	Variable	0.396067	Dmnl	Variable represents the probability that a levee "section" in poor condition will fail given a low intensity hazard.	Derived from IPET (2009b)
P (Failure of Levee in Poor Condition | Medium Intensity Hazard)	Variable	0.5542	Dmnl	Variable represents the probability that a levee "section" in poor condition will fail given a medium intensity hazard.	Derived from IPET (2009b)

Variable	Category	Definition	Unit	Comment	Data Source
P (Levee Deteriorates from Fair to Poor)	Variable	IF THEN ELSE(Infrastructure Management Investment Policy to Implement=1, 0.4, IF THEN ELSE(Infrastructure Management Investment Policy to Implement=2, 0.1, IF THEN ELSE(Infrastructure Management Investment Policy to Implement=3, 0,0)))	1/Year	Variable represents the probability that a levee "section" will deteriorate from fair to poor condition due to time and potentially other factors.	User Selection - Needs Further Research
P (Levee Deteriorates from Good to Fair)	Variable	IF THEN ELSE(Infrastructure Management Investment Policy to Implement=1, 0.2, IF THEN ELSE(Infrastructure Management Investment Policy to Implement=2, 0.1, IF THEN ELSE(Infrastructure Management Investment Policy to Implement=3, 0.1, 0)))	1/Year	Variable represents the probability that a levee "section" will deteriorate from good to fair condition due to time and potentially other factors.	User Selection - Needs Further Research
P (Levee Deteriorates from Good to Poor)	Variable	IF THEN ELSE(Infrastructure Management Investment Policy to Implement=1, 0.1, IF THEN ELSE(Infrastructure Management Investment Policy to Implement=2, 0.1, IF THEN ELSE(Infrastructure Management Investment Policy to Implement=3, 0,0)))	1/Year	Variable represents the probability that a levee "section" will deteriorate from good to poor condition due to time and potentially other factors.	User Selection - Needs Further Research
P (Levee Improves from Fair to Good)	Variable	IF THEN ELSE(Infrastructure Management Investment Policy to Implement=1, 0, IF THEN ELSE(Infrastructure Management Investment Policy to Implement=2, 0.2, IF THEN ELSE(Infrastructure Management Investment Policy to Implement=3, 0.4, 1)))	1/Year	Variable represents the probability that a levee "section" will improve from fair to good condition given an infrastructure management investment policy.	User Selection - Needs Further Research
P (Levee Improves from Poor to Fair)	Variable	IF THEN ELSE(Infrastructure Management Investment Policy to Implement=1, 0, IF THEN ELSE(Infrastructure Management Investment Policy to Implement=2, 0.2, IF THEN ELSE(Infrastructure Management Investment Policy to Implement=3, 0.4, 0)))	1/Year	Variable represents the probability that a levee "section" will improve from poor to fair condition given an infrastructure management investment policy.	User Selection - Needs Further Research
P (Levee Improves from Poor to Good)	Variable	IF THEN ELSE(Infrastructure Management Investment Policy to Implement=1, 0, IF THEN ELSE(Infrastructure Management Investment Policy to Implement=2, 0, IF THEN ELSE(Infrastructure Management Investment Policy to Implement=3, 0.2,1)))	1/Year	Variable represents the probability that a levee "section" will improve from poor to good condition given an infrastructure management investment policy.	User Selection - Needs Further Research

Variable	Category	Definition	Unit	Comment	Data Source
P (System Failure | High Intensity Hazard)	Variable	1-((1-"P (Failure of Levee in Fair Condition | High Intensity Hazard)")^((Levee in Fair Condition+Levee under Repair from Fair Condition to Good Condition)*Levee Section Unit Conversion Factor for Analysis)*(1-"P (Failure of Levee in Good Condition | High Intensity Hazard)")^(Levee in Good Condition*Levee Section Unit Conversion Factor for Analysis)*(1-"P (Failure of Levee in Poor Condition | High Intensity Hazard)")^((Levee in Poor Condition+Levee under Repair from Poor Condition to Fair Condition+Levee under Rehabilitation from Poor Condition to Good Condition)*Levee Section Unit Conversion Factor for Analysis))	Dmnl	Variable represents the probability that the levee system will fail given a high intensity hazard.	N/A
P (System Failure | Low Intensity Hazard)	Variable	1-((1-"P (Failure of Levee in Fair Condition | Low Intensity Hazard)")^((Levee in Fair Condition+Levee under Repair from Fair Condition to Good Condition)*Levee Section Unit Conversion Factor for Analysis)*(1-"P (Failure of Levee in Good Condition | Low Intensity Hazard)")^(Levee in Good Condition*Levee Section Unit Conversion Factor for Analysis)*(1-"P (Failure of Levee in Poor Condition | Low Intensity Hazard)")^((Levee in Poor Condition+Levee under Repair from Poor Condition to Fair Condition+Levee under Rehabilitation from Poor Condition to Good Condition)*Levee Section Unit Conversion Factor for Analysis))	Dmnl	Variable represents the probability that the levee system will fail given a low intensity hazard.	N/A
P (System Failure | Medium Intensity Hazard)	Variable	1-((1-"P (Failure of Levee in Fair Condition | Medium Intensity Hazard)")^((Levee in Fair Condition+Levee under Repair from Fair Condition to Good Condition)*Levee Section Unit Conversion Factor for Analysis)*(1-"P (Failure of Levee in Good Condition | Medium Intensity Hazard)")^(Levee in Good Condition*Levee Section Unit Conversion Factor for Analysis)*(1-"P (Failure of Levee in Poor Condition | Medium Intensity Hazard)")^((Levee in Poor Condition+Levee under Repair from Poor Condition to Fair Condition+Levee under Rehabilitation from Poor Condition to Good Condition)*Levee Section Unit Conversion Factor for Analysis))	Dmnl	Variable represents the probability that the levee system will fail given a medium intensity hazard.	N/A

Variable	Category	Definition	Unit	Comment	Data Source
Percentage of Population Moderately Vulnerable Due to High Intensity Hazard	Variable	Percentage of Population Severely Vulnerable Due to High Intensity Hazard*Moderately to Severely Vulnerable Ratio	Dmnl	Variable represents the estimated percentage of people who would be moderately vulnerable in the event of a high intensity hazard.	N/A
Percentage of Population Moderately Vulnerable Due to Low Intensity Hazard	Variable	Percentage of Population Severely Vulnerable Due to Low Intensity Hazard*Moderately to Severely Vulnerable Ratio	Dmnl	Variable represents the estimated percentage of people who would be moderately vulnerable in the event of a low intensity hazard.	N/A
Percentage of Population Moderately Vulnerable Due to Medium Intensity Hazard	Variable	Percentage of Population Severely Vulnerable Due to Medium Intensity Hazard*Moderately to Severely Vulnerable Ratio	Dmnl	Variable represents the estimated percentage of people who would be moderately vulnerable in the event of a medium intensity hazard.	N/A
Percentage of Population Severely Vulnerable Due to High Intensity Hazard	Variable	(17136+5886+3+530)/257501	Dmnl	Variable represents the estimated percentage of people who would be severely vulnerable in the event of a high intensity hazard.	IPET (2009a)
Percentage of Population Severely Vulnerable Due to Low Intensity Hazard	Variable	(37+31+8)/257501	Dmnl	Variable represents the estimated percentage of people who would be severely vulnerable in the event of a low intensity hazard.	IPET (2009a)
Percentage of Population Severely Vulnerable Due to Medium Intensity Hazard	Variable	(50+93+35)/257501	Dmnl	Variable represents the estimated percentage of people who would be severely vulnerable in the event of a medium intensity hazard.	IPET (2009a)
Population	Stock	INTEG (Birth Rate+Immigration Rate-Death Rate-Emigration Rate, Initial Population)	people	Stock represents the population that resides in the geographic area of interest.	N/A
Population Density	Variable	Population/Territorial Capacity	people/(mile *mile)	Variable represents the population density of the geographic area under study.	N/A
Population Growth	Stock	INTEG (Expected Net Change in Population-Recorded Net Change in Population,0)	people	Stock captures the yearly population growth or shrinkage.	N/A

Variable	Category	Definition	Unit	Comment	Data Source
Present Worth of Amount Society Willing to Invest to Prevent Casualties	Variable	Amount Society Willing to Invest to Prevent Casualties*Discount Factor	$	In present value terms, amount represents what society would be willing to invest to save all lives throughout the analysis period.	N/A
Present Worth of Amount Society Willing to Invest to Prevent Injuries	Variable	Amount Society Willing to Invest to Prevent Injuries*Discount Factor	$	In present value terms, amount represents what society would be willing to invest to prevent everyone from getting injured throughout the analysis period.	N/A
Present Worth of Building Consequence	Variable	Total Building Value*Discount Factor	$	Variable is the total estimated value of residential buildings in the studied geographic area, adjusted to present value terms.	N/A
Present Worth of Built Environment Consequence	Variable	Present Worth of Building Consequence+Present Worth of Residential Home Consequence	$	This is an estimation of the consequence linked with the built environment. The amount only includes residential homes and buildings values.	N/A
Present Worth of Built Environment Consequence | High Intensity Hazard	Variable	Present Worth of Built Environment Consequence*"Estimated Percentage of Property Losses | High Intensity Hazard"	$	This is an estimation of the consequence linked with the built environment given a hazard of high intensity. The amount only includes residential homes and buildings values.	N/A
Present Worth of Built Environment Consequence | Low Intensity Hazard	Variable	Present Worth of Built Environment Consequence*"Estimated Percentage of Property Losses | Low Intensity Hazard"	$	This is an estimation of the consequence linked with the built environment given a hazard of low intensity. The amount only includes residential homes and buildings values.	N/A
Present Worth of Built Environment Consequence | Medium Intensity Hazard	Variable	Present Worth of Built Environment Consequence*"Estimated Percentage of Property Losses | Medium Intensity Hazard"	$	This is an estimation of the consequence linked with the built environment given a hazard of medium intensity. The amount only includes residential homes and buildings values.	N/A
Present Worth of Economic Environment Consequence | High Intensity Hazard	Variable	Economic Environment Consequence | High Intensity Hazard*Discount Factor	$	This is the economic consequence of a high intensity hazard adjusted to present value terms.	N/A
Present Worth of Economic Environment Consequence | Low Intensity Hazard	Variable	Economic Environment Consequence | Low Intensity Hazard*Discount Factor	$	This is the economic consequence of a low intensity hazard adjusted to present value terms.	N/A

Variable	Category	Definition	Unit	Comment	Data Source
Present Worth of Economic Environment Consequence | Medium Intensity Hazard	Variable	Economic Environment Consequence | Medium Intensity Hazard*Discount Factor	$	This is the economic consequence of a medium intensity hazard adjusted to present value terms.	N/A
Present Worth of Infrastructure Management Investment	Variable	Corresponding Infrastructure Management Investment*Discount Factor	$	Variable is the adjusted investment to present value.	N/A
Present Worth of Residential Home Consequence	Variable	Total Residential Home Value*Discount Factor	$	Variable is the total estimated value of residential homes in the studied geographic area, adjusted to present value terms.	N/A
Present Worth of Societal Environment Consequence | High Intensity Hazard	Variable	Present Worth of Amount Society Willing to Invest to Prevent Casualties*Percentage of Population Severely Vulnerable Due to High Intensity Hazard+Present Worth of Amount Society Willing to Invest to Prevent Injuries*Percentage of Population Moderately Vulnerable Due to High Intensity Hazard	$	This amount represents the estimated societal consequence in prevent value terms when a high intensity hazard occurs.	N/A
Present Worth of Societal Environment Consequence | Low Intensity Hazard	Variable	Present Worth of Amount Society Willing to Invest to Prevent Casualties*Percentage of Population Severely Vulnerable Due to Low Intensity Hazard+Present Worth of Amount Society Willing to Invest to Prevent Injuries*Percentage of Population Moderately Vulnerable Due to Low Intensity Hazard	$	This amount represents the estimated societal consequence in prevent value terms when a low intensity hazard occurs.	N/A
Present Worth of Societal Environment Consequence | Medium Intensity Hazard	Variable	Present Worth of Amount Society Willing to Invest to Prevent Casualties*Percentage of Population Severely Vulnerable Due to Medium Intensity Hazard+Present Worth of Amount Society Willing to Invest to Prevent Injuries*Percentage of Population Moderately Vulnerable Due to Medium Intensity Hazard	$	This amount represents the estimated societal consequence in prevent value terms when a medium intensity hazard occurs.	N/A

Variable	Category	Definition	Unit	Comment	Data Source
Public Risk Perception Level Based on Levee Condition	Variable	IF THEN ELSE((Levee in Good Condition+Levee under Rehabilitation from Poor Condition to Good Condition+Levee under Repair from Fair Condition to Good Condition)>(Levee in Fair Condition+Levee under Repair from Poor Condition to Fair Condition), IF THEN ELSE((Levee in Good Condition+Levee under Rehabilitation from Poor Condition to Good Condition+Levee under Repair from Fair Condition to Good Condition)>Levee in Poor Condition, 1, 0), 0)+IF THEN ELSE((Levee in Fair Condition+Levee under Repair from Poor Condition to Fair Condition)>=(Levee in Good Condition+Levee under Rehabilitation from Poor Condition to Good Condition+Levee under Repair from Fair Condition to Good Condition), IF THEN ELSE((Levee in Fair Condition+Levee under Repair from Poor Condition to Fair Condition)>Levee in Poor Condition, 2, 0), 0)+IF THEN ELSE(Levee in Poor Condition>=(Levee in Good Condition+Levee under Rehabilitation from Poor Condition to Good Condition+Levee under Repair from Fair Condition to Good Condition), IF THEN ELSE(Levee in Poor Condition>=(Levee in Fair Condition+Levee under Repair from Poor Condition to Fair Condition), 3, 0), 0)	Dmnl	Variable measures the level of risk perception. The levels of risk perception are as follow: poor condition perceived = 3, fair condition perceived = 2, good condition perceived = 1. Perception is measured in accordance to the condition of the levee.	N/A
Recordation Time Period	Variable	1	Year [1,1,1]	Variable helps determine the frequency for removing population changes already recorded.	Default
Recorded Net Change in Population	Flow	Population Growth/Recordation Time Period	people/Year	This is the rate at which population changes are recorded and removed from stock.	N/A
Repair and Rehabilitation Time Duration	Variable	1	Year	This is the estimated time duration for individual repairs and rehabilitations.	User Selection - Needs Further Research
Residential Homes	Stock	INTEG (-Conversion Rate of Residential Homes into Buildings, Initial Number of Residential Homes)	home	Stock represents the number of residential homes in the studied geographic area.	N/A
Risk Aversion Level	Variable	**<USER SELECTION>**	Dmnl [0,1,1]	This variable activates risk-averse decision making: risk neutrality = 0, and risk aversion = 1.	User Preference

Variable	Category	Definition	Unit	Comment	Data Source
Risk Due to High Intensity Hazard	Variable	Annual Probability of Occurrence of High Intensity Hazard*"P (System Failure | High Intensity Hazard)"*("Present Worth of Economic Environment Consequence | High Intensity Hazard"+"Present Worth of Societal Environment Consequence | High Intensity Hazard"+"Present Worth of Built Environment Consequence | High Intensity Hazard")	$	Variable represents the annual probabilistic risk attributed to a hazard of high intensity.	N/A
Risk Due to Low Intensity Hazard	Variable	Annual Probability of Occurrence of Low Intensity Hazard*"P (System Failure | Low Intensity Hazard)"*("Present Worth of Economic Environment Consequence | Low Intensity Hazard"+"Present Worth of Societal Environment Consequence | Low Intensity Hazard"+"Present Worth of Built Environment Consequence | Low Intensity Hazard")	$	Variable represents the annual probabilistic risk attributed to a hazard of low intensity.	N/A
Risk Due to Medium Intensity Hazard	Variable	Annual Probability of Occurrence of Medium Intensity Hazard*"P (System Failure | Medium Intensity Hazard)"*("Present Worth of Economic Environment Consequence | Medium Intensity Hazard"+"Present Worth of Societal Environment Consequence | Medium Intensity Hazard"+"Present Worth of Built Environment Consequence | Medium Intensity Hazard")	$	Variable represents the annual probabilistic risk attributed to a hazard of medium intensity.	N/A
Square Feet to Square Mile Conversion Factor	Variable	5280^2	(foot*foot)/ (mile*mile)	Factor serves to convert miles into feet.	Default
Table for Effect of Economy on Immigration Rate	Table	([(-4,0)-(20,40)],(-4,0),(-3,0),(-2,0.25),(-1,0.75),(0,1),(1,3),(2,6),(3,10),(4,15),(5,21))	Dmnl	Table determines the relationship between the state of the economy and immigration rates. The effect causes immigration rates to increase as the economy grows. Immigration rates conversely decrease when the economy shrinks.	User Selection - Needs Further Research
Table for Effect of Population on Economic Growth Rate	Table	([(-1,-2)-(10,10)],(-1,-2),(0,1),(1,2),(2,1),(3,1),(4,1),(5,1))	Dmnl	Table describes the effect population has on economic growth. As population increases, the economy grows, until the economy starts growing at a slower rate, become steady.	User Selection - Needs Further Research
Table for Effect of Public Risk Perception Level on Emigration Rate	Table	([(0,0)-(10,10)],(1,1),(2,1),(3,2))	Dmnl	Table captures the effect of risk perception on immigration rates. Immigration doubles when risk perception is high.	User Selection - Needs Further Research

Variable	Category	Definition	Unit	Comment	Data Source
Table for Effect of Public Risk Perception Level on Infrastructure Management Investment	Table	([(0,0)-(10,10)],(1,0),(2,0),(3,1))	Dmnl	Table captures the effect of risk perception on social pressure. Only when risk perception is high, social pressure occurs.	User Selection - Needs Further Research
Territorial Capacity	Variable	49.64	mile*mile	Variable represents the size of the geographic area under study.	US Census 2000
Time Unit Conversion Factor for Analysis	Variable	1	Year	Factor is used to convert year units into dimensionless units for the analysis of climate change.	Default
Total Building Value	Variable	Buildings*Average Value of Building	$	Variable is the total estimated value of residential buildings in the studied geographic area.	N/A
Total Residential Home Value	Variable	Residential Homes*Average Value of Residential Home	$	Variable is the total estimated value of residential homes in the studied geographic area.	N/A
Total Risk	Variable	Risk Due to High Intensity Hazard+Risk Due to Medium Intensity Hazard+Risk Due to Low Intensity Hazard	$	This is the total probabilistic risk in a given year of the analysis period.	N/A
Transaction Time Period	Variable	1	Year	This is the time period required between the decision to construct a building and the actual building construction.	User Selection - Needs Further Research
Transition from Fair to Good	Flow	Levee in Fair Condition*"P (Levee Improves from Fair to Good)"	section/Year	Flow represents the rate at which levee "sections" improve from fair to good condition.	N/A
Transition from Fair to Poor	Flow	Levee in Fair Condition*"P (Levee Deteriorates from Fair to Poor)"	section/Year	Flow represents the rate at which levee "sections" deteriorate from fair to poor condition.	N/A
Transition from Good to Fair	Flow	Levee in Good Condition*"P (Levee Deteriorates from Good to Fair)"	section/Year	Flow represents the rate at which levee "sections" deteriorate from good to fair condition.	N/A
Transition from Good to Poor	Flow	Levee in Good Condition*"P (Levee Deteriorates from Good to Poor)"	section/Year	Flow represents the rate at which levee "sections" deteriorate from good to poor condition.	N/A
Transition from Poor to Fair	Flow	Levee in Poor Condition*"P (Levee Improves from Poor to Fair)"	section/Year	Flow represents the rate at which levee "sections" improve from poor to fair condition.	N/A
Transition from Poor to Good	Flow	Levee in Poor Condition*"P (Levee Improves from Poor to Good)"	section/Year	Flow represents the rate at which levee "sections" improve from poor to good condition.	N/A
Upper Bound Threshold for Major Investment	Stock	INTEG (Upper Bound Threshold for Major Investment Net Growth, Initial Upper Bound Threshold for Major Investment)	$	This is the ceiling amount for the major investment policy after economic growth adjustment.	N/A

Variable	Category	Definition	Unit	Comment	Data Source
Upper Bound Threshold for Major Investment Net Growth	Flow	Upper Bound Threshold for Major Investment*Economic Growth Rate	$/Year	This is the annual adjustment to threshold levels (ceiling amount for major investment) given the economic growth rate.	N/A