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A Risk Assessment of the Impacts of Coastal Flooding and Sea Level Rise on the Existing and New Pump Stations 113, Norfolk, VA

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A RISK ASSESSMENT OF THE IMPACTS OF COASTAL FLOODING AND SEA-LEVEL RISE ON THE EXISTING AND NEW PUMP STATIONS 113 NORFOLK, VIRGINIA

by

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ABSTRACT

A RISK ASSESSMENT OF THE IMPACTS OF COASTAL FLOODING AND SEA-LEVEL RISE ON THE EXISTING AND NEW PUMP STATIONS 113 NORFOLK, VIRGINIA

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Old Dominion University, 2015
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The author assessed the risk to a wastewater pump station and a planned replacement located nearby due to coastal flooding and rising sea levels. The locations for the pump stations are in the Larchmont neighborhood by the Lafayette River tidal estuaries in Norfolk, Virginia. The Lafayette River is a tributary to the Elizabeth River, which flows to the Chesapeake Bay. The low-lying areas along the river are subject to coastal surges caused by tropical and extra-tropical storms that flood the bay.

The region is considered one of the urban areas most exposed to the accelerating rate of rising sea levels. Six of the highest storm surges on record have occurred since 2003 and even more moderate events have inundated the existing pump station. The flooding impacts the service and reduces the life cycle performance of the pump system.

The study compares the vulnerability of the existing pump station to an alternative to replace the station in a new location. It uses systems engineering to define the challenge caused by coastal flooding and future sea levels, and risk-informed decision methodologies to define the exposure. The findings show that the investment in a new pump station reduces relative risk due to coastal flooding nearly fivefold; but over the 50-year life cycle of the pump station the risk increases again because of higher sea levels.

This thesis is dedicated to my dog Abbie named after Young Frankenstein's brain, Abbie Normal.

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NOMENCLATURE

AE	FEMA Code for Land Covered by 100-year Base Flood
ALARP	As Low As Reasonably Practical
ASCE	American Society of Civil Engineers
BFE	Base Flood Elevation
CO	Clean Out
Elev.	Elevation
EPA	Environmental Protection Agency
EPS	Existing Pump Station
ERP	Elizabeth River Project
ETA	Event Tree Analysis
FEMA	Federal Emergency Management Agency
F-N	Frequency of N or More Fatalities Per Year
HMGP	Hazard Mitigation Grant Program
HP	Horse Power
HRPDC	Hampton Roads Planning District Commission
HRSD	Hampton Roads Sanitation District
HSE	Health & Safety Executive
Interm	Intermediate
MARI	Mitigation and Adaptation Research Institute
MHHW	Mean Higher-High Water
MSL	Mean Sea Level

NAE	National Academy of Engineering
NAVD	North American Vertical Datum
NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
NPS	New Pump Station
NRC	National Research Council
ODU	Old Dominion University
O/U	Over-Under
PAR	Population At Risk
PS	Pump Station
RPM	Revolutions Per Minute
SCADA	Systems Control and Data Analysis
SDVF	Single-Dimensional Value Function
SPGF	Submersible Pump Grinder F model
SWL	Stillwater Level
TDH	Total Discharge Head
USACE	U. S. Army Corps of Engineers
VA	Virginia
VAC	Virginia Administration Code
VDOT	Virginia Department of Transportation
VIMS	Virginia Institute of Marine Services
WSU	Wave Set-Up
w/	with

A	Area
A_1, A_2…A_i	Events in Sample Space Ω
b	Constant for a rate of sea level rise measured at a tide gauge
dx_1, dx_2, …dx_i	Derivative of the function of $f\bar{x}$
E[M]	Expect Value of M, Margin of Safety
F	Force
F_{x_1}, F_{x_2}	Distribution Functions for Variables X_1, X_2
$\boldsymbol{f}_r$	R Function
f_s	S Function
$f\bar{x}$	Joint Probability Density Function
$f_r(x)$	Resistance Probability Density Function
$F_r(x)$	Resistance Probability Distribution Function
ft	feet
g	Failure Function
gpd	gallons per day
gph	gallons per hour
gpm	gallons per minute
H	Hydraulic Head (feet), Wave Height
h	Water Depth
i	Element I in a set of I
in	inches
k	Wave Number
L	Length, Wave Length

M	Margin of Safety Function
m	meters
m^3	cubic meters
mm	millimeters
m_R, m_S	Medians of R and S
N_L	Project Design Life
n	number
P	Load
P(A)	Probability of Event A
$P(A_1 \cup A_2 \cup A_3 \cup \dots)$	An infinite sequence of mutually exclusive events
$P(A_1 \cup A_2 \cup \dots \cup A_n)$	A finite sequence of mutually exclusive events
$P(A \cap B)$	Probability of both Events A and B occur
$P(B\|A)$	Probability of B given the Event A
P_E	Encounter Probability
P_f	Probability of Failure
P_F	Probability of Failure
P_L	Lifetime Probability
P(Ω)	Probability within the Sample Space
P(X>x)	Probability of sample value x is less than Random variable X
p	Probability
pdf	Probability Density Function
p_r	Probability of Failure, Area under Probability Density or Cumulative Probability Curve
Q	Volume of Flow (gpm)

R	Required Resistance or Capacity of a Structure
R	Risk
R_F	Reverse of the Probability of Failure
R(t)	Change of Resistance Over Time
S	Load Applied or Demand to a Structure
SF	Safety Factor
S(t)	Change of Strength Over Time
T, t	Time Period
T_R	Return Period
V(A)	Measure of Overall Impact of Risk Event
V_1, V_2, …Vi	Value of Consequences
V^+, v^+	Mean-Up-Crossing Rate
V_R	Coefficient of Variation for R
w_1, w_2,…w_i	Relative Weights of Consequences
$\bar{X}$	Vector-Valued Random Variable
X_1, $X_{,2}$, ...X_i	One-Dimensional Random Variables
X_{r1}, X_{r2}…X_{ri}	An R random variable
X_{s1}, X_{s2}…X_{si}	An S random variable
x_1, x_2	Values of Random Values X_1, X_2
$\bar{Z}$	Normalized Variable
Z_R	Normalized Value for R
Z_S	Normalized Value for S
∀	For All, For Any, or For Each

=	Equal Sign
∞	Infinity
$\mathcal{K}$	Dimensionless Number in wave set-up calculations
%	Percent
$\int$	Definite Integral
$\cup$	Union
$\cap$	Intersection
β	Reliability Index
β_{HL}	Hasofer and Lind's Reliability Index
Γ	Safety Factor
γ_R	Safety Factor for R
γ_S	Safety Factor for S
$\bar{\eta}$	Mean Water Level
$\bar{\eta}_b$	Wave Set-Down
$\bar{\eta}_{max}$	Maximum Wave Set-Up
$\bar{\eta}_s$	Wave Set-Up
h_b	Water Depth at $\bar{\eta}_b$
μ_g	Mean Value of the Failure Function, g
μ_M	Mean Value of the Variable M
μ_R	Mean Value of the Variable R
μ_S	Mean Value of the Variable S
π	Pi
σ_g	Standard Deviation of the Failure Function, g

σ_M	Standard Deviation of the Variable M
σ_R	Standard Deviation of the Variable R
σ_{lnR}	Standard Deviation of the natural log of the Variable R
σ_S	Standard Deviation of the Variable S
ρ_{RS}	Correlation Coefficient for Variables R and S
Σ	Summation
Φ	Cumulative Standard Normal Distribution Function
Ω	Sample Space

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CHAPTER 1

INTRODUCTION AND RESEARCH PROBLEM CONTENT

1.1 Problem Background

In May 2014, Kristen Lentz, PE, Director of Utilities for the City of Norfolk, asked if Old Dominion University (ODU) could revisit applications for grant funds to increase the resiliency of four submersible wastewater pump stations. (See Appendix A, May 23, 2014 entry.) The city submitted Pre-Application Form DR-4092-VA, Hazard Mitigation Grant Program (HMGP) to the Commonwealth of Virginia to seek Federal Emergency Management Agency (FEMA) funds to reduce the exposure of Pump Stations (PS) 109, 112, 113, and 114 (City of Norfolk, 2013b). All four are located in low-lying areas along the Lafayette River, a tidal estuary in the Lockhaven and Larchmont/Edgewater neighborhoods.

The city sought the funds to improve the resiliency of the pump stations when exposed to coastal flooding. The application noted such actions as (1) elevating control panels, (2) installing new submersible pumps, (3) raising the wet well elevations, and (4) installing watertight hatches. In the case of PS 113, the city is preparing to replace the existing station with a new station located on higher ground one block in-land (west) from the Lafayette River.

Ms. Lentz noted that the Commonwealth rejected the four pre-applications stating the risk to the stations was too low to justify the funding. She asked if the College of Engineering and Technology could study the risk to these stations.

Further discussions led to a refinement of the problem statement. The author proposed assessing the impact on PS 113 and its alternative to compare how improvements increased resiliency. Figure 1 provides a vicinity map and Appendix A provides a journal logging discussions with the city and associated contributors to this study.

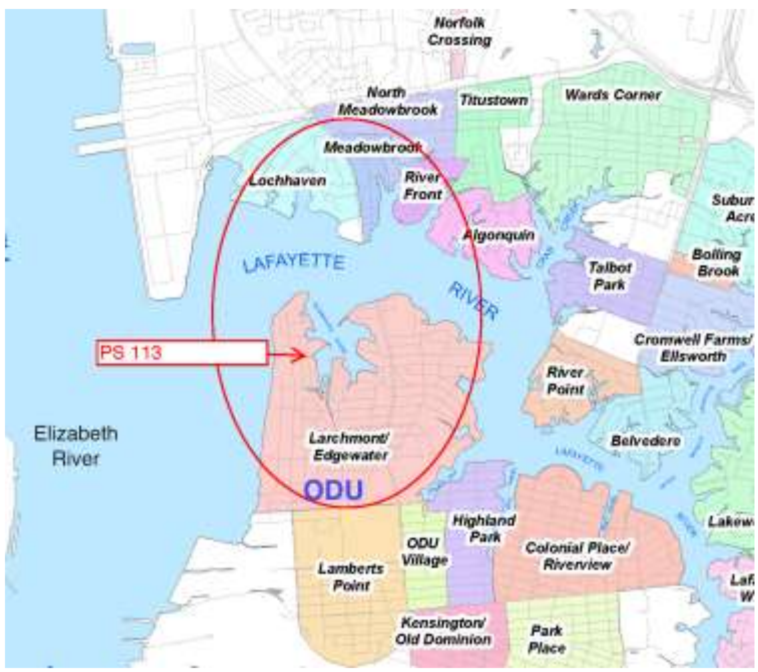

Figure 1. Vicinity Map for Pump Station 113 (City of Norfolk, 2013a)

1.2 Project Problem Statement

The problem statement is to determine the risk to existing Pump Station 113 and its planned replacement to an increase in coastal flooding caused by rising sea levels. The location for the existing pump station is in the Larchmont/Edgewater neighborhood at the corner of Walnut Hill Street and Sylvan Street. The new location is one block west at the corner of Walnut Hill Street and Rolfe Avenue. Figure 2 shows the sewerage shed area and pictures of the site are in Appendix A.

The Lafayette River tidal estuary drains into the Elizabeth River that leads to the Chesapeake Bay and the Atlantic Ocean. The low-lying areas along the river are subject to tidal flooding, and coastal surges caused by tropical and extra-tropical storms that flood the bay. There is an open storm drain at the east end of Walnut Hill Street where these hazards often flow up into the street, backup runoff from rain events and extend the flooding further inland.

Figure 2. Pump Station 113 Service Area (O'Brien & Gere, 2011)

Also, the tidal areas of Southeastern Virginia are experiencing an increased frequency of flooding due to rising sea levels (Boon, Wang, & Shen, 2008). Combinations of changes in the climate, regional subsidence, and ocean currents have caused regional sea levels to rise. In addition, the scientific community expects the rate of change to increase over the 21st century. As a consequence, future storm events will occur on ever increasing tide levels resulting in more frequent and extensive flooding of these low lying areas.

1.3 Project Study Objective

This study objective is to define present and future flood hazards, and analyze the impact of these hazards on the operational performance of the existing and new pump stations. The analysis translates the impact into a risk-informed decision framework that assesses the pumps' resiliency to coastal flooding.

The risk is a function of exposure to flood stages, pump station failure modes, and consequences due to failure. The results show how this combination changes as flood stages change over time and compares the difference in performance between the existing and new pump station locations. In addition, the framework provides the Department of Utilities a means to communicate the risks and the need for any adaptive actions to City Council and the public.

CHAPTER 2

LITERATURE REVIEW AND DISCUSSION

2.1 Outline for the Literature Review

The project question is: what is the risk to the existing Pump Station 113 and its planned new location to an increase in coastal flooding caused by rising sea levels? In order to address the question, it is necessary to determine how to assess the risk to a submersible wastewater pump station exposed to present day and future levels of coastal flooding. The literature review uses a list of subset questions listed below to outline an approach to develop an appropriate methodology to assess the risk. The review is structured to first understand an approach applicable to any form of infrastructure and then outline methods specific to submersible wastewater pumps.

a. What is the problem scenario?
b. What is an appropriate way to assess the problem scenario?
c. What is the appropriate risk-informed decision methodology to evaluate impacts?
d. How do rising sea levels impact the performance of the pump stations?
e. What is an appropriate means to demonstrate the impact on the performance of the pump stations?

2.2 Review by Subset Questions

2.2.1 Subset Question a: What is the problem scenario?

The City of Norfolk and the greater Hampton Roads region are experiencing an increase in the rate of coastal flooding caused by rising sea levels. *The Virginian-Pilot* has published numerous newspaper articles on how vulnerable the Tidewater region of southeastern Virginia is to rising sea levels (Tompkins & DeConcini, 2014). These media accounts have referenced sources identifying the Norfolk area as having the highest relative sea level rise rate on the east coast. They also have identified Norfolk as the most exposed urban environment in the United States, second only to New Orleans

An example that reinforces this perception is a study by the Virginia Institute of Marine Sciences (VIMS) that explains how sea level rise is increasing the region's vulnerability to the impacts of storm surge (Boon, 2005). The study compares the impact of Hurricane Isabel in 2003 with an unnamed hurricane in 1933 using data recorded on Tide Gauge 8838610, Sewells Point, Virginia located at Naval Station, Norfolk. Even though the 2003 event produced a lesser surge of approximately 1.45 meters (m), the storm tide high water marks equaled those of the 1933 hurricane that produced a surge of about 1.78 m. Boon (2005) in the above reference attributes the comparable impact of the lesser storm to the fact that sea levels in the region had risen some 0.30 m over the 70-year span between the two storms.

More recently, the National Oceanic and Atmospheric Administration (NOAA) website provided data on extreme water levels for the Sewells Point, Virginia (VA) tide gauge (NOAA, 2015). Figure 3 shows the historic upward trend in water levels and includes the 1 - percent (%), 10%, 50%, and 99% annual exceedence probability levels in red, orange, green, and blue.

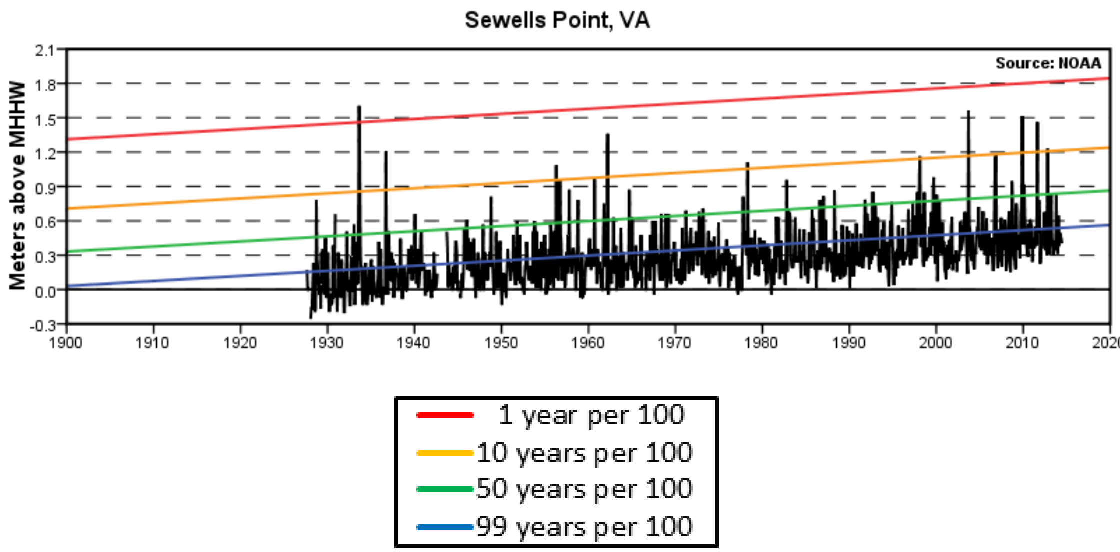

Figure 3. NOAA Extreme Water Levels, Tide Gauge 8838610, Sewells Point, VA (NOAA, 2015)

As evidence of this trend, NOAA includes a link at the same webpage to tables of the Top Ten Highest Water Levels for Long Term Stations in both feet and meters above Mean Higher-High Water (MHHW) (as of June 2014). Table 1 lists the top ten events for the Sewells Point Tidal Gauge. The trend shows four events occurred over 73 continuous years in the 20^{th} Century or about one every 18 years; however, six have occurred since 2001 at a rate of one every 2.5 years.

Table 1. NOAA Top Ten Highest Water Levels for Tide Gauge 8838610 Sewells Point, VA (NOAA, 2015)

Storm	Elevation Feet MHHW	Elevation Feet NAVD (88)	Elevation Feet MLLW
8.23.1933	5.26	6.41	8.02
9.18.2003	5.13	6.28	7.89
11.12.2009	4.97	6.12	7.73
8.28.2011	4.80	5.95	7.56
3.7.1962	4.46	5.61	7.22
10.29.2012	4.04	5.19	6.80
9.18.1936	3.96	5.11	6.72
11.22.2006	3.87	5.02	6.63
2.5.1998	3.82	4.97	6.58
10.7.2006	3.76	4.91	6.52

From a historic perspective, changes in sea levels have been relatively stable and our community has enjoyed imperceptible changes since its founding 500 years ago (Figure 4). However, for the first time in 7000 years, people are experiencing changes in sea levels that are perceptible and disruptive to our way of life. We now face the potential for dramatic change within one lifetime (Plag, 2014).

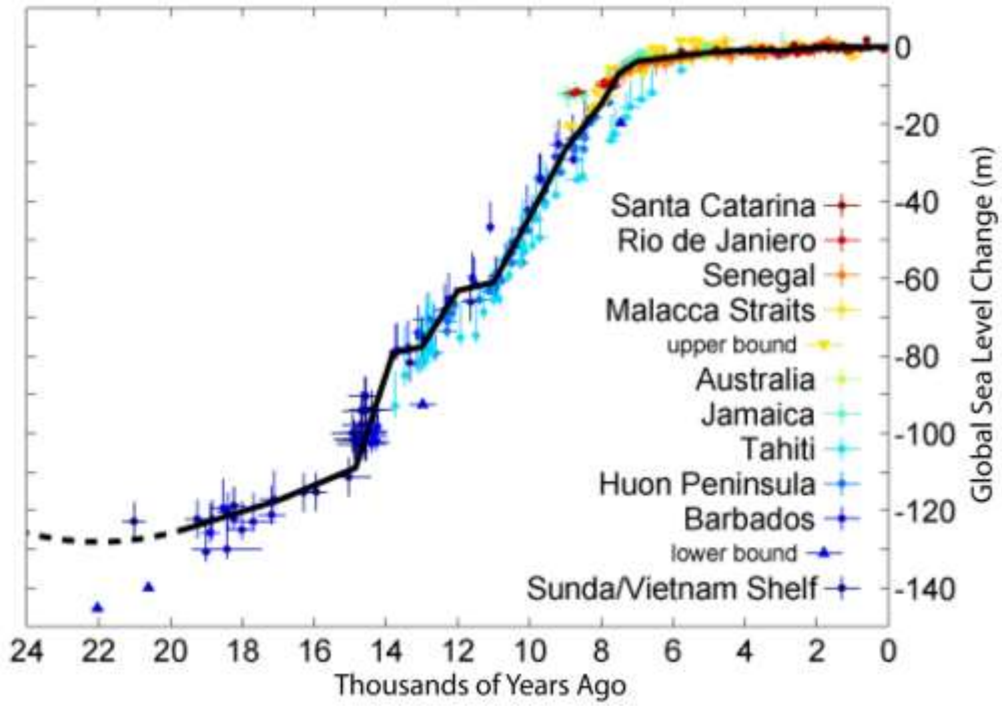

Figure 4. Global Sea Level Changes (Plag, 2014)

From a scientific perspective, it is the uncertainty associated with projecting a rate of rise and quantifying impacts that creates the complexity. In 1987, the National Research Council (NRC) warned that historic sea level rise trends have the potential to start accelerating (NRC, 1987). It further advised that the rate of future sea level rise is too uncertain to estimate expected probabilities. Therefore, the NRC recommends developing sea level rise scenarios to identify trends for planning adaptive measures.

Locally, the Virginia Institute of Marine Resources (VIMS) prepared a report for the Virginia General Assembly and included four sea level rise scenarios (VIMS, 2013). In addition, the Hampton Roads Planning District Commission (HRPDC) prepared a series of studies culminating with planning guidance for assessing the potential impact of rising sea levels that incorporates VIMS' four scenarios (McFarlane, 2013). Figure 5 and Table 2 provide current projections for Hampton Roads, Virginia based on the observed and projected sea level change at the Sewells Point Tide Gauge.

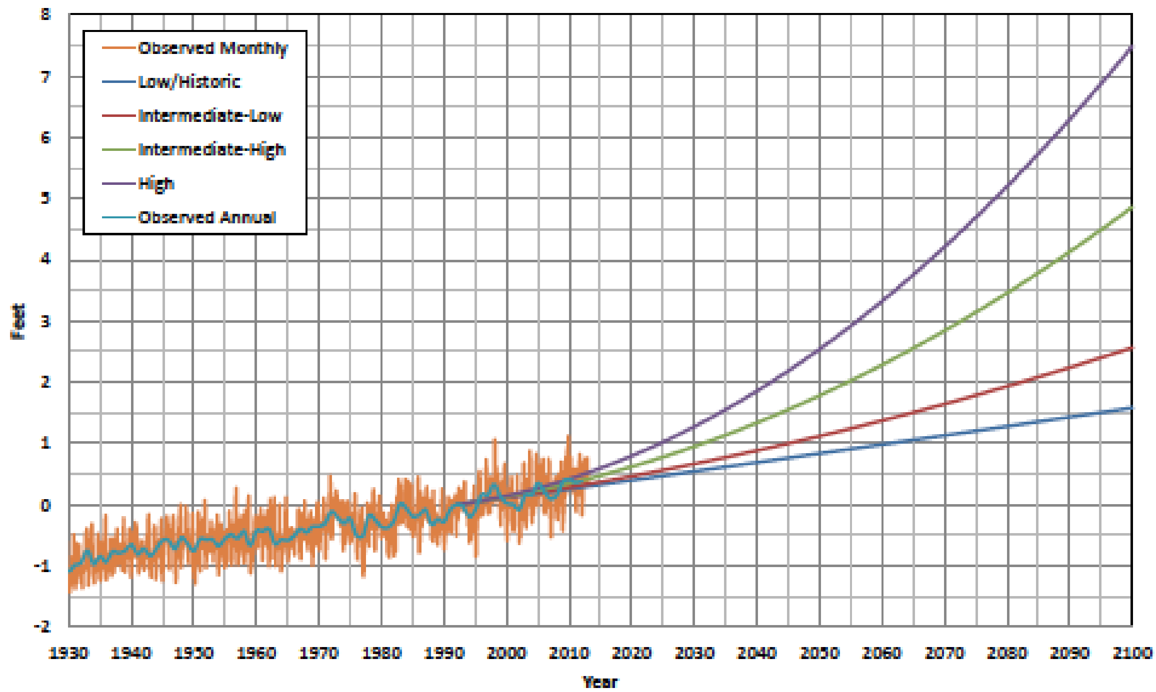

Figure 5. Observed and Projected Sea Level Rise Change, Norfolk, VA 1930-2100 (McFarlane, 2013)

Table 2. Sea Level Rise Projections for Norfolk, Virginia (McFarlane, 2013)

Scenario	Sea Level Rise, 1992 - 2100
High	7.5 feet (2.30 meters)
Intermediate to High	4.9 feet (1.50 meters)
Low to Intermediate	2.6 feet (0.80 meters)
Low (Historic Trend)	1.6 feet (0.50 meters)

So there is growing physical evidence and understanding of emerging long-term natural threats to the region and its vulnerabilities. However, there is a lack of political will to embrace long-term policies to adapt to these pending changes in the face of other competing needs. There is even an element of the state's political power that has challenged the science behind the causes (Luzzatto, 2014).

2.2.2 Subset Question b: What is an appropriate way to assess the problem scenario?

2.2.2.1 A Basis for Taking an Integrated Systems Approach

In the aftermath of forensic investigations of the devastating impact of Hurricane Katrina, the American Society of Civil Engineers (ASCE) is leading a national dialogue on critical infrastructure, which recommends the following guiding principles to protect the public's health, safety and welfare (ASCE, 2009), (ASCE, 2014.a) and (ASCE, 2014.b):

- Quantify, communicate, and manage risk
- Employ an integrated systems approach
- Exercise sound leadership, management, and stewardship in decision-making processes, and
- Adapt critical infrastructure in response to dynamic conditions and practice

It is the author's position that these four guiding principles should form the basis for understanding the impacts of rising sea levels and for applying adaptive measures to cope with this dynamic condition. Although PS 113 is a small system in scope and scale, how ODU researches the problem scenario and how the city addresses coastal risks requires an integrated systems approach in the form of a hierarchy. Therefore, it is necessary to frame the problem in such a way that the pump station aligns within a regional system adapting to the changing sea levels.

The word system has many meanings. For this study there are two aspects to applying the word system as a way to address the problem scenario. The first is to think of the word "system" as a noun; as a body that is composed of integrated parts that make it function. The second is to think of the word "systems" as an adjective as in a systems approach, a process to understand and describe how those integrated parts make that body function.

For our particular problem scenario, the project is within a coastal system. The physical extent of this system starts at the Atlantic Coast along the mouth of the Chesapeake Bay. It continues into the bay, its estuaries, and to the extent of tidal waters into the numerous tributaries that feed the bay. It includes all the aspects that have made Tidewater, Virginia a place for over a million people to call home.

Therefore, the coastal system is more than a physical entity. People are part of the system and have introduced many devices to manage the system and make it an environment that supports a coastal community. In answering this subset question, it is necessary to describe what constitutes a coastal system and devise a systems approach to understand how the integrated parts of a system function as a body.

2.2.2.2 The Coastal Environment as a System

The challenge is how do we describe our coastal system? The traditional approach defines a coastal system by its physical attributes and response to environmental changes. However, choosing to live on the coast is what makes rising sea levels a hazard for communities coping with its impact. Therefore, we need to describe a coastal system as a community living within a coastal environment, and this community is a group of people living in the same locality within one governing body exposed to a common hazard (Morris, 1976).

What the community needs to understand is the linkage between the natural system and the multiple forms of manmade subsystems that support living within a dynamic coastal environment. The National Academy of Engineering (NAE) promotes a systems approach to address the need to balance the various benefits and costs of a water resources project, and the need to integrate the project within a system framework to minimize impacts to other components (NRC, 2004).

For projects in river basins, the NAE notes watershed systems are easily delineated based on topographic divides; but for projects in a coastal environment, the complex and dynamic nature of the shoreline makes delineating a system more problematic. It further notes that a coastal system is highly vulnerable to the effects of human development activities. The U. S. Army Corps of Engineers (USACE) proposes delineating coastal systems by sand budgets, but acknowledges political challenges when it involves multiple jurisdictions (USACE, 2015a). One possible perspective is to describe our community on the coast in terms of an enterprise system.

George Rebovich, Jr. describes a concept termed “enterprise systems engineering”. He explains the need for a new way of thinking “a systems thinking that captures the fundamental relationships of information to complexity so that designers of every kind of enterprise can secure the benefits and avoid the pitfalls of enormous change.” This new systems thinking is rooted in “evolutionary biology” (Rebovich, 2005). Though his approach is more aligned with communication, information, and manufacturing type systems, it offers a means to assess the performance of infrastructure within a coastal system experiencing an evolutionary change in the form of sea level rise.

Pinto and Garvey present a structure for risk analysis in engineering enterprise systems based on Rebovich’s work (Pinto & Garvey, 2013). The concept is applicable to “…an enterprise of people, processes, technologies, and organizations.” A key feature is how it captures the way users interface with technologies and with one another. Also, Pinto and Garvey quote Rebovich to explain an enterprise as “an entity comprised of interdependent resources that interact with one another and their environment to achieve goals.”

This approach reflects how systems engineering has evolved to address social-technical challenges in engineering, asking how does a system affect society and how does society affect a system? This is a critical component to understanding a coastal community. It will take adaptation to cope with the dynamic equilibrium, i.e., an equilibrium that is experiencing an accelerating rate of change. Engineers will need to develop solutions that people will want to embrace. How do engineers do this given the emerging hazards?

One way is how Pinto and Garvey link Rebovich's work with that of J. Gharajedaghi about how modern system thinkers are viewing enterprises holistically (Pinto & Garvey, 2013). Gharajedaghi offers four characteristics of a holistic view (Gharajedaghi, 1999):

- A multi-minded sociological entity comprised of a voluntary association of members who can choose their goals and means
- An entity whose members share values embedded in a (largely common) culture
- An entity having the attributes of a purposeful entity
- An entity whose performance improves through alignment of purposes across its multiple levels

Rebovich's and Gharajedaghi's perspective offers a means to view a coastal community from a systems engineering perspective. It provides a basis for understanding the linkage between the region's natural system and the multiple forms of manmade subsystems that support living within the region's coastal environment.

Pinto and Garvey offer a framework to understand such linkages, which can be applied to assessing the impacts of rising sea levels on our infrastructure (Pinto & Garvey, 2013). They present a methodology using risk and decision theory to formulate a means for stakeholders to understand the hazards, the potential for consequences from those hazards, and an approach to judge appropriate solutions to adapt to these hazards. A key component to the framework is a value function quantifying the contributions of the various components that make up a system.

There are two challenges. How do we view the region as an enterprise system and how do we assess the value of infrastructure in order to measure risk? There is a wide range of disparate forms of infrastructure within any community. How do we assess their value in a consistent manner?

As noted above, the first of two subset questions is how do we view the region as an enterprise system? Simon Haslett applies a systems engineering perspective and explains the coast in a process-response system model (Haslett, 2000). He explains that coastal dynamics are a function of energy that drives processes, which cause changes in the shoreline. Primary sources are endogenetic energy, exogenetic energy, and the gravitational attraction of the sun and moon. Endogenetic energy is heat from within the earth's core lost at the surface by tectonic and volcanic activity and is not an energy source for this region. However, exogenetic energy and the solar gravitational attraction are dominant energy sources in southeastern Virginia.

Exogenetic energy is from solar energy, which drives kinetic (wind) energy and the hydrologic cycle. Solar energy heats the earth, which creates wind and waves that impact the shoreline. The hydrologic cycle is the result of the transfer of water in the form of rain from natural sources such as lakes, bays and oceans. The runoff drains to rivers that feed estuaries such as the Chesapeake Bay.

The gravitational forces drive the local tides, which have a semi-diurnal cycle in this region. The tides extend up the local rivers as far as Richmond on the James River.

It is these two sources of energy that dominate the local region and define its system dynamics. The resulting winds, waves, tides, rainfall and river flows move and shape the local terrain and shoreline. These changes have a direct impact on the region's vulnerability.

Haslett further explains it is best to observe a natural environment as an open system with inputs and outputs of energy and materials and how the components are inter-related (Haslett, 2000). The challenge is defining a coastal system's boundaries, identifying subsystems and their components, and understanding the relationship of energy and the resulting movement of material (water and sediment) through the coastal system.

He offers four basic ways to model how components are linked by energy and sediment flow within a coastal system: as a cascading system, a morphological system, a process-response system, and as an ecosystem. (Haslett, 2000). Of the four, the process-response system best describes how the dominant energy source induces sediment migration in the form of erosion and accretion within the Virginia coastal system.

The cascading system describes the dynamic relationships between components such as the flow or “cascade” of energy through the coastal environment. The morphological system describes the flow of sediment movement driven by the cascading energy between the components. However, the process-response system combines both the cascading and morphological concepts and best explains how changes in environmental forces such as rising sea levels will shape sediment migration and coastal formations (Haslett, 2000).

Continuing to follow Haslett’s model, an existing environmental condition reflects its current state of evolution as the coastal system adjusts to ever changing conditions. As our coast is exposed to changes in energy conditions, its morphology responds in an effort to seek a state of equilibrium. A state of steady equilibrium reflects minor changes over a long-term average such as adjustments to the rhythms of a tidal cycle. A state of meta-stable equilibrium is a dramatic adjustment to a short-term event such as a barrier island breach in response to a major storm like Hurricane Sandy. A state of dynamic equilibrium is an adjustment to a gradual long-term change such as shoreline retreat in response to a rising sea level.

For our region, the primary driver for change in terms of coastal conditions is a warming of the atmosphere and there are two outcomes that will impact our environment (VIMS, 2013). The first is an apparent acceleration in the rate of sea level rise and the second is the potential for greater and more frequent storms. Therefore, our region is experiencing a state of dynamic equilibrium with the potential for more frequent and larger intervening meta-stable adjustments in the equilibrium.

The challenge is how do we define the hazard and its potential impact within such a coastal system, how do we integrate adaptive measures, and how do we assess the risk to these measures?

As discussed above, this study examines the coastal system as an enterprise system. Per Pinto and Garvey, an enterprise system is a network of interdependent people whose processes and supporting technology are not fully under the control of any single entity. A characteristic of an enterprise system is an absence of firm and fixed specifications under the control of a centralized authority agreed upon by participants at different organizational levels. Solutions within this kind of structure require stakeholder involvement and agreement for any form of adaptation and are far more difficult than technology alone can solve.

This description is in line with our democratic society. We are a country composed of interdependent groups of federal, state and local governments. Diminished control is demonstrated by how responsibilities for certain laws, regulations, policies and codes are distributed at each of the government levels. Also, the lack of firm and fixed specifications are evident by the legal actions needed to resolve conflicting interpretations of these laws.

Therefore, an enterprise system structure offers an opportunity to assess vulnerabilities within the dynamics of a democratic society in an environment that is subject to dynamic evolution. The structure provides a basis for analyzing risk with stakeholder input and presenting it in a format to assist decision makers to make informed choices as to appropriate adaptive actions.

2.2.2.3 The Representation of a Coastal System

Whereas an enterprise system can serve as a social representation of a community, understanding impacts of a dynamic environment on infrastructure makes it a social-technical problem. It is the actions and decisions at the community level that will shape how the jurisdictions will adapt.

For example, if the community decides to build barricades along the oceanfront such as levees, seawalls and beach fills along the shoreline and a lock and dam at the mouth of the Chesapeake Bay and inlets, jurisdictions can expect minimal changes in sea levels and reduced impacts from storm surges. Such a condition promotes the status quo and a minimal need to make dramatic changes. If the decision is a partial retreat to barricade at the mouths of rivers and along the shoreline, then it will promote redirecting development more in-land. However, if the decision is a managed retreat to the west and to protect urban centers such as Richmond, Washington DC, and Baltimore, then investment in the locale will shift from capital improvement to mass migration.

From an enterprise system perspective, the need for the community to make decisions makes the social component more dominant than the technical component. It is important to represent this kind of system as a set of interrelated parts. It is the interaction between these parts as a whole system that generates emergent behavior, properties that are different from the capability of any of the parts acting alone. These properties are unknown in advance and patterns only emerge through the operation of the system. When this is the case, networking principles apply as a means to represent a social system for the purpose of explanation, prediction and control (Lawson, 2005).

A network approach describes the behavior of the system and the interactions between its parts. It is more appropriate for elements whose properties evolve as a result of these interactions and lead to emergent behavior that is not expected and unintended. This is the kind of behavior characteristic of a social system. Keys to success are stakeholder involvement, continuous learning in the face of change, and problem resolution (Decker, Ciliers, & Hofneyr, 2011).

From the infrastructure perspective, there is a need to emphasize the technical component of the problem. An appropriate methodology is to take a reductionist approach based on Descartes' guidance to divide a system into parts to explain, predict and control its behavior (Lawson, 2005). This approach is better for technical systems where elements can be presented in a hierarchical structure. Keys to success with this approach are defined conditions, control of resources, and modeling. A drawback of this type of representation is a weakness to predict and control possible emergent properties, particularly as the social component of a social-technical problem is more dominant relative to the technical component.

An alternative to the network approach is to recognize that a hierarchical representation is a special case of a network. Figure 6, based on work by Errol Lawson, is a representation of a social system where the heavy lines can represent a technical hierarchy within the network. It offers a means to “transition from a learning, problem solving, and task-defining network to a hierarchical structure, which facilitates reduction of a complicated program to a set of simpler tasks, unambiguous control, prediction of outcomes and control of resources.” (Lawson, 2005).

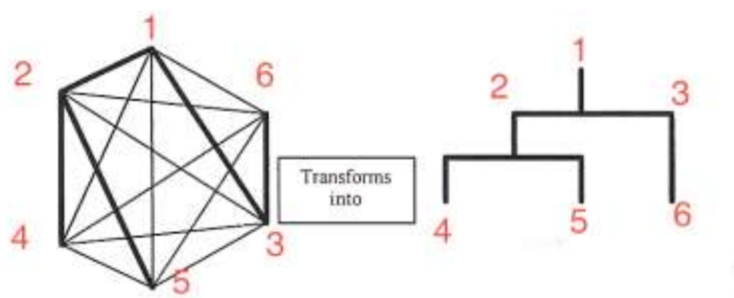

Figure 6. Transformation from Network to Hierarchy

For this example, the graphic represents a group of six entities within a network where the six points on the lopsided hexagon represent each of the entities. The lines in between the entities represent communication links, and the heavy lines represent the six entities selected to represent a particular hierarchy.

It is important to note that within a social-technical system, it is critical to establish the network first to comprehend the links before transforming to a hierarchy. If the hierarchy is defined by itself, it lacks the connections to mobilize the full social aspects of the social-technical system. It will fail to detect and cope with non-routine problems such as emergent behavior (Lawson, 2005).

It is beyond the scope of this project to explain a community and all its aspects such as governance, finance, insurance, health care, education, etc., as a network. In the absence of that kind of explanation, the author proposes a hierarchy as shown in Figure 7 to represent infrastructure that supports the broad community such as private utilities and public works within the community's network. Pump Station 113 fits within Level 3, where jurisdictions are responsible for the collection of their own wastewater for transfer to a regional authority (Level 2), Hampton Road Sanitation District (HRSD).

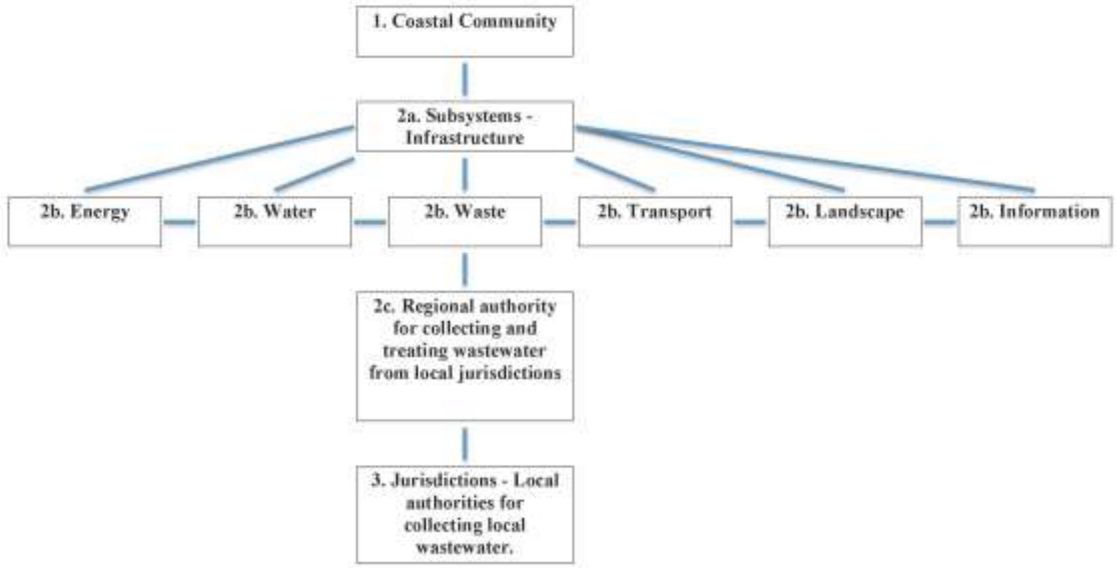

Figure 7. Hierarchical Structure of Local Infrastructure Systems

A hierarchical structure offers a simple way to reduce a portion of a complicated network to a simpler representation. The simplification helps facilitate aligning responsibilities, clarifying control, predicting of outcomes and controlling resources.

However, it must be understood such a hierarchical structure is a most limited representation within a dynamic environment. If a Level 2 subsystem ignores the full linkage of the community network, the subsystem gives the false impression it has control and the ability to predict outcomes. In reality, the subsystem will fail to cope with unforeseen problems and errors outside of its linkage.

With an understanding of these limitations, the top of the hierarchy in this example is the coastal community and as an enterprise system its primary function is governance. Margaret Peloso, Ph.D., ESQ, a physical scientist specializing in environmental law and climate change, examined the role of government in reducing vulnerability to sea level rise. She notes "the fundamental governance challenge in adapting…lies in crafting institutions that can critically examine our coastal assets and employ the best combination of defense and retreat to protect…resources from the threat of rising sea levels." (Peloso, 2012). She proposes a vulnerability approach to help government assess the risks posed by the changing environment and evaluate alternative adaptive measures.

Peloso presents a definition of vulnerability to climate change as "…a measure of society's inability to cope with shifts in climate patterns and the resulting changes in environmental conditions and resource availability." She explains that the definition "…recognizes that both natural and social factors contribute to vulnerability." Furthermore, she states there are three key elements of vulnerability: (1) exposure to natural hazards, (2) resilience, i.e. a system's ability to withstand disturbance and recover, and (3) adaptive capacity, i.e. society's ability to choose among various adaptive options. In addition, she adds reduction of near-term vulnerability need to focus on improving resiliency and the adaptive capacity of communities, or reduce exposure through retreat.

As she explains it, an increase in adaptive capacity can equip communities with tools to understand the effects of change, options available, and the costs and benefits of these options. These tools will provide a better understanding of options and enable decision makers to evaluate the merits of infrastructure and retreat alternatives.

Therefore, enhancing adaptive capacity can create the governance structures needed to generate and communicate scientific information about environmental change; and to do it in a way it can be used to make policy decisions reflecting the social values of its denizens.

It is at Level 1 (Figure 7), that a community's actions and decisions will shape how the jurisdictions adapt and reduce its vulnerability to rising sea levels. It is at this level that leaders in a community dialogue with the subsystems to define a desired quality of life in this new and dynamic environment.

In an effort to help Virginia's communities develop this capacity, William & Mary Law School established the Virginia Coastal Policy Clinic in 2013. Its goal is to debate science-based environmental and land use issues affecting the states coastal resources. It is striving to integrate science with legal and policy analysis to examine the implications of climate change on the coastal community (W&M, 2014).

Level 2a represents the range of interconnection, interdependent and relevant subsystems within the enterprise system such as public health care, education, social services, etc. It is at this level that subsystems strive to deliver and enhance the desired quality of life.

Level 2b represents the various forms of infrastructure that are critical components to supporting a community's quality of life. The author chooses to use classifications of infrastructure as defined in Institute of Sustainable Infrastructure, ENVISION™. This is a new a format for rating sustainable design for the forms of horizontally oriented infrastructure shown in Figure 7 (ISI, 2014) that complements existing guidance for vertical construction (USGBC, 2014). Also, the author links the infrastructure, because its various forms are interconnected and interdependent. For example, energy is critical to powering the water, waste, transport and information infrastructure across level 2b.

Level 2c represents subsets specific to the type of infrastructure. For this study, it is HRSD; a regional wastewater authority that serves a population of 1.6 million people living in seventeen jurisdictions in southeastern Virginia. It owns and operates nine major and four smaller treatment plants within a combined treatment capacity of 941,000 m^3/day (249 million gallons per day) (Morgan, Hubbard, Martz, Moore, & Wittenberg, 2012).

Level 3 represents the various cities and counties within HRSD's region. These jurisdictions collect and transport wastewater to HRSD pump stations where the wastewater is ultimately pumped to a HRSD treatment facility. It is at this level, Pump Station 113 collects wastewater that is moved to a HRSD pump station located on Powhatan Avenue within the Larchmont neighborhood for transfer to HRSD's Virginia Initiative Plant located on the Elizabeth River for treatment.

In framing the research problem, this study uses the hierarchical structure to explain how applying systems engineering can help the community cope with the impacts of rising sea levels. At each level it requires an understanding of systems philosophy and how that shapes the appropriate integrated systems approach to describe how the system's integrated parts work, This integrated approach forms the systems foundation needed to link the region's challenge with rising sea levels to PS 113.

2.2.2.4 A Systems Approach in the Form of Systems Engineering

As noted in section 2.2.1, Subset question a: "What is the problem scenario?" ASCE's guiding principles to protect the public's health, safety and welfare should form the basis for understanding the impacts of rising sea. A key aspect to these principles is developing a process to enable informed decisions as to the potential for loss in the face of uncertain conditions. Community leaders need such tools to judge and communicate appropriate risk reducing measures to mitigate losses.

Such decisions are hard and they have four primary sources of difficulty (Clemen & Reilly, 2001):

- A decision can be hard simply because of its complexity.
- A decision can be difficult because of inherent uncertainty in the problem situation.
- A decision maker may be interested in working toward multiple objectives, but progress in one direction may impede progress in other directions.
- A problem may be difficult if different perspectives lead to different conclusions.

According to Clemen & Reilly, a good decision “is one that is made on the basis of thorough understanding of the problem and careful thought regarding the important issues.” Decision analysis provides insight about the problem situation, uncertainty, objectives, and tradeoffs. Its outcome is to provide a tool to construct models of uncertainty and preferences to analyze a decision (Clemen & Reilly, 2001).

The critical step in a decision is getting an understanding of critical objectives. A strategy is to reduce a complicated problem into something smaller so that it can be more readily analyzed and understood. The goal is to develop a requisite decision model, which is one where the decision maker’s thoughts about the problem, beliefs regarding uncertainty, and preferences are fully developed (Clemen & Reilly, 2001).

Per the ASCE guidelines, employing an integrated systems approach is a means to structure a complex problem into something more manageable (ASCE, 2009). Incorporating risk as a means to assess uncertainty aids leaders to make informed decisions about potential trade-offs. Through risk, decision makers can communicate the potential for loss to the public.

Systems engineering is an outcome of military operations analysis, particularly during World War II. Its traditional approach is to quantify and seek optimal economic solutions. However, often economic optimization does not fully capture all the aspects of a decision. The process can inadequately represent or disregard aspects difficult to represent mathematically such as environmental impacts and social disruptions. Consequently, the public often rejects such optimized solutions (Checkland, 2000).

As a result, systems engineering is evolving to develop methodologies that try to cope with a scenario that is difficult to define. It is expanding its understanding of those aspects of a project that mathematics cannot easily represent. It is recognizing the need for satisficing alternatives, i.e., those that are not necessarily optimal, but good enough to balance economic, environmental and social needs (Keating, Calida, Sousa-Poza, & Kovacic, 2010).

A systems analysis offers a more holistic approach to assessing a problem scenario. The process provides a disciplined way of structured thinking grounded in a philosophical worldview often referred to by a German word, Weltanschauung. Its approach is more suitable for ill-defined problems, complex situations, and scenarios with emergent (unanticipated) outcomes (Keating, 2014).

As a start, it is important to frame the nature of the problem in order to focus further efforts. A problem is an undesirable situation or unresolved matter. A problem situation is when people hold different views when attempting to define the problem. The problem domain is defined by various attributes that describe the nature of a situation. These attributes are based on whether they reflect a traditional, well defined and agreed upon problem situation or a problem situation that is unique which involves human activity, is too ambiguous to define and is poorly understood (Table 3).

Table 3. The Nature of a Problem Situation (Keating, Peterson, & Rabadi, 2003)

Attribute	Traditional Problem	Unique Problem
Quantifiable	Yes	Not Easily
Structure	Understood	Emergent
Approach	Evident	Not Evident
Definition	Clear	Ambiguous
Environment	More Static	More Dynamic and Turbulent
Boundaries	Defined	Ambiguous

The challenge is judging where in the spectrum the attributes exist and whether the nature of the problem is causing shifts in the attributes. If circumstances vary temporally, then what worked in the past may not assure success in a more turbulent future. If they vary spatially, then what works in one place may be inappropriate in another region. Often, the problem evolves if the nature of the impacts change or the number and type of stakeholders change or if there is any new knowledge that better defines the problem. This challenge makes it difficult to develop optimal, resilient alternatives that would not change over a project's complete life cycle .

Therefore, there is a need for a process to help think through the problem. Figure 8 offers a graphic depiction of a systems engineering approach. The key all engineers can appreciate is the need for a solid foundation to build a systems understanding.

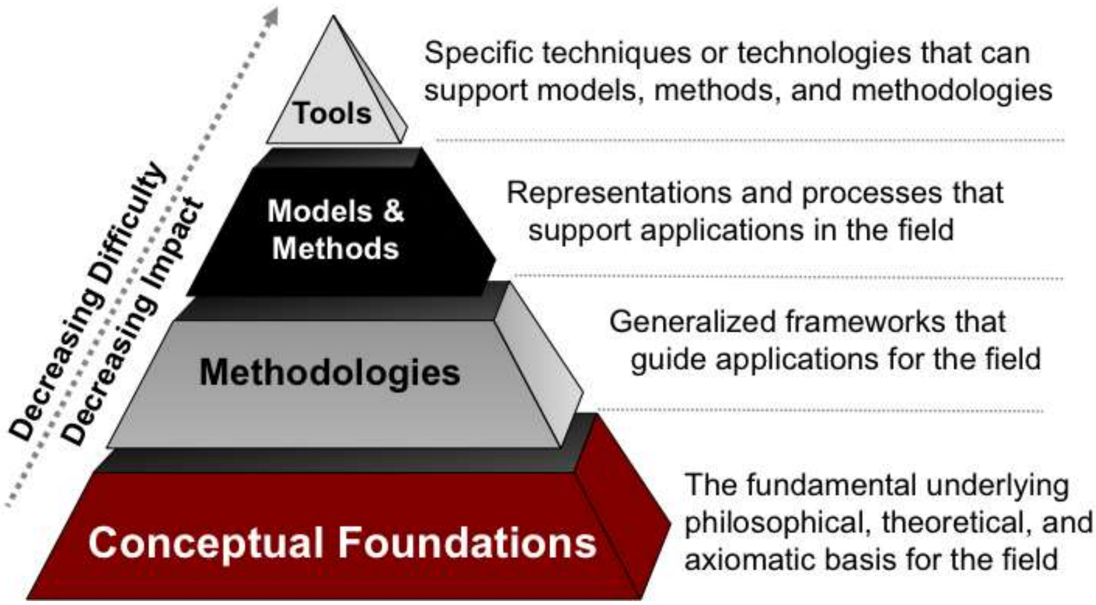

Figure 8. A Systems Engineering Process (Keating, 2014)

Figure 9 represents a disciplined approach to build the pyramid from the bottom-up. These elements help avoid a prescriptive viewpoint. This approach recognizes that systems thinking functions on multiple levels and provides a framework to seek input across these levels (Keating et al., 2010)

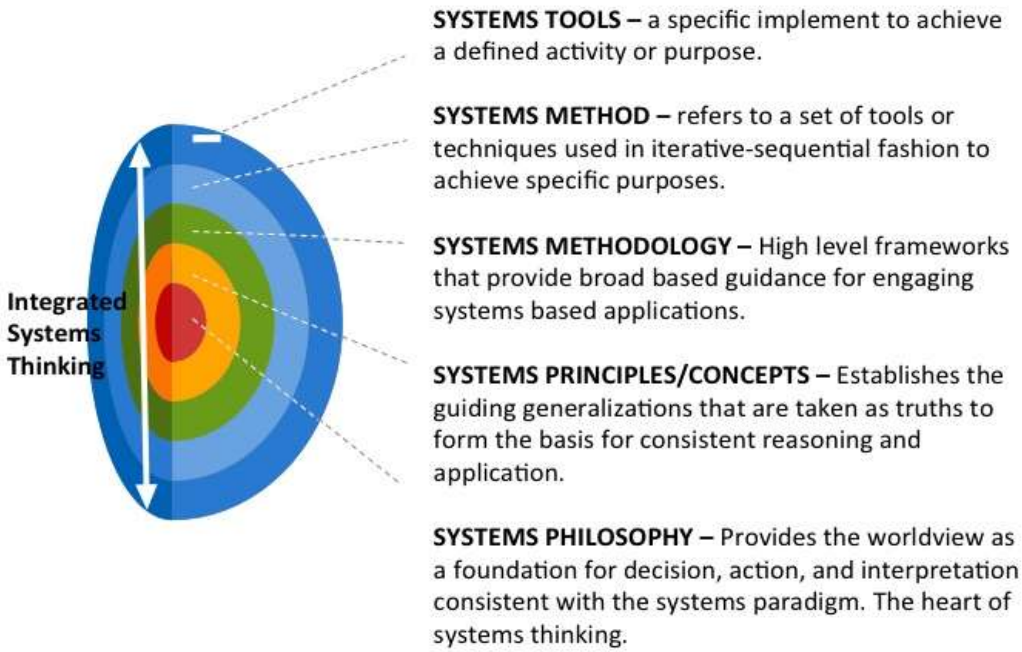

Figure 9. Foundations for Effective Systems Thinking (Keating et al., 2010)

However, it is the application of systems philosophy that most demands management skills. It is a starting point of the effort and where the engineer ensures he or she has the right stakeholders. It is this step where the engineer facilitates the philosophical discussions needed to define the stakeholders' problem situation.

There are conventional project management tools that an engineer can employ to help with this step such as performing an analysis of stakeholders' feedback, establishing a communications plan to support philosophical discussions, and building a knowledge management structure (Alavi & Leidner, 1999). In addition, other tools such as responsibility matrixes, work-breakdown structures and resource loading are applicable (Landaetta, 2010).

As an aid to fleshing out a philosophy, the engineer needs to ask seven questions to determine the degree of complexity (Keating, 2014).

1. What is the problem/need?
2. What are the interests and values of the primary stakeholders?
3. What is the relevant context (circumstances/factors/conditions that constrain/enable systems analysis and deployment such as social goals, values, and agendas)
4. What constitutes success/failure?
5. What is a compatible approach to proceed?
6. How do we circumvent likely failure modes?
7. What are the system problem boundaries?

Answering these questions lays out an analysis that will strive to assure that stakeholders' expectations are efficiently and continuously achieved throughout the project's life cycle. The engineer must continuously strive to ensure sufficient resources are available to support this critical aspect of systems thinking.

The goal of building a solid foundation is to avoid what is termed in systems analysis as Type III and Type IV errors (to differentiate from statistical errors Types I and II) (Keating, 2008a). A Type III error is solving the wrong problem precisely in the most efficient way possible. This is often caused by having the wrong stakeholders involved or letting biases shape the problem definition. A Type IV error is engaging in “muddled” thinking that is typically caused by a philosophical mismatch among stakeholders such that agreement is unlikely and movement to resolution is highly improbable.

2.2.2.5 Systems Philosophy

As noted in Figure 9, philosophy is the foundation for effective systems thinking. “A philosophy…provides the basis for making sense of what we perceive in the world.” (Keating et al., 2010). It provides the basis for an underlying worldview that informs a perspective, which drives some form of a consistent framework for decisions, actions, and interpretations.

There is no right or wrong philosophy, but there is a potential for disagreement among stakeholders as to what is the worldview as it applies to the problem, problem situation, and problem domain. An incompatibility of worldviews can render the best intentions impotent. This kind of disagreement can lead to a Type IV error described in section 2.2.2.4, A Systems Approach in the Form of Systems Engineering (Keating et al., 2010).

Figure 10 presents a range across two philosophical spectrums. Epistemology is the study of how we gain and communicate knowledge. It ranges from the objective to the subjective viewpoint. Ontology is the study of the nature of reality from which we derive knowledge. It ranges from reality being external or internal to the individual.

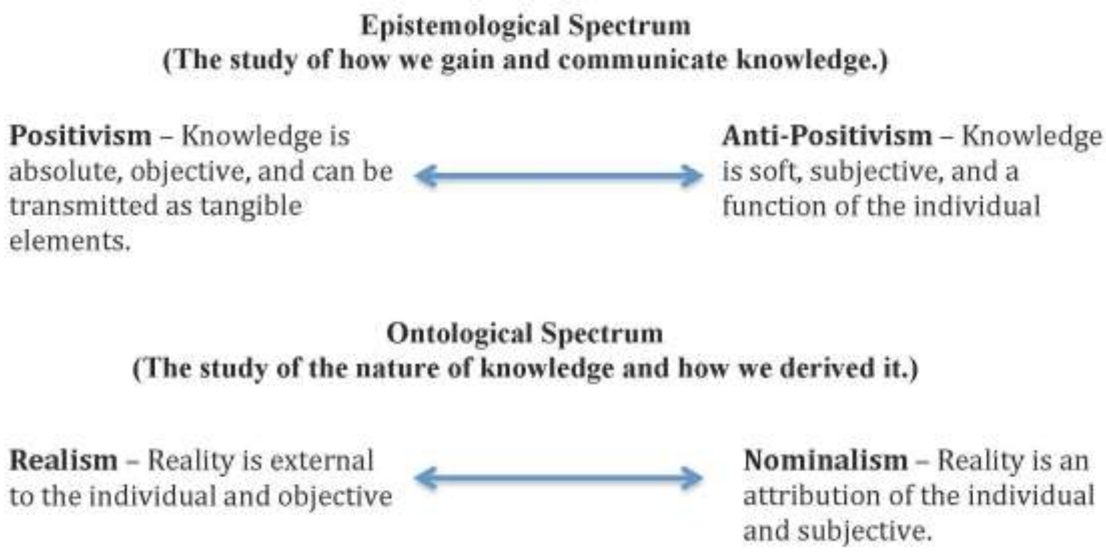

Figure 10. Endpoints of a Philosophical Spectrum for Epistemology and Ontology (Keating et al., 2010)

In examining the challenge of rising sea levels, it is important to understand the degree of complexity at each level of the hierarchy in Figure 7. The extent of the complexity will help choose which end of the spectrum of philosophy is applicable. This understanding in turn helps classify the systems principles that are compatible with that particular end of the spectrum.

Complexity is highest at the top level of the hierarchy, because of the diverse nature of an enterprise system. The degree of complexity will decrease with each lower level as the number of stakeholders diminishes and the knowledge needed to address the problem becomes more objective.

Complexity theory, in the form of Ralph Stacey's concept for a Zone of Complexity, is a way to help community leaders categorize an appropriate systems approach (Stacey, 2011). Figure 11, based on Stacey's Complexity Matrix, provides a graphic presentation to categorize appropriate management actions in a complex adaptive system. It is a function of a level of agreement on the issues in question as shown on the vertical axis and the degree of certainty as depicted on the horizontal axis.

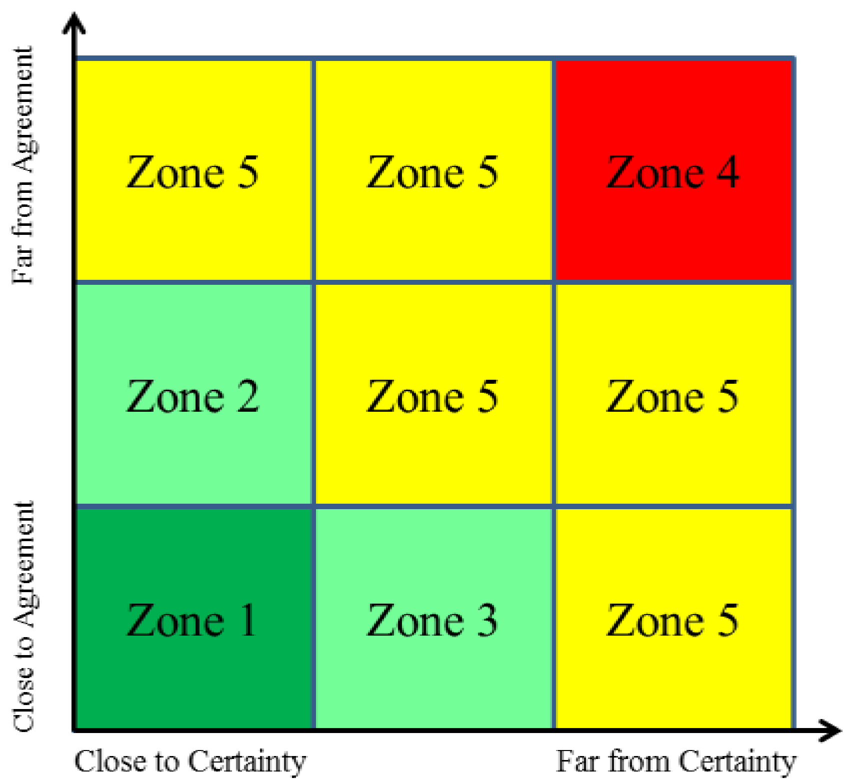

Figure 11. The Zones of Complexity

Far from Agreement implies just that, discord among stakeholders surrounding the issue. It may be difficult to find agreement on tradeoffs as the consequences of rising sea levels emerge. Far from Certainty means the situation is unique and new to the decision makers, and extrapolation from the past is an insufficient method to project outcomes. Furthermore, the certainty of a particular outcome is too ambiguous to quantify and requires planning scenarios to understand the problem situation.

On the right side of Zone 5 is where disagreement and uncertainty can lead to disintegration of the community as rising sea levels inundate the region. In our case, massive avoidance is not an option and disintegration would result in a retreat without any management of the consequences. The desired approach is to avoid Zone 4, keep the problem situation within Zone 5, and eventually shift into the lower zones. Even if the ultimate decision is retreat from the coast, it can be done in a way to manage the risks and minimize the consequences.

The degree of agreement is dependent on the level of political consensus at all levels of government to address the problem. Its degree of certainty is dependent on how well the community can define the problem scenario, i.e., how it understands emerging long-term natural threats.

Given the description of the problem situation in section 2.2.1, the political will among federal, state and local governments is disparate, and the level of future sea levels is too uncertain to define with any statistical degree of confidence. The author categorizes the problem situation as closer to the top of the Agreement axis and to the right of Zone 1 on the Certainty axis. This plots the situation within Zone 5 near Zone 4. Stacey terms

Zone 5 as the Complexity Zone, Zone 4 as Chaos Zone and the line between the zones as the Edge of Chaos.

With this understanding of complexity, the goal is to lead stakeholders to an agreed upon future state in the face of yet to be determined paths toward success. It is the author's opinion that traditional visions and mission statements will fail amid competing agendas focused on self-preservation. It will take politics, the building of coalitions, and negotiation and compromise on acceptable tradeoffs among the competing stakeholders. It will demand a diversity of approaches to deal with a range of contexts, methods to sort through alternatives, and risk informed decisions to weigh tradeoffs.

Systems' thinking offers a way to flesh out a framework to place the problem situation within Zone 5 and as a means to shift it to the lower zones. It can buy time until agreeable alternatives become apparent and more traditional project management principles can manage those outcomes.

The engineer's objective is "to help public and private decision and policy-makers to solve the problems and resolve the policy issues that they face. It does this by improving the basis for their judgment by generating information and marshaling evidence bearing on their problems and in particular, on possible actions that may be suggested to alleviate them. Thus, a systems analysis commonly focuses on a problem arising from the operations of a socio-technical system, considers various responses to this problem and supplies evidence about the costs, benefits, and other consequences of these problems." (Keating, 2014)

A systems analysis provides a means to span the philosophical spectrum. For a technical problem situation, a systematic (step-by-step) inquiry or hard systems approach is appropriate. Such an approach applies Descartes' reductionist reasoning that the sum of the behavior of the parts describes the system's properties.

This approach reduces a system to its constituent components. Each component behaves as a simple system displaying only a few variables. These variables are understood through common analytical processes. The approach assumes interactions between the parts are few, weak and linear (Beckman, 2000).

Its problem domain is in line with the traditional problem in Table 3. It uses quantitative objectives to reduce the problem situation to a mathematical model. This situation is termed "tame" or simple, because it has minimal ambiguity (Khisty, Mohammadi, & Amekudzi, 2012).

The process is simple in that it uses the model to predict the response of the system to changes in the environment and can produce an "optimal" solution. For a high degree of certainty, deterministic models can produce precise outputs. For those problem situations where mathematics can represent uncertainty, stochastic models can produce a probability of outputs in response to changes in inputs (Kirk, 1995).

This approach is termed hard systems engineering. It is based on Newtonian science where everything that happens has an identifiable cause and definitive effect.

This assumes a designer can predict the behavior of any component with certainty if he or she understands its state at any time. With sufficient knowledge a designer can predict the future evolution of the system with a high degree of confidence (Decker et al., 2011).

This approach is best for complicated technical systems, which is not the same as a complex system. Complicated systems can have many pieces, where each component is understood in isolation and the whole can be reassembled from its parts such as many mechanical systems. These pieces work as one system to accomplish its function, but one key defect can stop the function. Also, complicated technical systems lack the ability to adapt. Such systems require redundant or backup components to mitigate failure (Ottino, 2004).

However, for situations where human participation or judgment is a key component, reductionist methods can misrepresent the problem domain. The human aspect introduces relationships between stakeholders as well as complexities not easily represented by hard systems methodologies. These kinds of problems require decision makers to account for both the technical factors and the needs of stakeholders to achieve sustainable results (Kirk, 1995).

As shown in Figure 12, the influence of technology diminishes as complexity in the form of the human factors in Figure 13 increases. As these softer perspectives contribute more to agreeing to a solution, the ability of mathematical models to represent the problem situation diminishes. This increase in complexity requires shifting the focus from a hard systems approach suitable along the vertical side of the curve, to some hybrid approach at the bend, to a soft systems approach as the curve flattens out. This curve is helpful when the author later examines sea level rise from a systems hierarchy.

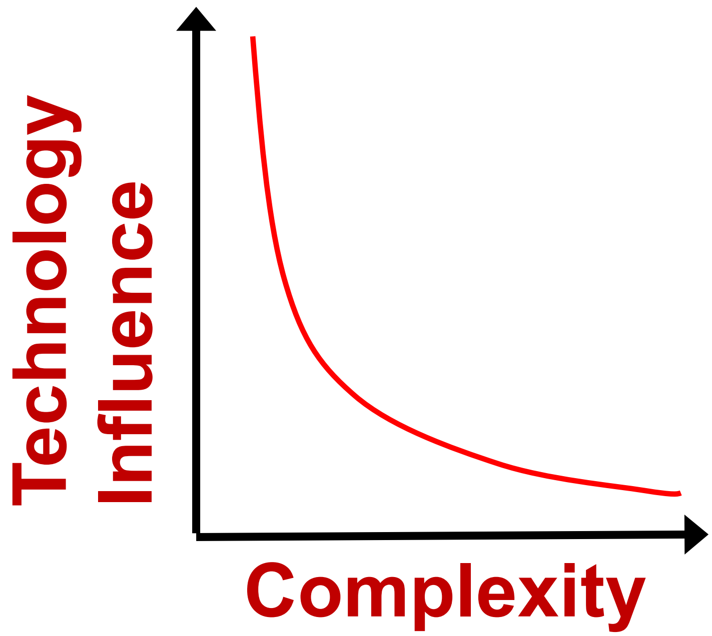

Figure 12. The Influence of Technology in the Solution Space (Keating, 2014)

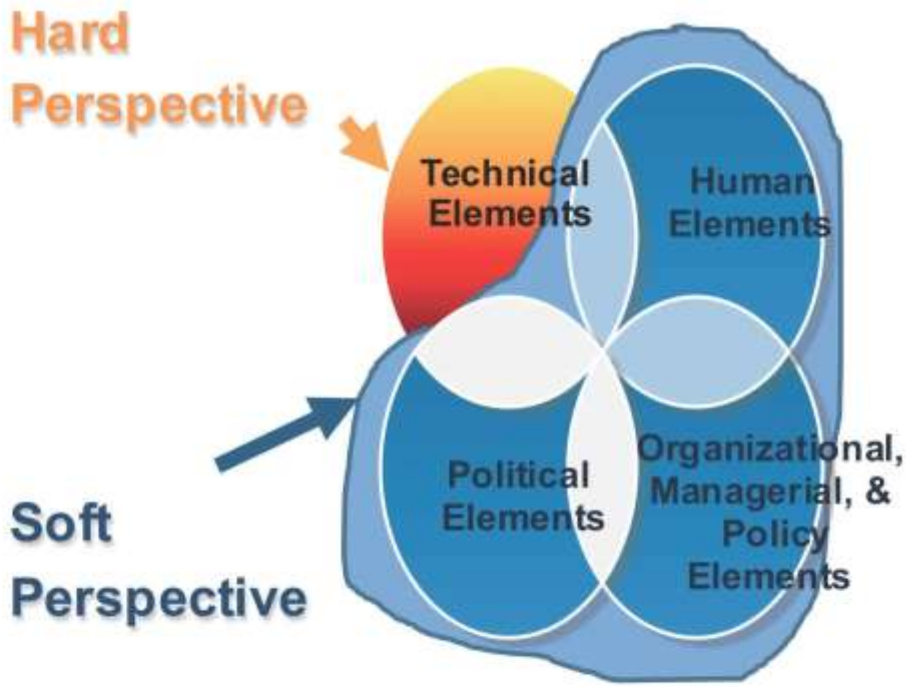

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Figure 13. Complex Problems Composed of Hard and Soft Perspectives (Keating, 2014)

For such social-technical problems, a systemic (holistic) inquiry or soft system approach is appropriate. It uses stakeholders to define qualitative objectives to develop a worldview (Weltanschauung) perspective of the problem situations. Its problem domain is more in line with the unique problem in Table 3.

These situations are termed “messy”, because the nature and circumstances of the problem change. Some characteristics of messy problems are a turbulent environment, the resolution is not apparent, and defining and bounding the problem is difficult (Keating et al., 2003). Often messy problems are termed “wicked” problems, which are “incomplete, contradictory, and changing; have intricate interdependencies; and have multiple and diverse stakeholders (Keating, 2008b).”

The process is not simple because it is dependent on the collective wisdom of the worldview. It uses iconic models to represent subjective interpretations of messy problem situations. Outcomes are in the form of a satisficing solution; i.e. an acceptable solution; a decision making process whereby one chooses an option that is, while not optimal, good enough (Keating & Katina, 2012).

The basis for the soft systems approach is the whole is greater than the sum of the parts and that sum results in emergent properties. The approach shifts the process away from optimization to one of learning how interactions generate emergent behavior. Emergence is where a system exhibits changes in structural and behavioral patterns over time as the system operates (Keating et al., 2003).

There are other distinctions between the hard and soft systems approaches. Table 4 summarizes these key differences. It is a simple guide to help understand "…the nature of the problem, the context within which the problem exists, and the appropriate forms of addressing the problem…"(Keating et al., 2010).

Table 4. Distributions between Hard and Soft Perspectives (Keating et al., 2010)

Attribute	Hard System Thinking	Soft System Thinking
Understanding Paradigm	Reductionism – focused on understanding through breaking apart (analysis). Performance of a whole can be understood through the parts.	Holism – a system is only understood at the (irreducible) whole system level. The behavior cannot be at the level of the parts.
Objective	Optimization – there is one solution, which is best (optimal) for system performance. This is the solution or configuration, which is sought.	Learning – the primary function of system exploration is to learn about the system and be capable of mounting appropriate response(s) based on that learning.
Methodology	Systematic – approach is defined by defined process that can be replicated independent of context – prescriptive.	Systemic – approach is a high level framework that provides a general guide –non-prescriptive.
Goal/Objectives	Clearly defined and agreed upon, the moving forward is assumed to be aligned with a singular perspective and objective	Ambiguous and multiple perspectives –clarity is not assured and multiple perspectives cast suspicion on the degree of alignment for goals– which may be ill defined.
Perspectives	Unitary – assumes that there is alignment of perspectives for the problem domain.	Pluralist – there exist multiple, potentially divergent, perspectives on the problem domain.
Context	Low – assume contextual influences are 'minimized' by successive bounding of the problem.	High – contextual influences are seen as integral to the problem and not easily separable for investigation.
Environment	Stable – disturbances in the environment are minimal and rate/depth of changes not considered overbearing on system solution	Turbulent – disturbances are potentially extensive and influential in ability to develop system solution.
Systems-of-Interest	Simple – low variables, interaction capable of being understood, somewhat static/deterministic.	Complex – high number of variables, rich interactions, dynamic and uncertain (emergent) pattern/ behaviors.
Modeling Preference	Mathematical/quantitative – exact relationships and predictive (mathematically) behavior dominate.	Non-mathematical/qualitative – forms of representation non quantitative in nature. Behavior not precisely predictable.
Boundaries	Clearly delineated – boundaries are definitive and understood.	Unclear and shifting – boundaries are ambiguous and evolving.
Worldview	Aligned – divergence in worldviews not made explicit or considered central to understanding.	Potentially divergent – divergence considered probable, with focus on clarity of divergence.
Defining metaphor	Mechanistic – clear understanding of predictable interrelationships.	Contextual – lack of clarity in nature of interrelationships.
Behavior	Predictable – system behavior is deducible from understanding historical patterns or trends.	Emergent – system behavior cannot be known in advance. Patters emerge through operation of the system.

In Table 5, the author has inserted Stacey's Zones of Complexity and the philosophical spectrum within work by Charles Keating (Keating, 2014). The table offers a guide to classifying a system based on where it plots in Figure 11, describes its characteristics, and recognizes the system's appropriate place on the philosophical spectrum. This linking of complexity thinking with systems thinking will help the engineer visualize a framework to address the impacts of rising sea levels within a hierarchical structure.

Table 5. Classification of Systems (Keating, 2014)

Characteristic	Simple Apply Hard System Thinking	Complex Apply Soft Systems Thinking
Stacey's Zones	1 and 3, a hard systems approach 2, a hybrid approach to address politics	5 and 4, a soft systems approach
Number of elements	Small	Large
Interactions between elements	Few	Many
Predetermined Attributes	Yes	No
Interaction organization	Highly org	Loosely org
Laws governing behavior	(1) Well defined (3) Probabilistic (2) Physical laws defined or probabilistic, with uncertain social environment	Undefined. Need to move problem to lower zones to represent behavior
System evolution over time	Not evolve	Evolves
Subsystems pursue own goals	No	Yes (Purposeful)
System affected by behavioral influences	No	Yes
Predominantly closed or open to the environment	Largely closed	Largely open
Epistemological Spectrum	Positivism	Anti-Positivism
Ontological Spectrum	Realism	Nominalism

2.2.2.6 Systems Methodology

As depicted in Figures 8 and 9, methodology serves as a broad framework that links the conceptual foundation built on philosophy and related axiomatic laws with models, methods and tools. It offers a general guide to work through the range of systems approaches that best fits the problem situation.

Systems engineering offers a disciplined way of structured thinking grounded in a philosophical worldview (Weltanschauung) to avoid making Type III and IV errors. A systems environment provides a means to think of our coastal community within a dynamic coastal environment as an integrated social and technical problem. Systems representation presents our community as an enterprise system and as a network where aspects can be depicted as a hierarchy. Systems philosophy helps classify the problem situation and describe its domain characteristics at any level in the hierarchy based on its degree of complexity. What is needed is a systems methodology that provides the framework to apply systems analysis to resolve real problems.

There are multiple kinds of methodologies offered in the literature (Keating, 2014) and (Khisty et al., 2012). There are many examples of applying hard systems thinking to complicated natural and physical systems; and of applying soft systems thinking to complex organizations and industrial processes. However, a key weakness of this study is there is limited information and experience on applying soft systems thinking to public works type infrastructure.

The author examined two soft systems approaches applicable to public works infrastructure problem situations that plot in Zones 5 and 4 in Figure 11; Checkland's Soft Systems Methodology (Checkland, 2000) and Ackoff's Interactive Planning (Ackoff, 2001). Both methodologies are appropriate for what Ackoff calls "messy" social-technical problems (Keating et al., 2003). Checkland's methodology uses CATWOE (Customers, Actors, Transformation process, Weltanschauung, Owners, and Environmental Constraints) elements (Wikipedia, 2014) to flesh out root causes, a methodology Khisty uses for transportation applications (Khisty et al., 2012). However, it is the author's opinion that Ackoff's methodology is more applicable to large-scale challenges such as the impact of rising sea levels over a wide region.

Ackoff's Interactive Planning is a generalized approach that is broad enough to help think through a unique social-technical problem at any point on the curve in Figure 12. The approach has three underlying principles:

- Participation – All stakeholders should participate in the planning process. The act of the process is more important than the plan itself. The stakeholders must lead the process and not leave it to outside experts. It is critical that the stakeholders go through this group learning experience to buy into a common worldview. The purpose of expertise is to facilitate, advise, and encourage stakeholders to participate, and not to interfere or impose undue influence.
- Continuity – Stakeholders should plan to continuously revise theirs plans. Stakeholders need to recognize that input is temporal. Stakeholders, values and perceptions can change over time. Also, stakeholders must plan for emergence, i.e. unanticipated changes characteristic of complex problems only evident as the problems unfolds.

- Holism – Stakeholders should plan for the widest array of the systems levels possible. This principle means stakeholders need to both coordinate planning across the hierarchical levels and integrate at different levels of the hierarchy at the same time. It is the inclusiveness that promotes holism and an agreement in the worldview needed to address the impact of rising seas.

Per Ackoff, the iterative planning objective "is directed at creating the future. It is based on the belief that an organization's future depends at least as much on what it does between now and then, as on what is done to it. Therefore, this type of planning consists of the design of a desirable present and the selection or invention of ways of approximating it as closely as possible. It creates its future by continuously closing the gap between where it is at any moment of time and where it would most like to be."(Ackoff, 2001).

The author considers this approach in line with Bayes Theorem for conditional probability. Its underlying philosophy is as "we learn about the universe that we learn about it through approximations, getting *closer and closer to the truth* as we gather more evidence." (Silver, 2012)

The methodology involves five stages as shown in Figure 14. The first two stages are termed Idealization, identifying the gaps between business-as-usual and an ideal future. The remaining three stages are about removing and reducing these gaps. The process is non-linear demanding multi-lateral sharing of knowledge gained and iterative steps to continuously refine alternatives and close the gaps.

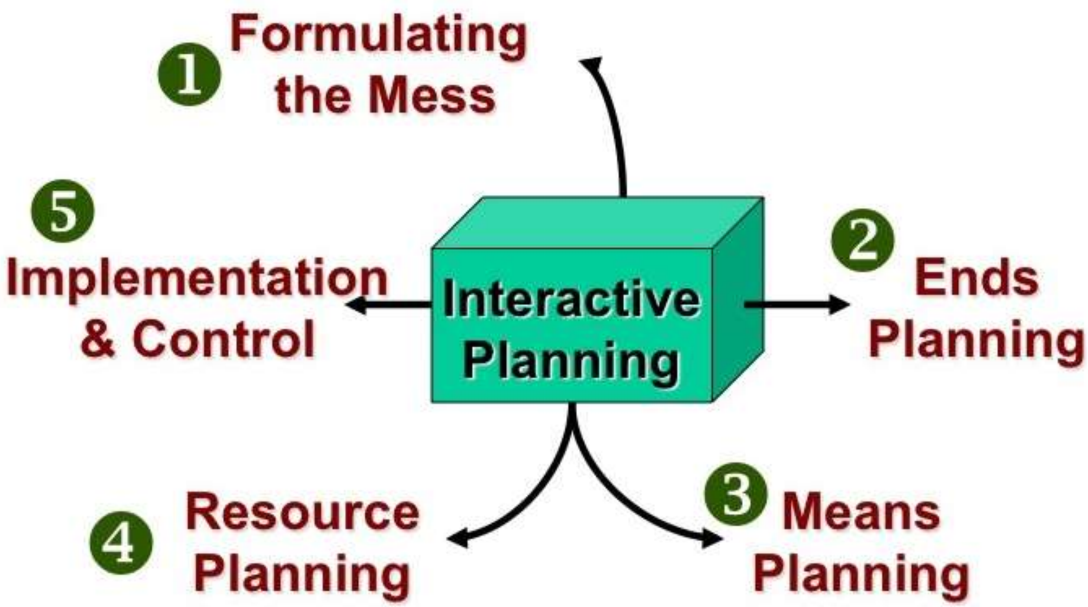

Figure 14. Five Phases of Interactive Planning (Keating, 2014)

- Formulating the Mess (Situational Analysis) – This phase determines how the community would eventually destroy itself if it were to continue to behave as it is currently doing in the face of a changing environment; even one that is predictable. This phase engages in the discussions that lead to the worldview. It involves three steps that lead to a reference scenario (problem, problem situation, problem domain): (1) A systems analysis, developing a representation of the community as a system; (2) An obstruction analysis, identification of barriers and constraints to adaptation; and (3) Reference projections, if things continue as is, what will the system look like? The output is a reference scenario, a synthesis of the three steps that provides a description of how and why the community would destroy itself in the face of rising sea levels if the assumptions for the future prove valid.
- Ends Planning – This phase determines what the community would ideally like to be if it could do whatever it wanted in the face of changing sea levels, an ideal scenario.

- The output is a comparison between the ideal and reference scenarios and the identification of the gaps between the two end states.
- Means Planning – This phase determines needed actions to remove or reduce the gaps identified in Ends Planning. This involves the community identifying how it can redesign itself to achieve the ideal design. It will require revising laws, regulations, policies, and practices. As with any ideal plan, the final design is a function of the availability of resources in a timely manner. For the case of an uncertain rate of rising sea levels, it becomes a question of whether the community has the capacity to adapt at a pace that the environment is changing.
- Resources Planning – This phase identifies resources needed for the community to redesign itself. Given the enormity of the impact of rising sea levels, identifying financial resources in a timely manner is perhaps most critical.
- Implementation and Control – This is the project management phase. Implementation determines who is to do what, when, and where, etc. Control monitors implementation-planning decisions to determine whether they are producing as expected, and if not, determining corrective action.

A way to understand how this methodology provides a framework is to describe an example of using systems analysis within 'Formulating the Mess' to develop a representation of the problem situation. As previously noted in section 2.2.2.5 Systems Philosophy, the community at large lacks agreement on a way forward in the face of uncertain rates of rising sea levels. The author used Figure 11 to categorize the problem situation as closer to the top of the Agreement axis and past Zone 3 on the Certainty axis.

This plots the situation in Zone 5 and possibly Zone 4. In order to find alternatives that we can represent mathematically, it is necessary to move the plot to within Zones 1 and 3, and possibly 2. This will require iterative discussions at the highest levels in the community network, i.e. at Level 1 (Figure 7) and across Levels 2a and b that include dialogue with Levels 2c and 3.

In examining Figure 12, the problem situation in the above paragraph plots on the far right of the curve and the three elements of the soft perspective shown in Figure 13 dominate the process. Table 5 provides the characteristics of a complex system and Table 4 lists the kind of soft systems thinking needed to address the problem situation. From Figure 10, anti-positivism and nominalism will shape how we derive and communicate knowledge.

Another example is assuming that science has identified a projected sea level rise scenario, the community has successfully worked through the iterative planning process, and there is agreement on adaptive measures. This agreement gives guidance for those subsystems at Levels 2c and 3 on how to protect their assets and to take adaptive measures specific to their needs. This plots the problem situation within Zones 1, 2 or 3 in Figure 11 depending on the degree of any disagreement on technical issues and the need for stochastic analyses within mathematical models.

In examining Figure 12, the problem situation in the previous paragraph plots more on the left of the curve and the technical element of the hard perspective shown in Figure 13 has a greater influence in the process. Table 5 provides the characteristics of a simple system and Table 4 lists the kind of hard systems thinking needed to address this kind of problem situation. From Figure 10, positivism and realism will shape the philosophical discussions in the form of mathematical models to represent and resolve problems at this level in the hierarchy.

This methodology is flexible enough to engage a large number of stakeholders to determine the community's future in the face of the impending changes in coastal waters. Though it has phases, the process is iterative and no phase is ever complete. It allows for revisiting the end state as stakeholders' interests evolve and the rates of change become more certain. It helps reduce the social component of the social-technical problem through greater agreement, and lets the technical component have a greater influence to improve certainty. It is a tool to help shift the intersection of the degree of agreement and certainty in Figure 11 from plotting in Zones 4 or 5 to plotting in one of the lower zones.

An example of successful iterative planning, if not by formal design, but by practice is the Elizabeth River Project (ERP) (ERP, 2014). It is the outcome of a grassroots, non-profit effort started in 1991 to restore the Elizabeth River, a tributary of the Chesapeake Bay. Its mission is to restore the river to the highest practical level of environmental quality through government, business and community partnerships while maintaining its value to the region's port economy.

The key to the ERP's success is the community effort that has engaged all the stakeholders who depend on the river for national defense, business, recreation, etc. Through dialogue, the stakeholders gained a mutual understanding of how a cleaner river is a benefit to the community at large. This understanding has resulted in changes in policies and practices that have reduced pollution and impacts, as well as projects that have restored the environment.

ODU has taken similar first steps to bring the community together and initiate a form of iterative planning. In early June 2014, the university and the Marine Technology Society hosted a workshop that announced a pilot project to engage regional government leaders in a dialogue (MTS, 2014). The project explores options for a “Whole Government” approach to adaptation to sea level rise and other climate change impacts on the region.

Subsequent to the early June meeting, ODU established the Center for Sea Level Rise and hosted the *Meeting the Challenge: Hampton Roads Sea Level Rise and Preparedness Actions at the Federal Level*, June 30, 2014 (ODU, 2014). It was a bipartisan forum lead by U. S. Senator Tim Kane (D – VA) and regional congressional representatives. The conference provided the congressional delegation the opportunity to dialogue with regional interests and expertise to understand the potential climate change challenges facing the community.

The purpose of the pilot project is “…to develop a regional ‘whole of government’ and ‘whole of community’ approach to sea level rise preparedness and resilience planning in Hampton Roads that also can be used as a template for other regions." (ODU, 2014). It includes multiple working groups to create an intergovernmental planning organization to address preparedness and resilience.

The author participates on the Infrastructure Working Group, which includes representatives of public and private infrastructure. The group's mission is to "…review critical infrastructures in the Hampton Roads region, determine which are most suited to and will be most positively affected by adaptation planning, and, make recommendations to the Steering Committee for intergovernmental coordination of that planning." (ODU, 2015)

Overall, these kinds of interactive planning offer the community a process to bring multiple stakeholders together to discuss complex issues. They try to create alternative futures for consideration and to iteratively work toward an agreed upon future state. This forward thinking is necessary for the community to plan future capital improvement investments that are compatible with this vision.

2.2.3 Subset Question c: What is the appropriate risk informed decision methodology to evaluate impacts?

2.2.3.1 Design Principles

As noted in section 2.1, ASCE led a national dialogue on critical infrastructure following the impact of Hurricane Katrina on the Gulf Coast (ASCE, 2009). A key outcome from that dialogue is a framework that includes the need to quantify, communicate, and manage risk. A key component to following ASCE's framework for the design of structures is the need to change from deterministic to probability based design principles.

Philosophically, deterministic design principles assume (1) there is a form of causality between the starting condition and the outcome, (2) uncertainty is non-existent, and (3) the deterministic model is appropriate given limitations on knowledge, the nature of the process, and/or the requirements of the decision scenario (Pinto & Garvey, 2013).

A classic example is the equation $F = ma$, which expresses a causality between the three parameters, force, mass, and acceleration (Pinto & Garvey, 2013). The equation provides a value of the force vector, *F*, without uncertainty when the acceleration vector, a, and the mass scalar vector, *m* are not random values. The outcome is always certain as long as the inputs are certain.

For deterministic design, the basic equation is $R > S\ x\ (Safety\ Factor)$, where R is the required resistance of the structure and *S* is the load applied to the structure. The safety factor (SF) is a nominal value recommended by code to address uncertainties. It is based on the degree of control applied to the manufacturing of construction materials and construction of the structure under design. The code sets the factor of safety to achieve some level of assurance that loads do not exceed some defined allowable limit.

The equation represents the maximum load condition over the life of the structure. In this form of analyses, the output is the same every time the input is the same. R and S have no random characteristics. Failure occurs when load equals or exceeds resistance, $R \leq S\ (SF)$. Performance models a step function and the probability of failure, P_F, steps from 0 to 1.

A deterministic approach allows decision makers to make simple and economical judgments. Failure is a step function because it only occurs when stress exceeds capacity. In referring back to Figure 11, this form of analysis is most appropriate for Zone 1 where there is a high degree of certainty and agreement. It is best for simple decisions with minimal consequences.

However, the deterministic approach lacks representation of any uncertainty about the starting condition necessary for risk analyses. It does not provide any information about the possibility that $S\ > SF(R)$ during the design life of the structure. For example, this form of analysis would not capture the uncertainty in the design variables in Figure 11 for Zones 3 and 5; nor is it relevant to Zone 4 where the uncertainty is too ambiguous to quantify. It is not appropriate for representing any degree of disagreement in Zones 2, 5 and 4.

There are philosophical discussions about the meaning of uncertainty and how to represent the starting condition (Baecher & Christen, 2003), (Vick, 2002) and (Pinto &

Garvey, 2013). This study defines uncertainty as a lack of knowledge about a quantity or condition and describes it as either an aleatory or epistemic uncertainty.

Aleatory uncertainty is a function of randomness independent of anyone's knowledge of it. It represents those starting conditions that are due to chance. Like the role of dice, our knowledge has no influence on the outcome. However, we can observe a number of trials, identify a degree of frequency and estimate an expected value with a range of variability.

For modeling, we treat natural events such as earthquakes and storms as random events. We have no influence over the outcome, but we can observe and define their behavior as some frequency of occurrence event. This allows us to apply hard systems (systematic) principles to define a hazard as a repeatable event; i.e. two or more observers with the same data should converge to a similar observation.

Epistemic uncertainty is a function of a lack of knowledge and/or a range of multiple perspectives. As it pertains to knowledge, we can apply hard systems principles to reduce the lack of knowledge through new or better information. As it pertains to a perspective, it is a property of the observer. It plays a role in unique or non-repeatable events where the observer is not sure about the conditions and/or outcomes. The basis for judgment is a matter of the strength of an opinion or a degree of belief (Baecher & Christen, 2003).

Each individual's perspective is unique and offers a personal view of a condition. People can observe the same evidence, but form different opinions. Their perspectives are shaped from where they are making the observation and biases people bring to the process (Plous, 1993). This is pertinent to the degree of agreement in Figure 11 and plays a role in Zones 2 and 5, and it is critical to avoiding Zone 4. Typically, external peer review is a good tool to cross-examine perspectives and reduce this form of epistemic uncertainty.

As noted, given uncertainty, the deterministic approach is inadequate to assess the reliability of a design, for example the probability that the design load value is exceeded during the design life of the structure. A probabilistic approach makes it possible to design a structure for a specific reliability, i.e. understand how it performs under the load leading up to the design event, and how it performs when the hazard event exceeds the design event.

Mathematically, probability is defined by the following set of axioms that specify properties that probability must have (Pinto & Garvey, 2013):

Axiom 1 $0 \leq P(A) \leq 1$ *for any event A in* Ω, the sample space

Axiom 2 $P(\Omega) = 1$

Axiom 3 For any infinite sequence of mutually exclusive events A_1, A_2…defined on Ω

$$P(A_1 \cup A_2 \cup A_3 \cup \ldots) = P(A_1) + P(A_2) + P(A_3) + \cdots \qquad (1)$$

And for any finite sequence of mutually exclusive events A_1, A_2, …A_n defined on Ω

$$P(A_1 \cup A_2 \cup \ldots \cup A_n) = P(A_1) + P(A_2) + \cdots P(A_n) \tag{2}$$

Axiom 1 means the probability of any event is a non-negative number in the 0 to 1 range. Axiom 2 means the event is certain. Axiom 3 means for any sequence of mutually exclusive events, whether the sequence is infinite or finite, the probability of at least one of these events occurring is the sum of their respective probabilities.

From a public works infrastructure perspective, using these axioms requires statistical data representing structural performance or outcomes from laboratory or field experiments. However, this kind of data is either limited or non-existent. In practice, for coastal structures, engineers use the limit state design principle for the probabilistic design of structures (Kamphuis, 2010).

The U. S. Army Corps of Engineers (USACE) has adopted this approach in developing design guidance for coastal structures (USACE, 2002). The USACE method evaluates the structural safety defined by failure modes. In simplistic terms each failure mode must be described by a formula, and the interaction (correlation) between the failure modes must be known.

The USACE probabilistic design ties its concepts to the Limit State Equation in the form of failure function, $g = R - S$. Failure is when $g < 0$, the limit state is $g = 0$, and non-failure is when $g > 0$. The quantities R and S are functions of many random variables: $R = f_r(X_{r1}, X_{r2}, X_{r3} \ldots X_{ri})$ and $S = f_s\ (X_{s1}, X_{s2}, X_{s3} \ldots X_{si})$.

The limit state $g = 0$, defines a failure surface, a line that delineates between the safe and failure region based on the Limit State Equation. *R* represents a range of resistances and *S* represents a range of loads within a period of time, *T*. For design, the engineer assumes probability density distributions for *R* and *S* are independent of time, *T*. Typically time is represented in years.

This allows the engineer to represent the probability of failure, P_F, for any reference time of duration *T* years as $P_F = Prob\ (g \leq 0)$. With this value, the engineer can define reliability of the structure, R_F, as the inverse to the probability of failure, $R_F = 1 - P_F$.

For Limit State Design, engineers design structures to meet two limit states, a serviceability limit state and an ultimate limit state. This means engineers can design a structure to survive a range of loads. For example, the serviceability limit state represents a flood stage or earthquake condition where deformations exceed defined performance requirements and the structure only needs minor repairs. The ultimate limit state defines conditions where the structure collapses or requires major repairs.

USACE’s classification for methods of probability analysis (USACE, 2002) align with those developed by the Joint Committee on Structural Safety for three levels of probabilistic design, repeated below (Thoft-Christensen & Baker, 1982).

- Level I: Design methods in which appropriate degrees of structural reliability are provided on a structural element basis (occasionally on a structural basis) by the use of a number of partial safety factors, or partial coefficients, related to pre-defined characteristics or nominal values of the major structural and loading variables.
- Level II: Methods involving certain approximate iterative calculations procedures to obtain an approximation to the failure probability of a structure or structural system, generally requiring an idealization of failure domain and often associated with a simplified representation of the joint probability distribution of the variables.
- Level III: Methods in which calculations are made to determine the “exact” probability of failure for a structure component, making use of a full probabilistic description of the joint occurrence of the various quantities which affect the response of the structure and taking into account the true nature of the failure domain.

In general, Level I is a form of a quasi-deterministic method, but with safety factors based on probabilistic data. These data come from Levels II and III analyses that account for the effects of probability distributions and a target P_F. Thoft-Christensen and Baker outline the mathematics of probabilistic design for each of the levels (Thoft-Christensen & Baker, 1982). USACE provides detailed descriptions for each level as it relates to coastal structures (USACE, 2002).

Level III is at the top of the design hierarchy. At this level engineers use actual density functions to address a large number of realizations *x* of the random variables X_i representing *R* and *S*. It uses simulation tools to estimate a P_F and to approximate the proportion of outcomes where $g \leq 0$.

A random variable is a function that identifies an outcome or event within a sample space and its domain. When working with *n* dimensional variables, the analysis works with random vectors expressed in the form of vector-valued random variables $\bar{X}$. Mathematically, the random vector can take the form of an ordered set $\bar{X} = (X_1, X_2, X_3 \ldots X_n)$ of one-dimensional random variables defined on a same sample space Ω.

Assuming only two variables, the order set reduces to $\bar{X} = (X_1, X_2)$. For the condition that the random vector is continuous, a joint probability density function, f_x expresses the probability of failure in the following equation:

$$P_f = Prob(g < 0) = \int_{-\infty}^{x_1} \int_{-\infty}^{x_2} f_{\bar{x}}\,(x_1\,, x_2) dx_1 dx_2 \qquad (3).$$

Note x_1 and x_2 are values for the random variables X_1 and X_2. The following equations determine the distribution functions F_{X_1} for the single variable X_1, and F_{X_2} for the single variable X_2:

$$F_{X_1}(x_1) = P(X_1 < x_1) = \int_{-\infty}^{x_1} \int_{-\infty}^{\infty} f_{\bar{X}}(x_1, x_2) dx_1 dx_2 \qquad (4)$$

and

$$F_{X_2}(x_2) = P(X_2 < x_2) = \int_{-\infty}^{x_2}\int_{-\infty}^{\infty} f_{\bar{X}}(x_1, x_2)dx_1dx_2 \qquad (5).$$

When there is more than one random variable, the analysis needs to distinguish between the joint probability distributions of X_1 and X_2. The individual probability distributions are termed marginal density functions. Differentiating these two equations provides the marginal density functions for X_1 and X_2:

$$f_{X_1}(x_1) = \int_{-\infty}^{\infty} f_{\bar{X}}\,(x_1, x_2)dx_2 \qquad (6)$$

and

$$f_{X_2}(x_2) = \int_{-\infty}^{\infty} f_{\bar{X}}\,(x_1, x_2)dx_1 \qquad (7).$$

USACE substitutes R and S for X_1 and X_2 and defines the failure surface as $R \leq S$. In addition, it assumes R and S are independent simplifying the two equations to the following expression:

$$P_f = \iint_{R \leq S} f_r\,(r) f_s(s)drds \qquad (8).$$

R can represent a frequentist or a subjective probability. A frequentist probability is for manufactured infrastructure where an engineer can represent variations in strength between nominally identified structures. For example, pumps are manufactured and the same type used in multiple applications. Engineers can model individual components as well as the operations of the pump for a systems response.

However, most civil engineering forms of infrastructure are one of a kind, sited at unique locations, and lack frequency performance data. For these conditions, P_F is dependent upon any lack of knowledge about the actual resistance capacity for the specific site and the constructed infrastructure. Also, it is dependent upon physical variability of the extreme load effects at that site over the life of the project. The structure's reliability changes as the state of knowledge about the structure changes and is referred to as subjective probability or Bayesian reliability.

For either form of probability, the engineer is most interested in whether the structure will fail when exposed to an extreme load or a certain limit state. Therefore, it is necessary to represent *R* as less than or equal to *x*. This is done by integrating the resistance probability density function, $f_r(x)$ to generate a resistance probability distribution function, $F_r(x)$ to identify the ultimate strength *R* for some specified mode of failure. P_F under the action of a single known load effect *s* is

$$P_{F=} P(R - s < 0) = F_r(s) = P(R/_S < 1) \qquad (9).$$

If the load effect *S* is a random variable with a distribution function F_s, the following equation replaces the above equation where F_r is the distribution function for *R*. Also, the lower limit -∞ is zero since strength is not a negative number:

$$P_F = P(R - S \leq 0) = \int_0^\infty F_r\,(x) f_S(x) dx \qquad (10).$$

- The equation represents the product of the probabilities of two independent events, summed over all possible occurrences that the probability *S* lies in the range of *x*, *x* + *ds*; and the probability *R* is less than or equal to *x*. Figure 15, after M. H. Faber and J. D. Sorensen, provides a graphic representation of the equation (Faber & Sorensen, 2002).

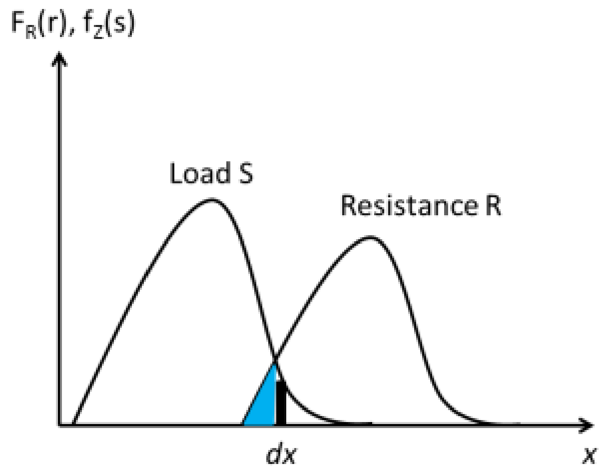

Figure 15. Illustration of the Integration of the P_F Equation

Level II is the next level of the design hierarchy. The mathematics is the same as Level III, but instead of simulating a large number of combinations of random variable, Level II assumes random variables have normal distributions. This allows the analysis to use expected values and the covariance between random values. This shifts the analysis away from determining failure along the entire failure envelope to checking at a single point on the failure surface.

USACE provides a description of Level II methods for linear (first order reliability method) and non-linear (second order reliability method) failure functions for normally distributed uncorrelated and correlated variables (USACE, 2002). For the linear (first order) failure functions, Level II defines a margin of safety function, *M*, as the difference between resistance and load, $M = R - S$.

When variables *R* and *S* are normally distributed, *M* is also normally distributed based on the first and second moments of the random variables. Its mean value is $\mu_M = \mu_R - \mu_s$ with a variance of $\sigma_M^2 = \sigma_R^2 + \sigma_S^2 - 2\rho_{RS}\sigma_R\sigma_S$ and standard deviation of $\sigma_M = \sqrt{\sigma_R^2 + \sigma_S^2 - 2\rho_{RS}\sigma_R\sigma_S}$. The parameter ρ_{RS} is the correlation coefficient and when it equals zero, the random variables *R* and *S* are uncorrelated and the standard deviation is $\sigma_M = \sqrt{\sigma_R^2 + \sigma_S^2}$.

The probability of failure may now use the cumulative standard normal distribution function, Φ where

$$P_F = P(R - S \leq 0) = \int_{-\infty}^{0} f_g(x)dx = \Phi\left(\frac{0-\mu_g}{\sigma_g}\right) = \Phi(-\beta) \tag{11}$$

and ${}^{\mu_g}/_{\sigma_g} = \beta$ is the reliability index. Figure 16, after Gregory Baecher and John Christian, is an illustration of the reliability index (Baecher & Christen, 2003). The index represents the number of standard deviations from the probable value of g to the failure surface where $g = 0$.

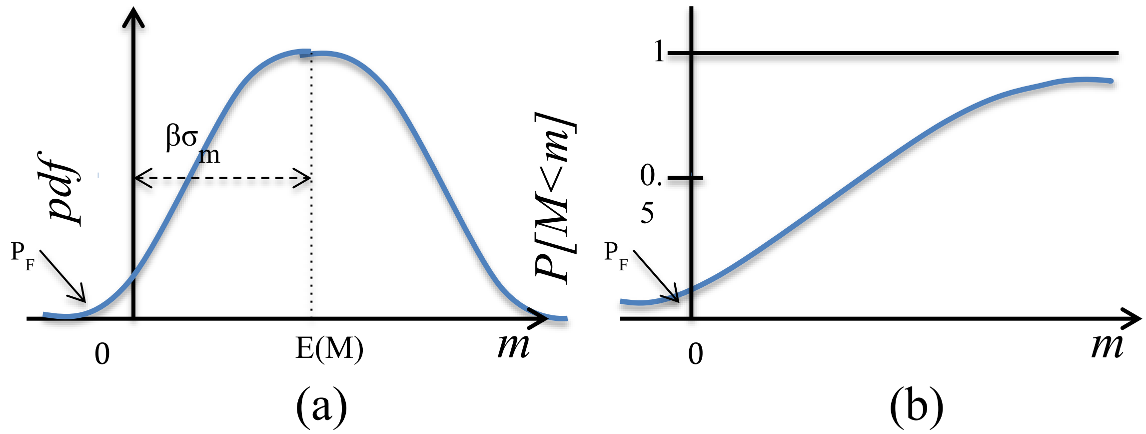

Figure 16. Probability Density (a) and Cumulative Probability (b) for Margin M. Note that the Area in (a) under the Curve and to the Left of the Axis is the Probability of Failure Identified in (b).

For the non-linear failure (second order) of normally distributed random variables, the mathematics provides methodologies to approximate values for $\mu_g$and σ_g. The basic variable $\bar{X} = (X_1, X_2 \dots X_i)$ are transformed into a set of normalized variables $\bar{Z} = (Z_1, Z_2 \dots Z_i)$ where $\mu_{Z_i} = 0$ and $\sigma_{Z_i} = 1$:

$$Z_R = \frac{R-\mu_R}{\sigma_R} \; and \; Z_S = \frac{S-\mu_S}{\sigma_S} \qquad (12).$$

Level II methods have shortcomings. Thoft- Christensen and Baker (Thoft-Christensen & Baker, 1982) discuss the problem of a lack of failure function invariance with the reliability index method. The value of β can be different for the same case dependent on the expression used to define an equivalent failure function. They recommend using the Hasofer and Lind's Reliability Index where β_{HL} is related to the failure surface and not to the failure function. The USACE reference provides more in-depth discussion.

Level I design is the simplest of the three methods. It is similar to deterministic design. The methodology develops an equation that has coefficients applied to parameters that represent R and S such that $g = {}^{R}/_{\gamma_r} - S(\gamma_s) = 0$. The coefficients are derived from Levels II and III probability analyses to reduce the value of R and increase the value of S to meet a target P_F. The resulting equation is $R = (\gamma_r \gamma_s)S = \Gamma S$ where Γ represents a safety factor.

For the design of coastal structures, all three levels need to consider any time variance in random variables. A structure is subject to changes in sea levels, storm surges and accompanying wave heights and periods over the life of a project. Also, a structure's resistance is subject to a time-varying strength/degradation as material properties change when exposed to loading.

Design guidance is available to assess coastal hydraulic loading. USACE and Kamphuis are two references that provide details ((USACE, 2002) and (Kamphuis, 2010). However, presently incorporating a change in material properties in reliability calculations is difficult.

The Joint Committee on Structural Safety and USACE offers insights to time variant reliability (Faber & Sorensen, 2002) and (USACE, 2002). An engineer needs to determine the probability that the structure's performance enters the failure region during some specified time interval. The failure function is $g\ (x(t) \leq 0$ for a time period, *t* during a time interval [0, T]. The value *x(t)* is a realization of a stochastic process.

The probability of failure during the interval is

$$P_F = 1 - P(g(X(t)) > 0, \forall t \in [0, T] \qquad (13).$$

Performing such an evaluation is difficult. It requires knowing how resistance changes over time, *R(t)* [0. T], while exposed to changes in loading over the same time interval, *S(t)*. An approximation is to determine an upper bound of the probability of failure in the time interval [0,T] where v^{+} *[R(t)]* is a mean-up-crossing rate when *S(t)* exceeds *R(t):*

$$P_F(T) \leq \int_0^T \mathrm{v}^+ \, [R(t)]dt \qquad (14).$$

As an alternative to knowing material degradation and understanding the maximum load values within the time interval, USACE recommends setting *T* equal to one year (USACE, 2002). Instead of calculating P_F over the life of the project, the analysis determines the P_F in a 1-year period, P_F (1 year). If the engineer assumes failure each year is independent for all variables, the engineer can apply a binomial distribution to determine the probability over *T* years. It becomes a sum of the probability occurring in the first year, the probability occurring in the second year…up to *T* years where P_F over *T* years is

$$P_F(T\ years) = \sum_{i=1}^{T} p(1-p)^{T-1} = 1 - [1 - P_F(1year)]^T \qquad (15).$$

Assuming that failure each year is independent simplifies the analysis. However, this has its shortcomings. It ignores that deterioration in one year is dependent upon the state of resistance in the previous year. Also, computing annual projections of the significant wave height, *Hs* will be different than computing *Hs* over the life of the project.

However, the binomial distribution offers a means to estimate the probability of failure for a design condition during the lifetime of a project. Kamphuis offers the following expression where P_E is an encounter probability, T_R is a return period of a design event (load) over T years, and N_L is the project design life (Kamphuis, 2010):

$$P_E = 1 - (1 - \frac{1}{T_R})^{N_L} \text{ or } T_R = (1 - (1 - P_E)^{1/N_L})^{-1} \qquad (16).$$

Equation (17) determines the probability the structure will encounter a particular loading (storm, wave, etc.) over the project design life. Kamphuis then uses P_E in the following equation

$$P_L = P_E(P_F) \qquad (17)$$

where P_L is the lifetime probability of failure for the design event. For example, using equation (16) where T_R for the design storm surge is 100 years (1% chance of being equaled or exceeded in one-year) and $N_L = 50\ years$, then P_E = 0.64. Assuming for that given storm surge, the P_F = 0.10, the probability of failure over the lifetime of the project is P_L = (0.64)(0.10) = 0.06.

Calculating P_F and P_L are important because there is always going to be an event that equals or exceeds the design event; and there can be consequences whether the structure collapses or remains intact and functions. This potential for exceedence is part of what defines residual risk, i.e. that portion of the probability distribution that exceeds the design event and the resulting consequences.

This knowledge helps the designers to quantify the residual risk for a range of design events and project costs. This gives the decision makers the knowledge to select a project based on a balance of risks with net benefits. In addition, it provides the tools needed to communicate residual risk to the public and the need for additional actions to mitigate residual risk.

Equation (17) is the frequency component in equation (18) where risk, R equals the probability of failure over the life of the project for the given load times the consequences, i.e. the probability that an event generates a load that exceeds the design during the structure's lifetime and results in loss of life, property, etc.

$$R = P_L(Consequences) = P_E(P_F)(Consequences) \tag{18}$$

Figure 17, after William Lowrance, presents the relationship in a generalized exposure – effect correlation plot (Lowrance, 1976). This correlation is also referred to as a fragility curve or a systems response curve (Schultz, Gouldby, Simm, & Wibowo, 2010).

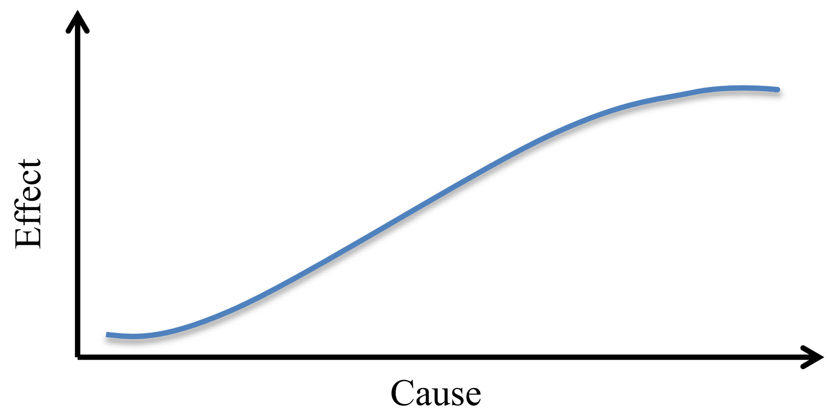

Figure 17. Generalized Exposure - Effect Correlation

USACE provides guidance on the development of fragility curves and resilience for coastal type structures (Schultz, Gouldby, et al., 2010; Schultz, McKay, & Hales, 2012). The 2010 report summarizes a literature review and offers the following classification for developing fragility curves:

- Judgmental – Fragility curves are a function of expert opinion or engineering judgment.
- Empirical – Fragility curves are a function of observational data obtained through natural or scientific experiments.
- Analytical – Fragility curves are a function of models.
- Hybrid – Fragility curves are some combination of two or more of the above approaches.

The report notes no one approach will satisfy all purposes. The appropriate approach depends on the availability of data and models, how well the engineers understand failure modes, and available resources to perform analyses. However, if the distributions of the variables are not normal or lognormal distributions or are unknown, the results are approximations. The outcomes can only be interpreted in nominal or relative terms, not as absolute values.

Schultz et al, tie the development of fragility curves to reliability methods based on a conditional P_F relationship. The approach assumes all of the uncertainty is in the capacity term and the method derives the curve by varying the demand parametrically. It assumes the uncertainty follows a lognormal distribution based on recent studies and, therefore, the fragility curve does as well.

The following relationship estimates the conditional P_F:

$$p(Z \leq 0|S = s) = F_R(s) = \Phi(-\beta) = \Phi\left(\frac{\ln(s/m_R)}{\sigma_{\ln R}}\right) \tag{19}$$

The cumulative distribution function, $F_R(s)$ gives P_F conditional on the demand applied to the system, $p(Z \leq 0|S = s)$. The variable m_R is the median of the probability distribution characterizing uncertainty in the capacity and its standard deviation is $\sigma_{lnR} = \sqrt{1 + V_R^2}$. The value V_R is the coefficient of variation for capacity, $V_R = {}^{\sigma_R}/_{\mu_R}$.

Figure 18 presents the relationship. In Figure 18a, the load m_R ranges in values from 100 to 1000 while the uncertainty σ_{lnR} is held constant at 0.5. By increasing the median load where failure occurs, it reduces the conditional probability of a system at which it will fail.

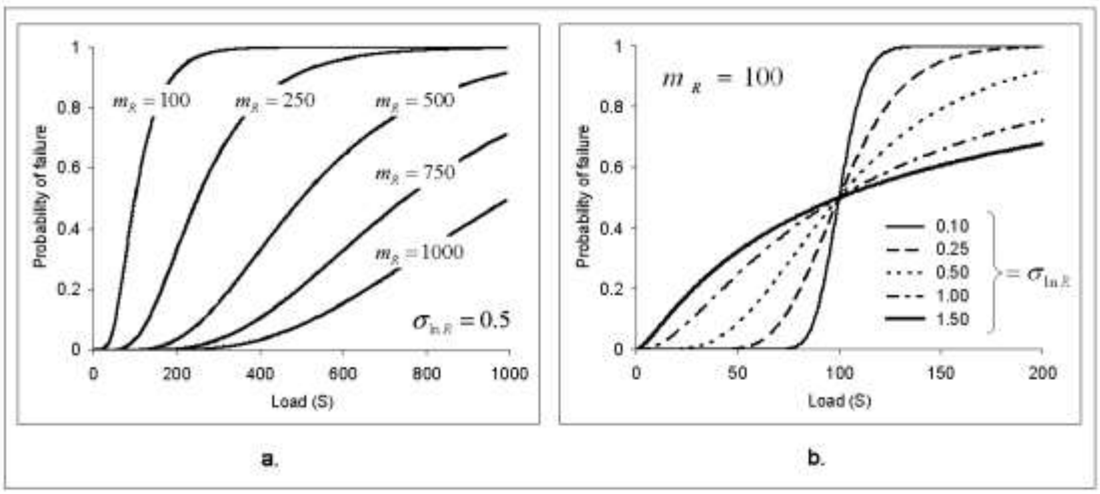

Figure 18. Examples of Fragility Curves Derived from the Reliability Index (Schultz, Gouldby, et al., 2010)

In Figure 18b, the uncertainty in the capacity of a system, σ_{lnR} ranges in values from 0.1 to 1.5 while the load m_R is held constant at s =100. As the uncertainty increases, the curve tends to flatten out. It implies P_F increases when the applied load is less than the constant median load and decreases at loads greater than the constant median load, i.e. the greater the uncertainty the more likely failure can occur at a lower load.

Such a probabilistic approach makes it possible to design a structure for a specific reliability, i.e. understand how it performs under the load leading up to the design event, and how it performs when the hazard exceeds the design event. This is important because there is always going to be an event that exceeds the design event and the question is whether the structure collapses or remains intact and functions. This potential for exceedence is part of what defines residual risk, i.e. that portion of the probability distribution that exceeds the design event and the resulting consequences.

This knowledge helps the designers to quantify the residual risk for a range of design events and project costs. This gives the decision makers the knowledge to select a project based on a balance of risks with net benefits. In addition, it provides the tools needed to communicate residual risk to the public, and the need for additional actions to mitigate residual risk.

However, the challenge for the design of structures is having an adequate database of the performance of various components under load. At present, there is insufficient data to support empirical and analytical type fragility curves for many types of structures exposed to coastal loads. In the interim, assessments will depend on expert elicitation to judge the performance aspects of such systems.

2.2.3.2 Tolerable Risk

As part of the ASCE's national dialogue, some discussion focused on what is an appropriate level of residual risk for the design of coastal flood risk reduction systems. The discussion ranged from the standards applied in the Netherlands (10^{-4} chance annual probability for major metropolitan areas) to lower risk levels associated with modern, well-engineered dams (as low as 10^{-6} for new dams).

Baecher and Zielinski, in an unpublished paper, examined the reasonableness of the recommended levels. In doing so, they make the following points important to this paper (Baecher & Zielinski, 2008):

- People are willing to tolerate higher risk when their exposure to the risk is voluntary. For the case of living within a coastal system, people choose to live close to the ocean for the benefits of living near the water. They voluntarily accept the hazards associated with coastal storms in exchange for those walks on the beach. This is opposed to involuntary risk such as the construction of a dam upstream from where people live. The public has a lower sense of control and demand more stringent requirements to reduce their exposure to risk.
- For civil works infrastructure and exposure to natural hazards, the practice is to base criteria on societal risk, i.e. the risk of multiple fatalities from a single event. This approach is opposite to using individual risk, i.e., the risk of death to the average person. The latter case applies to activities such as accident rates. The difference in criterion is that a societal risk is a probability function and individual risk is a simple probability.
- The United Kingdom Health and Safety Executive (HSE) approach to safety regulation based on societal risk is an appropriate application to public works infrastructure (HSE, 2001). The basis for the HSE approach is a 1949 British legal case where the court determined whether the defendant had taken actions to lower risk ‘so far as reasonably practicable’. This case gave birth to the application of the ALARP (as low as reasonably practicable) principle to industrial and other hazards. The HSE bases ALARP on the concept of tolerable risk and implements it in the form of a F:N curve concept. A tolerable risk is one that is acceptable to society to secure the benefits gained from building the infrastructure. When the

benefits are insufficient given the level of risk, society takes action to lower that risk to levels as low as practicable.

- The recommendation for a 10^{-4} annual risk of casualty is an appropriate level of societal risk for urban areas where the risk is voluntarily accepted and the management of risk is subject to the ALARP principle.

In Figure 19, based on work by the HSE, the upper horizontal line represents the maximum risk that society will tolerate in any circumstance and below the lower line the risk is small enough to accept (HSE, 2001). In between the lines, society needs to implement measures to reduce the risk to a level as low as is practicable. This approach is suitable for technical systems where elements can be presented in a hierarchical structure. Keys to success with this approach are defined conditions, control of resources, and modeling. A drawback of this type of representation is a weakness to predict and control possible emergent properties; particularly as the social component of a social-technical problem is more dominant relative to the technical component federal and state dam and levee safety programs in the U. S. For this study, the upper limit is the 10^{-4} annual risk of casualty noted above. The lower limit could be 10^{-6}, a level appropriate such that exposure to risk is involuntary.

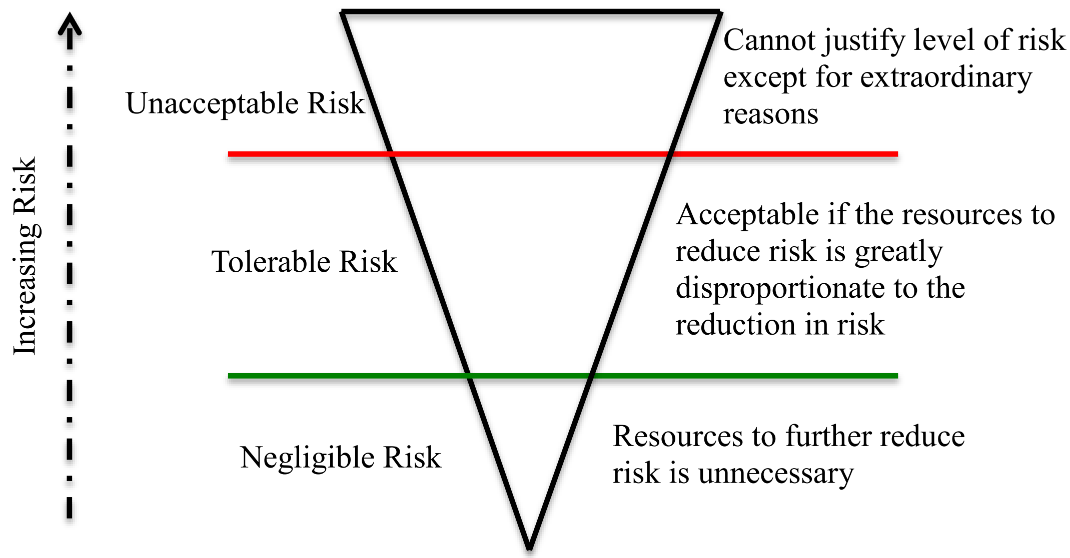

Figure 19. Framework of Risk Acceptability

Figure 20, after Dimitri Diamantidas, illustrates an example of using an F-N curve with the ALARP framework when assessing the involuntarily accepted risk for loss of life (Diamantidis, 2008). For public works infrastructure, the ordinate typically reads F, Frequency of N or More Fatalities Per Year and represents the sum of the individual risks to all within the exposed population or the population at risk (PAR). This is the probability that anyone within the PAR loses his or her life as result of the failure of the structure.

The target is to reduce societal risk to below the unacceptable region to the extent achievable by ALARP. At a minimum, the 500-year flood event (0.2% chance of being equaled or exceeded in one-year) should be used to calculate tolerable risk levels where loss-of-life is an issue. However, for consequences that do not involve loss of life, society may accept higher levels of risk based on how much loss it is willing to tolerate.

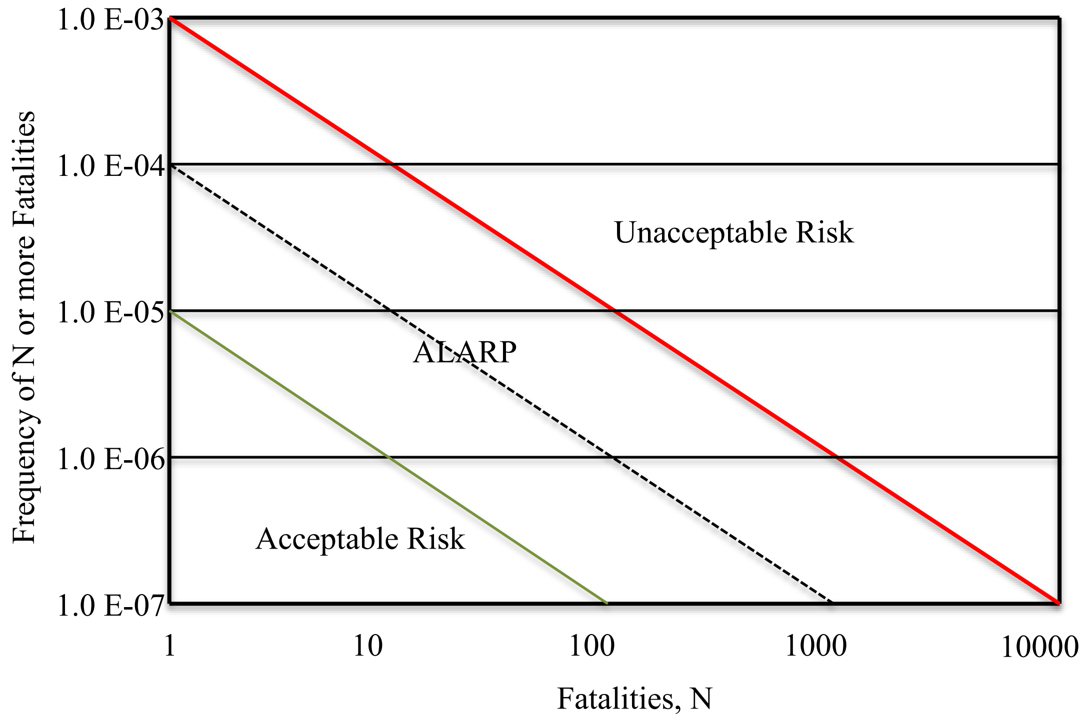

Figure 20. F-N Curve and Illustration of ALARP Range

As in the case of submersible wastewater pump stations, the Commonwealth of Virginia, the Virginia Administration Code, Agency 25, State Water Control Board, Chapter 790, Sewage Collection and Treatment Regulations defines the requirements for sewage pumping. Section 9VAC25-790-380. Sewage Pumping states “All mechanical and electrical equipment which could be damaged or inactivated by contact with or submergence in water (motors, control equipment, blowers, switch gear, bearings, etc.) shall be physically located above the 100-year flood/wave action or otherwise protected against the 100-year flood/wave action damage (1% chance of being equaled or exceeded in one-year). All stations shall be designed to remain fully operational during the 25-year flood/wave action.”

However, these standards are a function of exposure, not risk. As for the first requirement, Pump Station 113 (corner of Walnut Hill and Sylvan Streets) and its proposed new location (corner of Walnut Hill Street and Rolfe Avenue) are located within Zone AE in accordance with the National Flood Insurance Program (NFIP), Map Number 5101040090F, revised September 2, 2009 as shown in Figure 21 (FEMA, 2009).

Zone AE is land covered by the 100-year base flood defined as having a 1% chance of being reached or exceeded in a single year. The NFIP maps designate this floodplain as the Special Flood Hazard Area, and for this specific site, the base flood elevation is 8.1 feet, North American Vertical Datum, 1988 (NAVD (88)). Whether the designated equipment is above the specified flood level is a simple matter of checking its elevation.

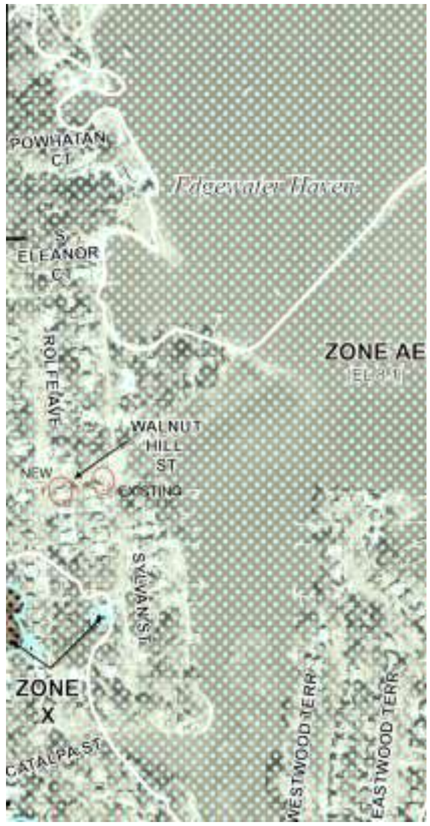

Figure 21. PS 113 Location on Segment of NFIP Map Number 5101040090F (FEMA, 2009)

As for the second requirement, the station must remain operational when exposed to a 4% annual exceedence flood/wave event. It implies zero probability for failure or no risk. However, every structure has a potential for failure most likely due to uncertainty due to lack of knowledge. For example, FEMA's Multi-Hazard Loss Estimation Methodology Flood Model, HAZUS-MH MR 4, Technical Manual (undated) available at https://www.fema.gov/media-library/assets/documents/16579, identifies the vulnerability for pump/lift stations in Table 7.1, page 7-3. It identifies inundation as a high vulnerability, and scour/erosion and debris impact/hydraulic pressure as having no impact. It makes no mention of the duration of flooding, which this study identifies in the following section as a possible failure mode.

Also, in order to address the city's request to identify risk, it is essential to define a performance level for remaining operational. However, the literature is absent of any discussion as to what are appropriate performance levels for pump systems.

2.2.4 Subset Question d: How do rising sea levels impact the performance of a pump station?

There are two basic sources during storm and flooding conditions that impact the capacity of wastewater collection systems. One is groundwater infiltration and the other is inflow from stormwater runoff and/or coastal flooding.

Groundwater infiltrates into gravity line segments and manholes. The volume of infiltration increases with a rising groundwater table caused by heavy rains, and fluctuations in the water table elevation caused by tidal changes. A rise in the sea level will induce a natural rise of the watertable increasing infiltration by an increasing head and the submergence of more line segments.

Stormwater runoff drains into manhole covers when intense rainfall events cause localized flooding. This volume of inflow increases when rainfall occurs during high tide cycles. In low-lying areas, tidal waters backflow through the storm drains inundating the streets and manholes contributing to inflow. Also, coastal storm surge contributes to inflow often concurrent with storm runoff and high tides. A rising sea will result in more frequent flooding and flooding over a wider extent of terrain along the shoreline. This kind of inflow also introduces saline water into wastewater systems.

A study of four wastewater treatment systems in North Carolina examined responses to rainfall and tide levels (Flood & Cahoon, 2011). The portion of total flow attributable to infiltration and inflow ranged from 10 to 100% of base flow. Infiltration contributed the majority of the flow. Another study identified as much as 60% of infiltration occurs along house service laterals or building connections (Field & O'Conner, 2002). In addition, a study in Hawaii showed that tidal changes and high-surf events caused fluctuations in groundwater levels within the coastal plain as far as 5 kilometers (km) inland (Norcross-Nu'u, Fletcher, Barbee, Genz, & Romine, 2008).

The North Carolina study further notes that an increase in groundwater levels from rainfall and rising sea level will pose three threats: (1) a reduction in treatment efficiencies, (2) an increase in the risk of bypass flow, and (3) the introduction of saline water which may have negative consequences for the mechanical and biological integrity of these systems. These threats will result in higher operating and maintenance costs. The study recommended further investigations of the impacts of saltwater infiltration.

Hurricane Sandy had a dramatic impact on the infrastructure system within the City of New York (NYC, 2013). The city has 96 pumping stations within low-lying areas that lift wastewater and stormwater. The storm damage caused the loss of power to 42 of the 96 pumping stations. Power outages caused half of the impacts with storm surge accountable for the other half of the impacts. Many of these pumping stations are underground and were inundated. For these stations, recovery required unwatering and repair of electrical equipment caused by the corrosive impact of saltwater.

Recovery required an immediate response. The city was able to restore operations to most of the pump stations and water treatment to 99% of its customers within 4 days. However, the consequences included both the cost of recovery and the release of wastewater into New York's waterways. The report did not note any impacts such as backups and overflows within service lines.

The primary concern for the Norfolk study is failure or inefficient pump performance results in release of wastewater into floodwaters. The Environmental Protection Agency (EPA) estimates 400,000 to 500,000 unauthorized discharges of untreated raw sewage from sanitary sewage systems in U. S. each year (Robbins, 2007). Most occur at manholes releasing untreated wastewater on to roads, into waterways, and overland. In addition, approximately 40,000 of these releases occur at sewerage hookups backing into basements of customers. These releases pose a health risk and are illegal under Section 301 of the Clean Water Act, which prohibits the discharge of pollutants into waterways without a permit.

In summary, infiltration and inflow increase the volume of flow reducing the capacity of line segments to convey wastewaters to pump stations. In turn, the pump stations have to move more fluid to minimize the potential for overflow spilling into the streets and open waters. Also, coastal storms disrupt power sources and corrode equipment, both causing pump shut downs.

2.2.5 Subset Question e: What is the appropriate means to demonstrate the impact on the performance of the pump stations?

Based on the work presented in section 2.2.2.3, Representation of a Coastal System and Figure 7, the pump station is at Level 3 within a technical hierarchical structure. Per Table 5 a simple, hard systems approach is appropriate for projects at Level 3. As noted in section 2.2.2.5, Systems Methodology, this type of project fits in Zones 1 or 3, where its degree of certainty and agreement is high. For this case, simplicity will shape the dialogue and positivism and realism will shape the philosophical discussions.

The civil engineering profession has long understood the mechanics of wastewater systems and has developed models that can adequately represent systems performance. An example is a recent collaborative effort by HRSD to define data requirements and choose an appropriate model to represent the entire collection system across the 17 jurisdictions it serves (Morgan et al., 2012). Through this effort, the community agreed on data standards and selected a common means to represent its wastewater collection system.

From a systems perspective, HRSD is located at Level 2c in Figure 7 within the technical hierarchy, just above the jurisdictions it serves. Using the HRSD example above, its initial position was in Zone 2 in Figure 11, but through efforts to seek agreement HRSD simplified the problem to where it could apply a mathematical model, a hard system methodology. The agreement moved the systems representation to Zone 1 or Zone 3 depending on whether HRSD needs to perform stochastic analysis to clarify any numerical uncertainty.

Therefore, in accordance with systems thinking, a hard systems analysis is most appropriate for understanding the pump's performance. In the subject literature review, efforts comparable to a hard systems approach specific to pump stations are mainly studies by utility districts or jurisdictions (King County, 2008). These studies assess generalized impacts using risk models based on asset management practices; however, there is little information specific to how rising sea levels impact pump stations. The consultants used experts to judge performance and qualitative scales to assess relative risk levels (O'Neal & Martin, 2005), (Benson & Stahr, 2008), (King County, 2008) and (USACE, 2014).

Based on these examples, the author used the following outline to study the impacts of incremental rise in sea levels on PS 113 and its proposed replacement:

- Describe submersible pump stations in an asset management format.
- Identify what assets are vulnerable and how the increase of flow volume and coastal flooding impact the operations of the pump stations.

- Use expert elicitation to judge impacts, select an appropriate fragility curve to represent the impacts, and identify consequences.

The resulting fragility curve and consequences form the basis for assessing risk.

The Environmental Protection Agency provides a list of assets for pump stations that is sufficient for this study (EPA, 2007). This author complements the list with details from a manufacturer’s manual (JES, 2012)

- Inlet Sewerage and Screen
- Superstructure
- Wet Well (Capacity)
- (Dual) Submersible Pump(s) and Motor(s) (power entry gland, motor assembly, stator, motor bearings, shaft, oil chamber, mechanical seals, housing, volute, wear ring, and impeller)
- Valves
- Valve Vault
  - Electrical System
  - Pump Control Systems
  - Force Main
  - Land and Surroundings
  - Power Source
  - Power Generator (as a backup power source)

These assets represent both the design capacity and physical components of a submersible pump station. The volume of flow could overwhelm the pump’s capacity and water levels could affect physical components disrupting operations, both of which can be interpreted as part of a fragility curve.

Figure 22 provides a cross-section of a typical wastewater pump system and Figure 23 shows a plan view and cross section of a typical dual submersible pump system.

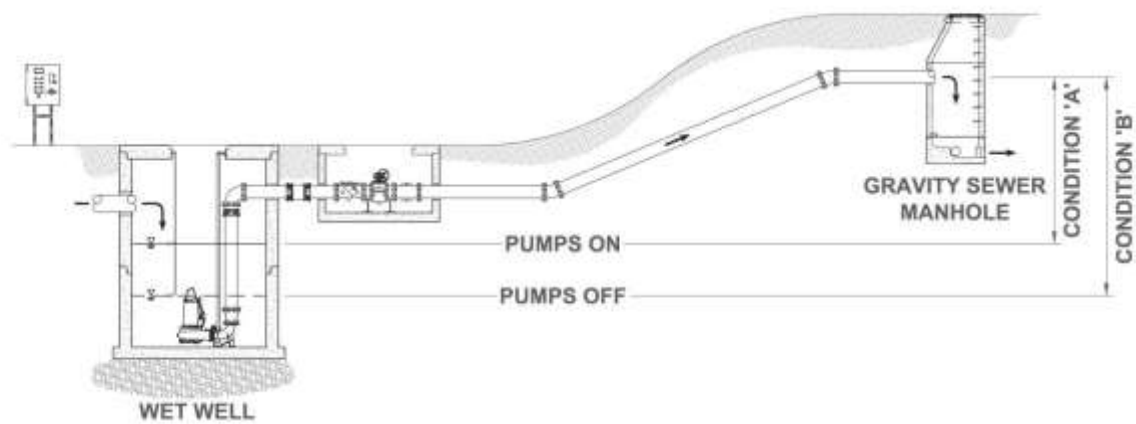

Figure 22. Cross Section of Typical Wastewater Pump Station (JES, 2012)

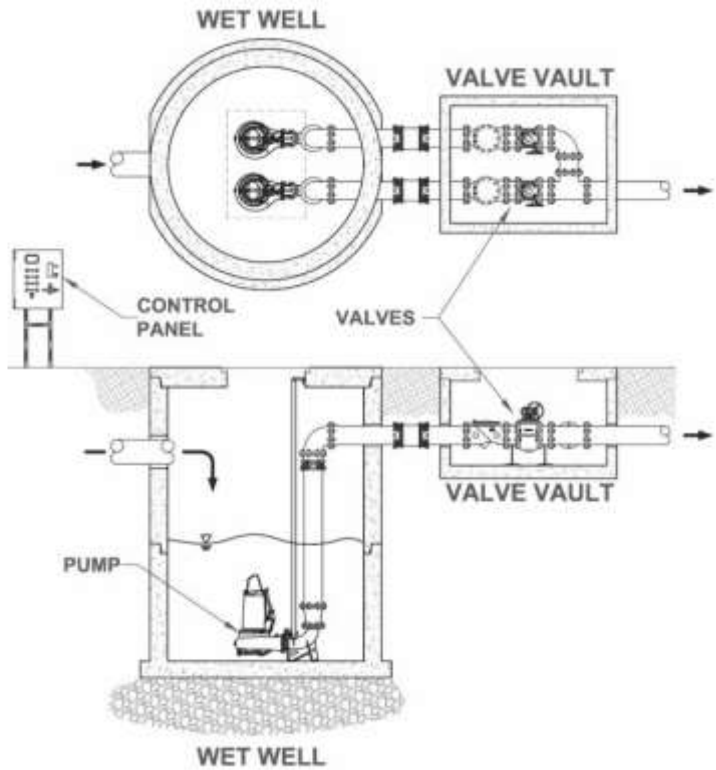

Figure 23. Overview and Cross Section of Typical Lift Pump Station (JES, 2012)

The dual system shown in Figure 23 is for pumps in parallel; an arrangement more suitable for a wide range of discharge volumes with no appreciable head change. The second pump starts when the discharge demand reaches a particular level to supplement the first pump.

Designing a submersible pump system requires identifying the type of wastewater to be pumped, determining the inflow rates and occurrence of flows, determining system headlosses and the vertical lift elevation difference from the wet well to discharge elevation. Headlosses are a function of static losses representing the difference in elevation or pressure between the inlet and discharge and of dynamic losses due to friction of liquid flow through the pipe and fittings. A key understanding for design is how losses increase as the flowrate increases (JES, 2012).

An engineer can use the above information to calculate a system curve, which is the required head versus the flowrate. It illustrates the loss of energy in the system with a variation of the flowrate and represents the amount of energy the pump must generate to operate at a given flowrate. Given the system curve, the engineer can select a type and size of pump, determine the size of infrastructure components (wet well, valve vault, valve and pipes) and needed electrical system control, etc., (JES, 2012).

As an illustration of a design, a submersible (centrifugal) pump performance is a function of three characteristic curves: (1) pumping head versus discharge, (2) brake horsepower versus discharge and (3) efficiency versus discharge. For simplicity, Figure 24, after Ram Gupta (Gupta, 2001) shows typical curves for a single pump for a single pump speed. A key understanding of pump performance is that as headlosses increases a pump's capacity decreases.

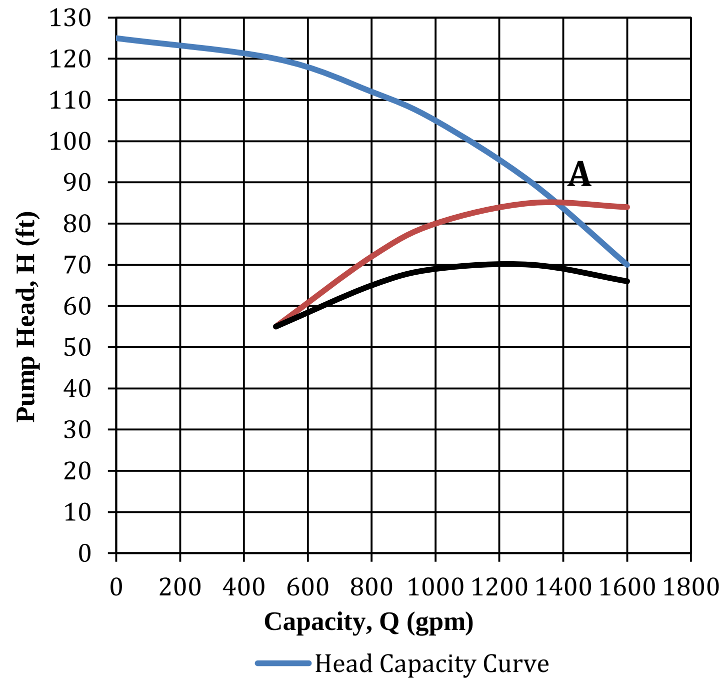

Figure 24. Pump Characteristic Curve

Figure 24 represents the behavior of a particular pump operating at one speed. A pump rating is a function of the head and discharge that provides the maximum efficiency. For this figure, point A is the best efficiency point for a discharge capacity of 1300 gpm.

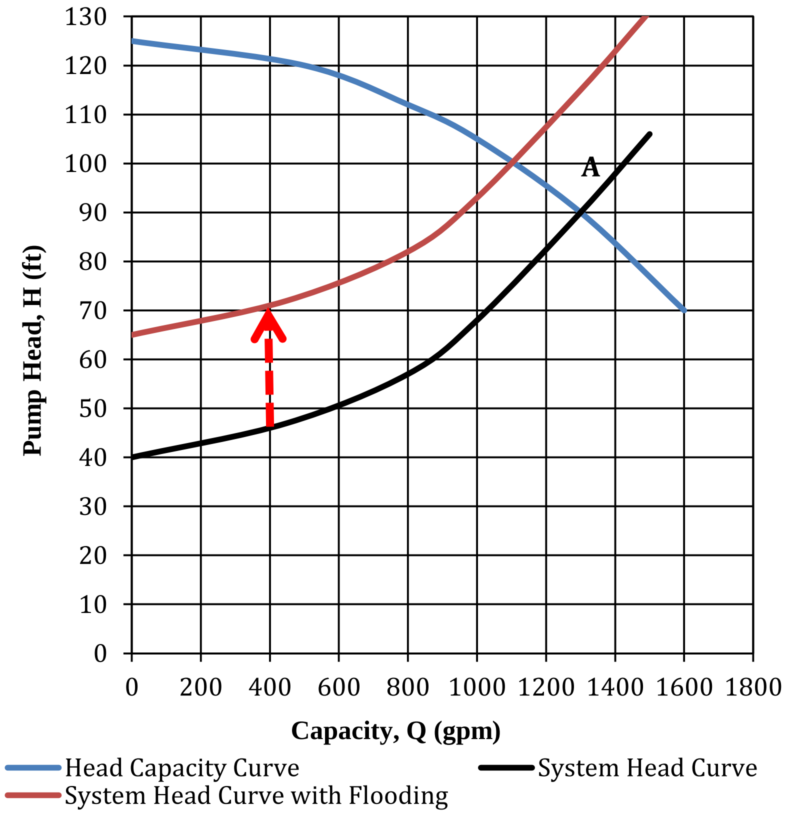

Figure 25. Determination of Pump Operating Condition (Gupta, 2001)

Again for simplicity, Figure 25 shows the intersection of the pump characteristic curve shown in Figure 24, and the system head curve. This intersection is the same point A from Figure 24. However, as infiltration and inflow increases due to flooding, the system-head curve shifts up (red arrow in Figure 25). As it shifts, Point A shifts up along the pump characteristic curve reducing the system's capacity.

The pump itself has various components that are exposed to inundation and salt water. Below is a list of key components and possible impacts. Most of the verbiage is directly from a Jensen Engineering System design manual (JES, 2012).

- **Impeller** (open, closed, semi-open which includes vortex, or non-clog) - a component that is the heart of the pump and the only part that adds energy to the fluid. Energy is added by accelerating the liquid from the smaller radius at the impeller inlet to a larger radius at the impeller exit. Increasing the outside diameter of the impeller, or increasing the speed at which it operates can amplify the amount of energy input into the fluid. However, energy added by a spinning impeller exits as a high-speed fluid, which is not very useful for process applications. Pump output requires higher pressure, not higher speed. To convert from higher speed to higher pressure, the flow must be diffused (speed reduced) converting high velocity energy into pressure and energy. It is a function of Bernoulli's Equation. (**Failure mode** – de-ragging trash.)
- **Motor** - a function having enough HP to drive the pump and often selected to be non-overloading at the end of the curve. Two kinds, (1) oil-filled motors best for high thermal transfer and high moisture. Keeps bearings and windings lubricated and protects against water leaks into motor system. (2) air-filled motors, which have a lower drag. Best where liquids are always cool and provide heat dissipation. . (**Failure modes** – vibration or start-up torque causes insulation on windings to wear and short-out the motor; insulation tends to break down in moist environments.)
- **Cable Connections** - a power cable enters the motor housing at a junction box located below the liquid level. There are two kinds of connections. One is a rigid permanent connection with built-in strain relief. Includes packing gland around entrance to junction box, and a secondary seal to prevent leakage. The second is a quick disconnect to facilitate a frequent pump changes w/o need for electrician for de-ragging. (**Failure mode** – leakage.)
- **Bearings** - one of two kinds; (1) is the upper bearing designed to support the rotor (pump impeller, shaft, and motor rotor) in the radial direction, and (2) is the lower

bearing which is usually responsible for supporting the rotor in both radial and axial loading. (**Failure mode** – improper lubrication either from contamination of the lubricant or poor preventive maintenance.)

- **Mechanical Seals** - prevent the liquid being pumped from leaking around the pump shaft into the bearing and motor housing. Submersible wastewater pumps typically have a tandem arrangement. The system contains a seal chamber with two shaft seals mounted in the same direction located between the motor and pump with an oil barrier between the two seals. Each seal has a set of sealing faces with a clean barrier fluid injected between the seal faces. One sealing face rotates with the shaft against a stationary surface where the barrier fluid lubricates and cools the seal faces. (**Failure mode** – seal fails quickly when the surfaces run dry. Biggest cause for pump down time.)
- **Seal Face Materials** - one of four kinds; softer materials are carbon, ceramic, and harder materials are tungsten carbide, and silicon carbide. Dissimilar materials are typically used, one hard and one softer, to avoid adhesion between the surfaces. In wastewater applications, the upper seal is in oil and usually is a carbon versus a ceramic material; and the lower seal is exposed to pump fluid (and abrasives) and are silicon carbide versus a silicon carbide material or silicon carbide versus tungsten carbide material. (**Failure mode -** Carbon and ceramic materials are easily scratched in an abrasive environment causing the seal to fail. Ceramic is also subject to thermal shock (quick temperature change) causing it to shatter.)
- **Moisture Sensors** - used in submersible pumps to detect moisture in the motor cavity where there should be none. (**Failure mode** – moisture impacts motor and bearings requiring an immediate shut down).

Another critical asset is power supply. In Norfolk, the primary power source is separate from the city's system. Coastal storms can disrupt utility service and the city only has one submersible pump with a backup generator to manage power disruptions. (See Appendix A, March 5, 2015 and November 3, 2015 entry).

From an asset management perspective, rising sea levels and coastal storms will impact the capacity of the network to handle larger flows and the operating efficiency of pumps as discharges increase. The question remains how best to represent the performance of a pump system in the face of such impacts?

From a systems analysis perspective, there are two basic approaches to identifying risk scenarios (Pinto & Garvey, 2013); a bottom-up and top-down approach. The bottom-up approach uses knowledge of assets and how these assets work together. This method is compatible with reliability analyses and tools such as failure mode and effects analysis. A top-down approach is more appropriate when there is lack of data to support a bottom-up approach. The top down methodology works first with an understanding a system's objectives, and second with informed conjecture to establish a general set of risks.

From a bottom-up perspective, a Functional Dependency Network Analysis (FDNA) provides a way to assess impacts to judge dependencies between system components. It provides a means to add discipline and to document expert elicitations. The methodology "…is a way to measure inflows and outflows of value across a topology of feeder-receiver node dependency relationships" (Pinto & Garvey, 2013). It uses mathematical graph theory in the form of connected nodes, and applies relationships to assess how disruptions to nodal links impact the system's capability.

It has applicability to a wastewater network, and in particular, assessing the capability of the pump station. Volume of flow is its value in FDNA nomenclature.

Figure 26 is a modified graphical representation of a pump station based on an asset decomposition and dependency flow diagram from a study by the U. S. Army Corps of Engineers for Naval Station Norfolk (USACE, 2014). The mission for Norfolk's pump system is to provide support to residential customers. The pump station's objective is to remove a sufficient volume of wastewater to avoid any spillage that would result from overflow.

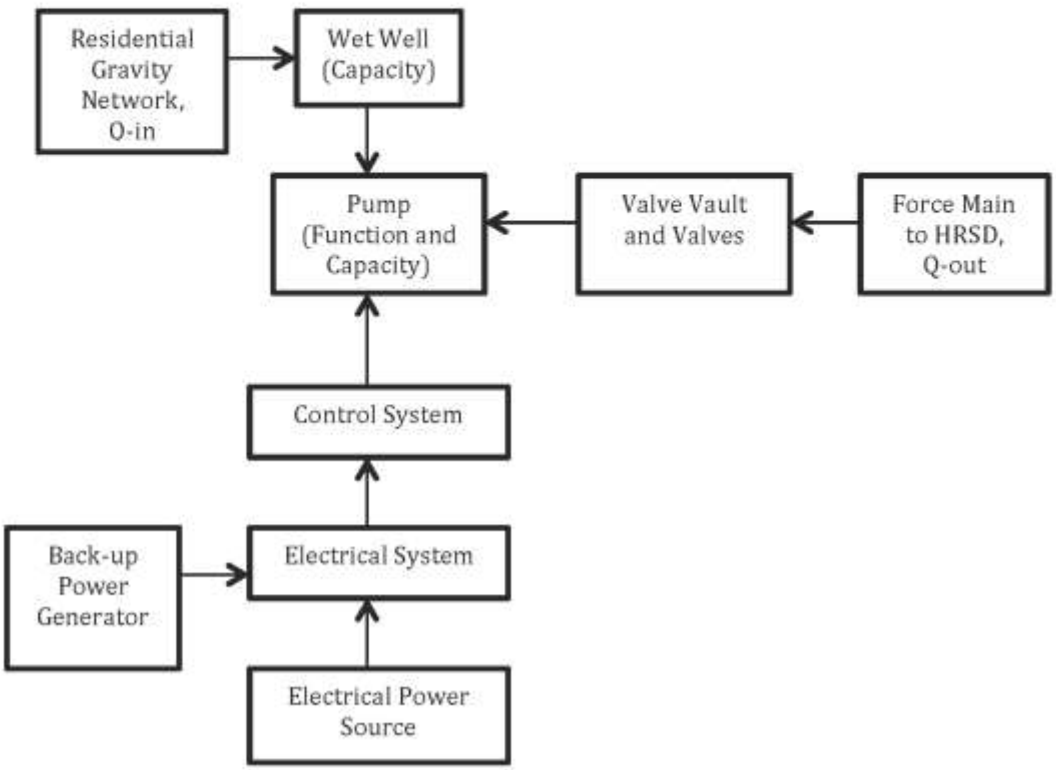

Figure 26. Asset Decomposition and Dependency Flow Diagram

The pump's performance is dependent on all components of the system operating satisfactorily to avoid any back up and overflow of wastewater, hence all arrows point to the pump. The pump performance is dependent upon four aspects: (1) a properly sized gravity network and wet well to handle the volume of influent, (2) a continuous supply of power and a functioning control system, (3) on the ability of the downstream components to handle the volume of effluent, and (4) its motor to function and to operate at an efficiency sufficient to handle the volume of influent.

Per discussions with the City of Norfolk, Operations Division, Department of Utilities typical shut downs caused by storms and flooding are (1) a loss of power supply because the pump station does not have a backup generator, (2) electrical short in the Quasar electrical junction box, (green box at grade level), (3) electrical short in the control panel when water levels are about one foot above the bottom of the panel, (4) overloaded pump runs continuously for 2 to 3 days of flooding reducing pump efficiency, and (5) dirt and sand chokes the pump, slowing it down and driving up the amperage burning out the motor. (See Appendix A, March 5, 2015 entry.)

The FDNA identifies potential ripple effects of losses in a supple network. It uses nodes to represent the various components with each node representing a measurable capacity to function. It also uses links between nodes to represent a potential to disrupt capacity of nodes and impact the network's overall capability. The FDNA measures the level of "operability loss" and a means to judge whether such impacts are an acceptable risk (Garvey & Pinto, 2014).

Figure 27 is a topology that translates Figure 26 into a mathematically directed graph representing capability in the form of a network with relationships between nodes.

The graph is a means to visualize dependency relationships between nodes and a methodology to measure the transmission of value between nodes (Pinto & Garvey, 2013). This form provides a means to study how well the network operates.

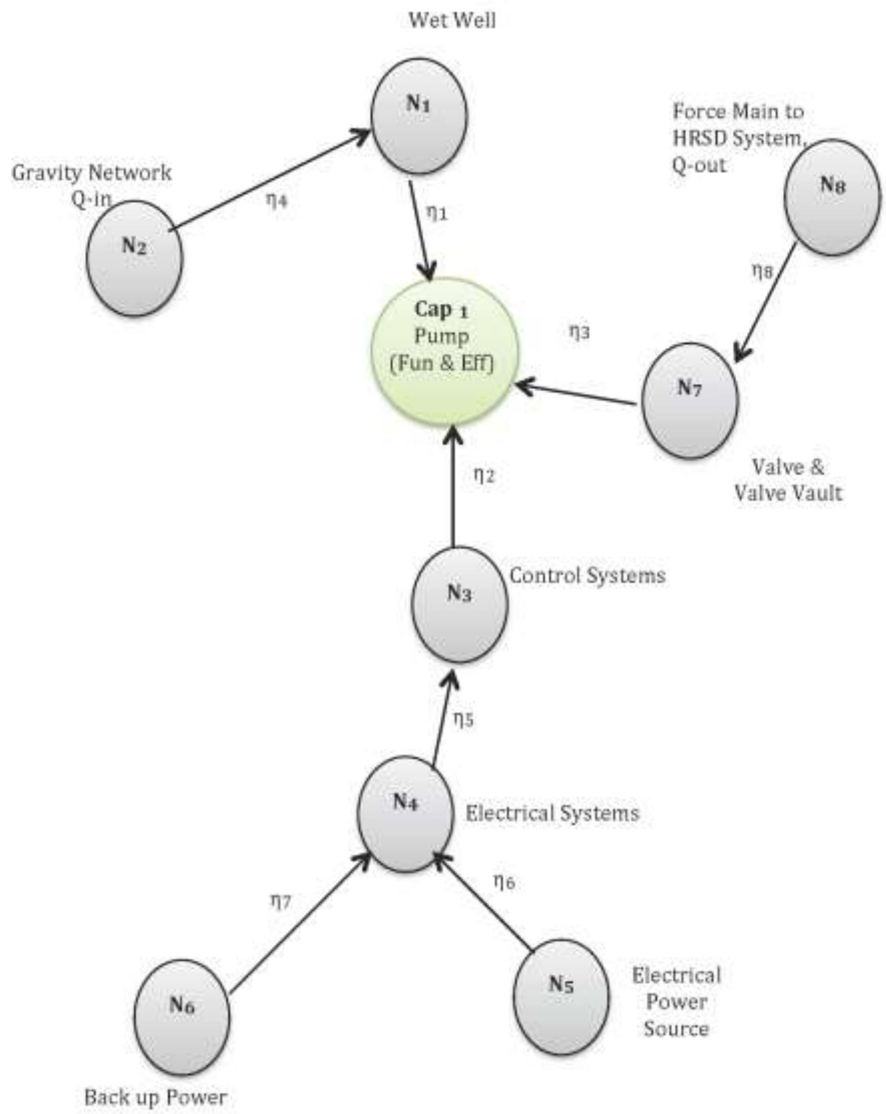

Figure 27. A FDNA Format Representation of Figure 26

The graph is a set of points and a set of lines, with each line connecting two points. The points of a graph are known as vertices or nodes. Outlying nodes such as N_2, N_5, N_6 and N_8 are leaf nodes that feed "contributions" to other nodes and are referred to as feeder nodes. Nodes such as N1, N3, N4 and N7 both receive and feed other nodes and are referred to as feeder and receiver nodes. (Pinto & Garvey, 2013).

The FDNA uses value functions to express the performance levels of the pairs of feeder and receiver nodes. This approach is in line with research by USACE for quantifying resiliency in coastal systems (Schultz et al., 2012). Its structure is compatible with existing mathematical models of wastewater systems and offers a means to integrate risk analysis within these models.

The challenge for an engineer is to generate data that permits understanding the performance of the system. This requires an analysis of current capacity, how the rate of infiltration and inflow increase with increasing sea levels, and how that increase affects the capacity of the system to function. However, the city has not conducted these kinds of studies. (See Appendix A, June 3, 2014 and March 13, 2015 entries.) .

As noted in this section, the pump's performance is dependent upon four aspects of which two potential failure modes are most pertinent for this analysis. Floodwaters cause electrical shorts in the pump station's electrical and control system; and as the depth and duration of inundation increases, headlosses increase and the pump's capacity decreases. As shown in Figure 23, when the system head curve continues to rise, a pump begins to lose efficiency and capacity.

However, there is very limited available data about the pump station. Also, ASCE notes there is a lack of guidelines for assessing the impact of climate change on existing infrastructure. In addition, the uncertainty of future weather makes the use of probabilistic methods difficult because properties of variables will be statistically different in the future (ASCE, 2015).

Consequently, this means there is a high degree of uncertainty due to a lack of knowledge, which makes it difficult to take a bottom-up approach to develop a fragility curve. An alternative is to use a top-down approach in the form of expert elicitation for informed conjecture to establish a set of relative general risks for the existing pump station and the proposed new station.

Fault and event trees are two forms of representation that can complement expert elicitation. A fault tree starts with the failure mode and works backwards to identify possible causes. However, the event tree is more in line with this study. It takes a mirrored approach starting with the initiating event such as in our case, coastal flooding, and works toward the consequences.

Event Tree Analysis (ETA) provides insights on how a system works and uncertainties about the way it functions. The process develops either a qualified or quantified probability that the system may fail to meet its objective, which is known as the probability of system failure. It reflects the aggregate uncertainty in knowledge about the performance of the pump station and about the initiating events (Baecher & Christen, 2003).

The objective for this pump system is to remove a sufficient volume of wastewater to avoid spillage that results in consequences. This study assesses the relative risk of the existing and new pump stations that either will fail to meet their objective.

2.3 Summary and Discussion

The author framed the literature review within ASCE's guiding principles for critical infrastructure. These four principles were born in the aftermath of infamous infrastructure failures in the first decade of the 21st Century. The discussions recognized a need to integrate a systems approach, risk analysis and decision-making within the life cycle of critical infrastructure to help communicate a project's performance to stakeholders.

An initial step to embracing ASCE's principles is to answer the *first question about what is the problem scenario*. Ample literature and media coverage about sea level rise that has made it obvious that the Tidewater region of Southeast Virginia is one of the most exposed urban areas in the country.

The scientific and engineering communities clearly recognize the threat to the region and acknowledge the low degree of certainty as to projected rates of sea level rise. The mayor of Norfolk is a leading spokesperson in the nation as to the impacts rising sea levels pose to the region's economy and public safety. However, numerous media articles highlight the lack of agreement among the elected representatives at various levels of government as to whether this is a real or imagined reality.

Addressing the second question as to what is an appropriate systems approach, the technical profession is well versed in using systems engineering in the form of mathematical representation to describe a problem situation. Engineers have had great success using a hard systems approach, i.e. models to define a system's performance and to identify an optimized solution. However, optimization can inadequately represent or disregard aspects difficult to represent mathematically such as environmental impacts and social disruptions. Consequently, the public often rejects such optimized solutions.

The literature shows that systems engineering is evolving to develop soft systems approaches that try to cope with problem situations that mathematics cannot easily represent. The engineering profession is recognizing the need for ficing alternatives, i.e., those that are not necessarily optimal, but good enough to offer options in an undesirable situation or unresolved matter.

This broader view offers a holistic approach to assessing a problem situation. It provides a disciplined way of structured thinking grounded in a philosophical worldview that offers a means to cope with both a well-defined problem and one that is ill defined. It is based on attributes that help engineers judge whether the scenario reflects a traditional, well defined and agreed upon problem situation or a problem situation that is unique, too ambiguous or poorly understood.

The challenge is judging where in the spectrum the attributes exist and whether the nature of the problem is causing shifts within the attributes. Often, the problem evolves if the nature of the impacts change or the number and type of stakeholders involved change or if there is any new knowledge that better defines the problem. All of this makes it difficult to develop optimal, resilient alternatives that could stand the test of time.

The literature review supports a way to use a philosophical worldview approach to examine the challenge of rising sea levels less on the response of the physical environmental and more on the response of a community. This leads the author to examine a coastal system as an enterprise system in the form of a network of interdependent organizations whose processes are not fully under control of any single entity.

This above description is in line with our democratic society in a country composed of interdependent groups of federal, state and local governments. Our laws, regulations, policies and codes are distributed at each of the government levels where we need legal actions to resolve conflicting interpretations of these laws. Therefore, an enterprise system provides a basis for analyzing risk with stakeholder input, and it offers a means to assist decision makers to make informed choices as to appropriate adaptive actions.

The literature shows that where an enterprise system is a social representation of a coastal community, understanding impacts on infrastructure performance is a social-technical problem. The author offers a worldview based on using a network to represent the community, and a hierarchy within the network as a subsystem to represent the social-technical problem. The hierarchy offers a means to reduce a complicated perspective of infrastructure at the top of the hierarchy to a simpler perspective at the bottom of the hierarchy.

The author presents a philosophical spectrum and complements it with a graphic depiction of Zones of Complexity to help categorize an appropriate systems approach at each level within the hierarchy. It is a simple tool to help engineers judge whether the scenario is a traditional, well defined and agreed upon problem situation or a problem situation that is messy. Given this understanding, the engineer can judge which component of a social-technical problem is dominant and classify whether a hard or soft systems approach is appropriate.

At this point in the summary, systems engineering offers a disciplined way of structured thinking grounded in a philosophical worldview; systems environment provides a means to think of our coastal community as an integrated social and technical problem; systems representation presents our community as a network where aspects can be depicted as a hierarchy; and systems philosophy helps classify the problem situation and describe its characteristics at any level in the hierarchy based on its degree of complexity. What is needed is a systems methodology that provides the framework to apply systems analysis to resolve real problems.

However, this is one topic in the literature the author found that needs further research. There are numerous references describing multiple kinds of methodologies. There are many examples of applying hard systems thinking to complicated natural and physical systems; and of applying soft systems thinking to complex organizations and industrial processes. However, there is limited information and experience on applying soft systems thinking specifically to complex public works type infrastructure.

This author offers a methodology as a framework to apply a systems analysis to the challenge of rising sea levels, but it is untested. At the writing of this paper, the U. S. Army Corps of Engineers is researching systems approaches in the aftermath of Hurricane Sandy in accordance with the Disaster Relief Appropriates Act of 2013 (Public Law 113-2) (USACE, 2015a). The Corps seeks optimized solutions within a coastal system defined by a sand budget that can cross multiple jurisdictions; but whether optimized alternatives can balance social-technical problems across multiple jurisdictions remains to be seen.

For the third question as to what is an appropriate risk-informed methodology, the literature is full of traditional probability math to define the hazard and performance components of the risk equation. It also includes publications that address quantifying performance specific to coastal infrastructure, and identifying reasonable risk exposure. However, the literature is absent of any discussion as to what are appropriate performance levels for pump systems.

As a follow-on to the absence of data of performance levels, the review to answer *the fourth question about impacts to pump stations* identifies a second topic that needs research. The literature lacks information specific to mathematically depicting impacts to wastewater systems or pump stations exposed to flood waters. Also, the literature lacks specifics to quantifying the consequence of pump failure as a component to the risk equation.

As for the fifth question about appropriate means to depict impacts to pump stations, available infrastructure concepts use a bottom-up approach focusing on asset management to assess performance. The shortcoming to this approach is asset management can demand large volumes of data that are lacking and expensive to collect. In the absence of a bottom-up approach, the alternative is a top-down approach. However, the literature lacks specific examples applicable to depicting impacts to the submersible wastewater pumps and is a third topic that needs research.

In summary, the benefit of a systems-based approach is it offers grounding in philosophy and systems thinking to cope with whether you are dealing with a unitary understanding of objectives or pluralistic perspectives. Tailoring a methodology to the problem situation provides a basis for designing an approach with tools capable of coping with emerging patterns and new knowledge. If the process is simple, a reductionist, prescriptive system analysis may be best, but if it is complex, the soft systems methods offer a holistic means to view the problem.

CHAPTER 3

APPLIED RESEARCH PROJECT METHODOLOGY

3.1 Risk Informed Decision Methodology

Per the literature review in section 2.2.1 Subset question a: "What is the problem scenario?" finds that employing an integrated systems approach is a means to structure a complex problem into something more manageable. Incorporating risk as a means to assess uncertainty aids decision makers to make informed judgments about potential trade-offs. It is through risk that decision makers can communicate the potential for loss to the public.

Although, PS 113 is a small system in scope and scale, applying a systems perspective made it necessary to frame the research problem within a coastal region adapting to the changing sea levels. Section 2.2.2, The Coastal Environment as a System and section 2.2.3, Representation of a Coastal System, describe the region as an enterprise system in the form of a network as shown in Figure 6. From within that network, Figure 7 presents infrastructure as a hierarchy where Pump Station 113 fits within Level 3.

Level 3 represents the various jurisdictions responsible for the collection of their own wastewater for transfer to HRSD. It is at this level where Pump Station 113 collects and pumps wastewater to a HRSD pump station within the Larchmont neighborhood for transfer to HRSD's Virginia Initiative Plant located on the Elizabeth River for treatment.

Using this hierarchical approach reduces the complex problem to a representation of the network that is easier to understand. In accordance with Table 5, a simple, hard systems approach is appropriate for projects at Level 3. As noted in section 2.2.2.6, Systems Methodology and Figure 11, Zone of Complexity, the degree of certainty and agreement is high and this type project fits in Zone 1 or 3, which is most appropriate for understanding the pump's performance. However, per the literature review, there is little information specific to how rising sea levels impact pump stations. The general practice is to use experts to judge performance and qualitative scales to assess relative risk levels (King County, 2008).

As noted in section 2.2.3.2, Tolerable Risk, the State Water Control Board defines the design standards for sewage pumping. Section 9VAC25-790-380, Sewage Pumping states Mechanical and electrical equipment must be located above the 100-year flood/wave action (1% chance of being equaled or exceeded in one-year). Also, all stations shall be designed to remain fully operational during the 25-year flood/wave action (4% chance of being equaled or exceeded in one-year).

The controlling physical factors are infiltration and inflow, which increase the volume of flow reducing the capacity of line segments to convey wastewaters to pump stations. In turn, the pump stations have to move more fluid to minimize the potential for overflow spilling into the streets and open waters. Also, coastal storms disrupt power sources and corrode equipment, both causing pump shut downs.

In section 2.2.5, “What is the appropriate means to demonstrate the impact on the performance of the pump stations?”, the author describes submersible pump stations in an asset management format. The assets represent both the design capacity and physical components of a submersible pump stations. The review identified that the pump performance is dependent upon four aspects; (1) a properly sized gravity network and wet well to handle the volume of influent, (2) a continuous supply of power and a functioning control system, (3) the ability of the downstream components to handle the volume of effluent, and (4) its motor to function and its efficiency to handle the volume of influent.

These aspects can be reduced to three potential failure modes: (1) loss of power supply caused by a disruption of service power, (2) electrical shorts caused by floodwaters in the pump stations electrical and control system; and (3) the pump’s capacity decreases or the motor simply burns out as the depth and duration of inundation increases and resulting headlosses increase. There are three key failure points. (See Appendix A, March 5, 2015 entry.) The first is the interruption of service power. The second is when flood elevations are about one foot higher than the bottom of the control panel causing electrical motors to short out. The third is when the duration of floodwaters exceeds 72 hours, a time long enough to impact pump efficiency and/or damage the pump motor.

However, this study only focuses on the second and third failure modes. As noted in 3.2.2 The Network and Existing and New Pump Station 113 Details, neither station has a backup generator. However, in order to focus on the fragility of the sewage system, this study centers on only those assets within the city's control and assumes that there will be no loss of service power. A broader study of an integrated system would require including assets that support the city.

The author employed a top-down approach. As noted in section 2.2.5, the pump station's objective is to remove a sufficient volume of wastewater to avoid any spillage that result in consequences. This study uses expert elicitation for informed conjecture in the absence of available data to establish a set of relative risks between the two pump station locations for a life cycle of 20 years typical for submersible wastewater pumps and over a 50-year design life for a pump station structure.

As noted in section 2.2.2.2, The Coastal Environment as a System, the basis for the decision theory is a value function. The author created an event tree to develop the value function. The event tree is a suitable way to represent the cascading effect of the impact of a natural event. The event tree is an excellent visual tool that starts with the initiating event such as coastal flooding, and works toward the outcomes. Figure 28 depicts an event tree representing the impacts on a pump station.

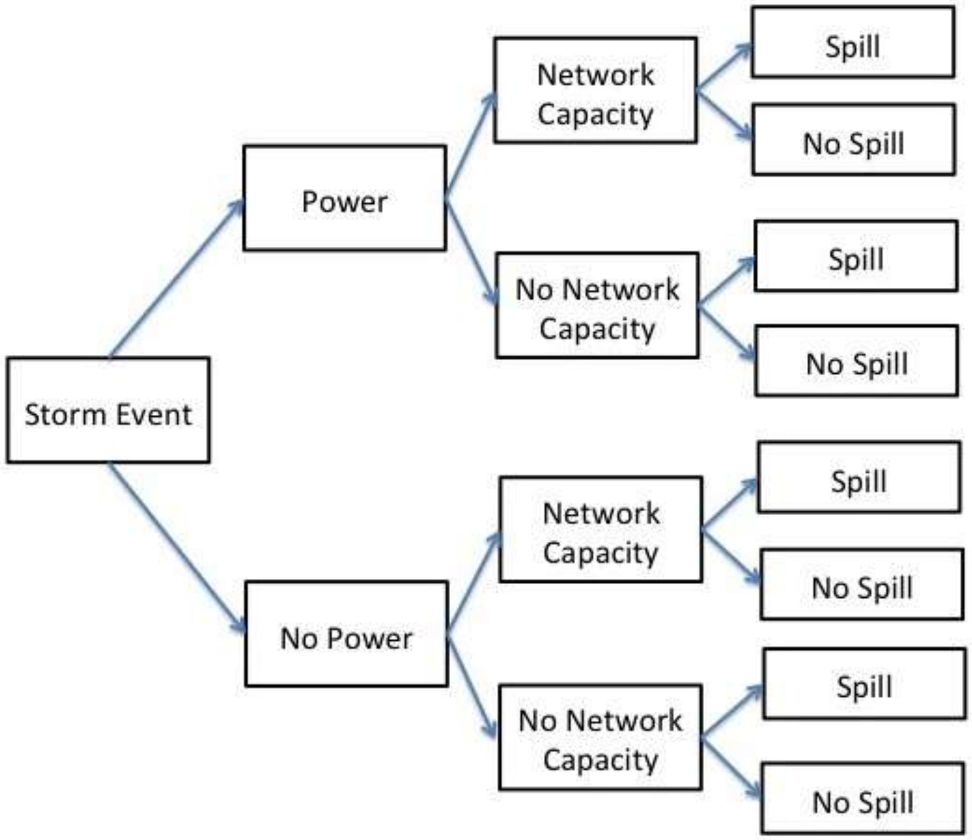

Figure 28. Event Tree for PS 113 and New Station

The analysis will assess the relative risk between the existing pump station and the proposed new pump station for the release of wastewaters, a violation of Section 301 of the Clean Water Act.

As discussed in section 2.2.3.1 Design Principles, the equation for computing risk, R is as follows:

$$R = P_E(P_F)(Consequences) \qquad (20)$$

where P_E is the probability of the storm event, P_F is the probability the pump station will fail when impacted by the storm event, and the consequences are the resulting losses from the failure of the pump station. Figure 29, after Desmond Hartford and Gregory Baecher (Hartford & Baecher, 2004), outlines the process for determining risk.

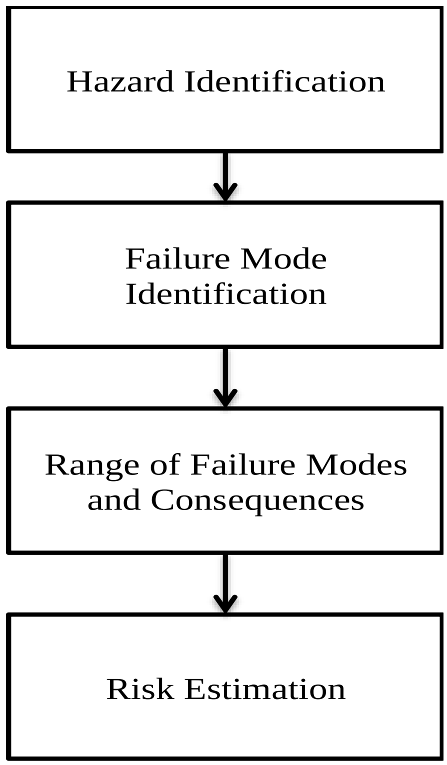

Figure 29. Risk Analysis Process (Hartford & Baecher, 2004)

For this study, this author assumes a storm event occurs upon an elevation representing a sea level rise scenario and the probability of this combination is represented by the annual storm frequency of the storm, P_E. The probability of failure, P_F, depends on subject matter experts who can qualitatively weigh the sum of the impacts of the pump performance for each stage of sea level and storm. The experts will also judge the appropriate consequences for the given failure condition. The assumptions for the risk analysis are as follows:

- Probability, $P(B|A) = P_E(P_F)$
- Conditioning Event (A) – A flood of [X]% frequency occurs at a sea level rise elevation of [X] feet, NAVD (88).
- Risk Event (B) – The pump station does not work or its operational efficiency is insufficient to prevent overflow of waste.
- Risk Statement –If a flood of [X]% frequency occurs at a sea level rise elevation of [X] feet, NAVD (88) then either the pump does not work or the pump's operational capacity is insufficient resulting in an overflow of wastewater.
- Pump Station System Performance Objective – Pump operates to move a sufficient volume of wastewater to prevent backups and overflow.
- Failure Modes – (1) The electrical system shorts and shuts down pump station. (2) The efficiency of the pump drops to a capacity that is insufficient to prevent overflow of waste or causes the pump to shut down.
- Consequences - This study will use a mathematical function to measure consequences presented in section 3.3 Consequences.

The product is a graphic showing the progressive changes of risk as sea levels rise. The results will show how this combination changes as flood stages change over time, any difference between the existing and new pump station locations, and a tipping point where performance is unsatisfactory.

3.2 Specific Project Research Design

3.2.1 Venn Diagram

Figure 30 is a Venn diagram showing the probabilistic causation between floodwaters and impacts to pump performance, i.e., the likelihood flooding will result in spillage (loss of pump performance, i.e. pump failure).

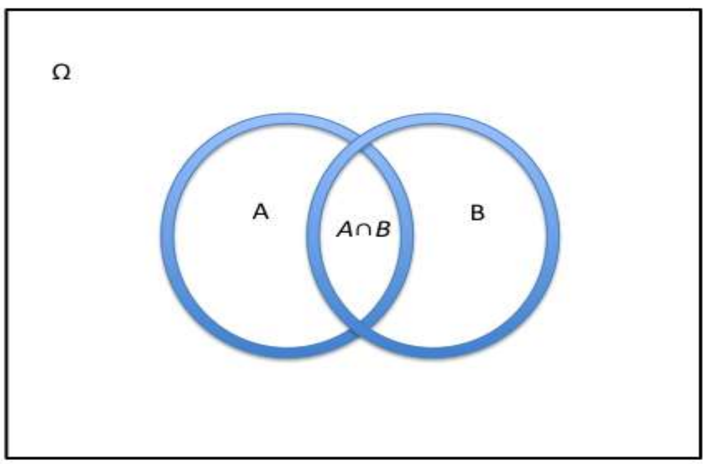

Figure 30. Venn Diagram of Probabilistic Causation

A (Flood elevation) and B (spill) are events in a sample space Ω with $P(A) > 0$ $and\ P(B) is\ unknown$. The probability of a spill (B) given the occurrence of flood elevation (A) is a conditional probability where $P(A \cap B) = P(B|A)P(A)$.

The author makes the following assumptions for this analysis:

- $P(A) > 0$ and is equivalent to the annual exceedence probability of a flood stage.
- $P(B|A) = 0$ when floodwaters are below a specified elevation where infiltration and inflow are sufficiently negligible because most of the network is at higher elevations.
- $P(B|A) > 0$ when floodwaters exceed the specified elevation because at this point inflow impacts the pump's performance. Expert elicitation will judge the probability of non-performance given the flood stage. Non-performance can take the form of a step function or a S-shaped function as shown in Figure 31.
- $P(B|A) = 1$ when flood waters reach the bottom of the electrical control panel because floodwaters will short the system and the pump will stop to function.

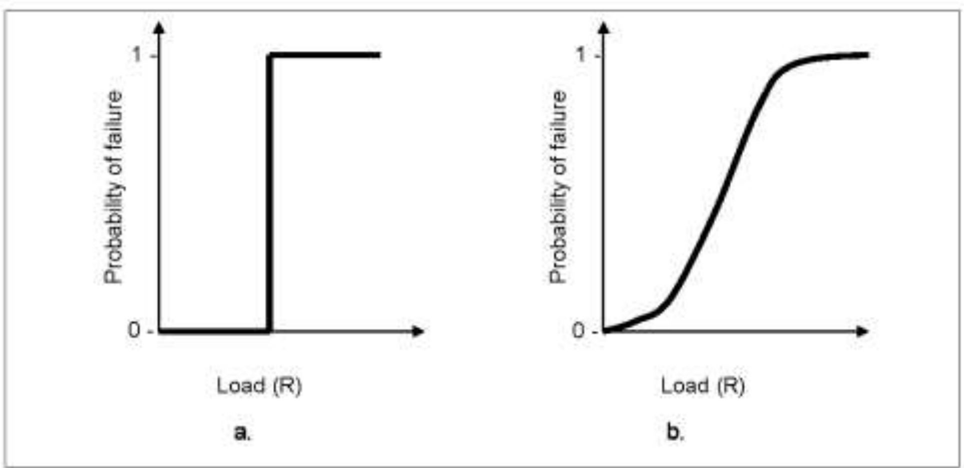

Figure 31. A Conceptual Fragility Curve. (The fragility curve is a step function (a) for a very well understood or brittle system. A fragility curve is an S-shaped function (b) for a poorly understood or elastic system.) (Schultz, Gouldby, et al., 2010))

3.2.2 The Network and Existing and New Pump Station 113 Details

The City of Norfolk, Department of Utilities, Sewerage Quads C-9B, 9C, 9D, and 10A show the plan view of the sewerage shed (service area), which covers about 135 acres (0.2 square miles). The land use is residential dwellings composed of single-family homes. There are approximately 190 to 200 units in the sewerage service area, but it is difficult to determine a precise number directly from the drawings. Table 6 lists the manholes from lowest to highest manhole elevation and what percent of the manholes are inundated as the flood stage increases.

Table 6. Manholes within Sewerage Service Area[2]

Rank[1]	Sheet, Station[2]	Street Location	Top of MH Elev., Ft NAVD(88)[3]	Notes[4]
1	C-09-C, 4+80	Sylvan & Walnut Hill	2.02	
2	C-09-C, 0+21.6	Sylvan & Walnut Hill	2.35	
3	C-09-C, 2+40	Rolfe & Walnut Hill	2.86	
4	C-09-C, 0+00	Sylvan & Walnut Hill	2.9	17% of MH under Elev. 3
5	C-09-B, 2+75	Sylvan	3.42	
6	C-09-B, 5+00	Rolfe	3.92	25% of MH under Elev. 4
7	C-09-D, 8+00	Rolfe	4.09	
8	C-09-B, 6+04.9	Powhatan & So, Eleanor	4.17	
9	C-09-D, 7+50	Sylvan & Catalpa	4.29	
10	C-09-C, 3+74	Sylvan	4.39	
11	C-09-B, 8+57.4	Powhatan	4.91	46% of MH under Elev. 5
12	C-09-B, 3+61.2	Powhatan & Powhatan Pl	5.2	
13	C-09-C, 3+72	Rolfe	5.85	
14	C-09-C, 4+75	Powhatan & Walnut Hill	5.97	58% of MH under Elev. 6
15	C-09-D, 7+79.7	Powhatan & Miscellaneous	6.33	
16	C-09-C, 3+81.6	Powhatan	6.76	
17	C-09-D, 2+35	Glenhaven	6.97	71% of MH under Elev. 7
18	C-09-D, 3+00	Studeley & Miscellaneous	7.21	
19	C-10-A, 5+13.5	Rolfe & McLean	109.36 MLW = 7.40	
20	C-09-C, 3+22.1	Studeley	109.37 MLW = 7.41	
21	C-09-D, 3+06.3	Glenhaven (offset)	7.71	
22	C-10-A, 2+82.2	Magnolia Ave	7.89	92% of MH under Elev. 8
23	C-09-D, 3+66	Glenhaven	8.03	
24	C-09-D, 1+82	Studeley	110.19 MLW = 8.23	

1. Rank of manholes from lowest to highest elevations.
2. Reference City of Norfolk, Department of Utilities, Sewerage Quads, June 03, 2010
3. Three elevations shown in old City of Norfolk 99.00 MLW datum where 101.96 feet, MLW = 0.00 feet, NAVD.
4. Percentage of manholes inundated by specified flood elevation. Elevations are in feet, NAVD (88).

Appendix A provides photographs of the existing and new pump station sites, and of Walnut Hill Street inundated by recent coastal flooding. It also provides a site plan that includes the locations of the existing and new pump station, a cross section of the layout for the new pump station, and cross sections of the existing and new pump station wet wells

For the existing pump station, the top of the pump station manhole elevation is 2.97 feet, NAVD (88) and the base of the wet well is at an estimated elevation -8.3 feet, NAVD (88). The author surveyed the site and measured the bottom of the existing control panel at 5.38 feet, NAVD (88). Also, the station does not have a backup generator.

The station has two constant speed Hydro-O-Matic (vertical) 5 Horse Power (HP) pumps in parallel. The model number for the pump is SPGF 500. It is a 2-in. x 4-in submersible grinder pump with a 3-phase, 60-hertz motor that operates at 1150 Revolutions Per Minute (RPM). The pump performance curve is for a Yeoman's Curve No. 3501.

Data in the HRSD files provided by the city is listed below (Appendix A, August 12, 2014 journal entry). The design pressure is 65 feet with a firm capacity of 150 gpm.

Norfolk Pump Station 113
- Number of Pumps: 2 (constant speed type)
- Design Pressure: 65 ft
- Firm Capacity: 150 gpm
- Wet well Top elevation: 2.24 ft NAVD 88
- Cross-sectional area of wet well: 28.27 square ft
- Lowest overflow point for the pump station service area: pump station wet well

Pump curve for each of the two pumps:

Total Head	Pump Flow
46 feet	500 gpm
65 feet	150 gpm
74 feet	50 gpm

During a first of two subject matter expert elicitations described in section 3.5 Expert Elicitation, one of the experts noted a discrepancy between the top of manhole elevation of 2.97 feet, NAVD (88) and of the top of the wet well and the elevation indicated in the HRSD files at 2.24 feet, NAVD (88). He thought the top of the manhole and wet well are one and the same elevation. The author had discussed the possible discrepancy with the city and confirmed the top of manhole elevation at the higher elevation (See Appendix A, March 13, 2015). The author did another review and opted to use the 2.97 feet, NAVD (88) for the top of the manhole. (See Appendix A, July 14, 2015 entry.)

For the new pump station, the top elevation is 8.10 feet, NAVD (88) and the base of the wet well is at elevation -17.06 feet, NAVD (88). The bottom of the electrical control panel is 11.10 feet, NAVD (88). The new station also does not have a backup generator.

The design of the new station will include two pumps in parallel each capable of pumping 120 gpm. The design Total Discharge Head (TDH) is 32 feet. Additional points on the pump curve are 140 gpm at 30 feet TDH and 180 gpm at 24 feet TDH. Over a standard day, the pump station is expected to pump approximately 60,000 gallons per day (gpd).

As previously noted, the drawings indicate approximately 190 to 200 residential units in the sewerage area. However, using the standard day of 60,000 gpd noted above, one can estimate a more accurate number. Based on the Regional Sewage Flow Projection Data, the average flow per residential unit is 310 gpd/unit (HRSD, 2015). Dividing this rate into the standard day of 60,000 gpd equates to 194 residential units in the sewerage service area.

At present, the city has just one pump manufacturer included on its approved products list, last updated 08-27-2014, which is Fairbanks Morse. A Flygt centrifugal grinder pump is a pump type currently in service at other pump stations. (See Appendix A, August 12, 2014 journal entry).

Based on the City of Norfolk, Department of Utilities, Sewerage Quads C-9B, 9C, 9D, and 10A drawings (City of Norfolk, 2010), the existing wet well cross section (O'Brien & Gere, 2011), and the new wet well cross section (City of Norfolk, 2014), the estimated volume of the network with the existing pump station is 72,400 gallons and with the new pump station, 82,800 gallons. This volume includes the 24 manholes, the all sewerage lines, all the clean-outs, and the wet well. It does not include lateral service lines to the residences. Figure 32 shows a breakdown of volume by foot of elevation.

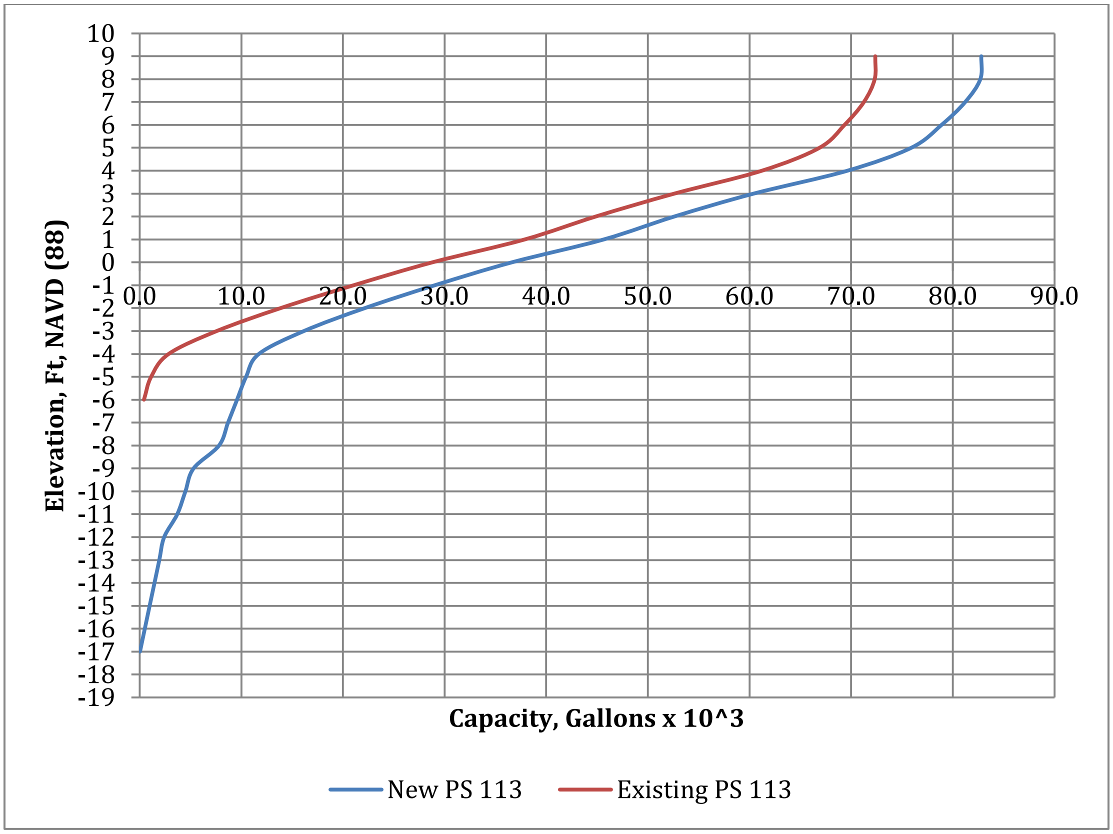

Figure 32. Sewerage System Storage Capacity

The volume that is of most interest is that capacity in the network above the lowest, top of manhole elevation at 2.02 feet, NAVD (88). Below this elevation, the network is typically full of flow due to sewage and infiltration from groundwater. The local groundwater elevations seasonally fluctuate in the 2 to 3 feet, NAVD (88) range and are influenced by tidal waters. Table 7 shows how that volume diminishes as the elevation of the system rises.

Table 7. Available Sewerage Network Capacity Above Elevation 2 Feet, NAVD (88)[1]

Available Network Capacity Above Elevation 2 Feet, NAVD (88)		
Elevation	**Existing Pump Station**	**New Pump Station**
Feet, NAVD (88)	**Gallons**	**Gallons**
2 to 3	27,505	30,209
3 to 4	19,772	22,403
4 to 5	11,155	13,174
5 to 6	5,495	6,902
6 to 7	3025	3,915
7 to 8	1119	1,585
8 to 9	55	97
9+	0	0

1. Reference City of Norfolk, Department of Utilities, Sewerage Quads, June 03, 2010 for physical description of network.

3.2.3 Variables

This assessment is for an empirical analytical study to measure the impact of the rate of rising sea levels on the capacity of PS 113. Figure 33 defines the relationship between study variables. The *explanatory* and *intervening variables* represent the hazard identification and definition portion of the risk analysis process. The *explanatory variable* represents the state of dynamic equilibrium as a series of incremental changes in sea level rise elevations based on recommended planning scenarios. The *intervening explanatory variables* represent the state of meta-stable equilibrium, the physical elements that contribute to a flood stage at the pump station.

Storms include a surge elevation, a wave height caused by that storm, the wave set-up caused by the breaking wave on the slope of the shoreline and the duration of the flood stage. The results are a suite of stage-frequency curves, one for each increment of sea level rise. Each curve plots the flood stage representing a sum of the increment of sea level rise, the storm surge and wave run-up at the pump station location versus the event frequency. In addition, the results include a probability distribution of the duration of flood stages and how it changes with rising sea levels.

For each stage-frequency curve, the author uses points on the curve to develop a *response variable,* the failure mode identification and range of failure probabilities portion of the risk analysis process. The study presents the *response variable* in the form of an event tree as a form of fragility showing loss of pump performance as the specific storm flood stage increases. The author solicited expert elicitation to judge the change in performance and used the resulting fragility within a risk equation.

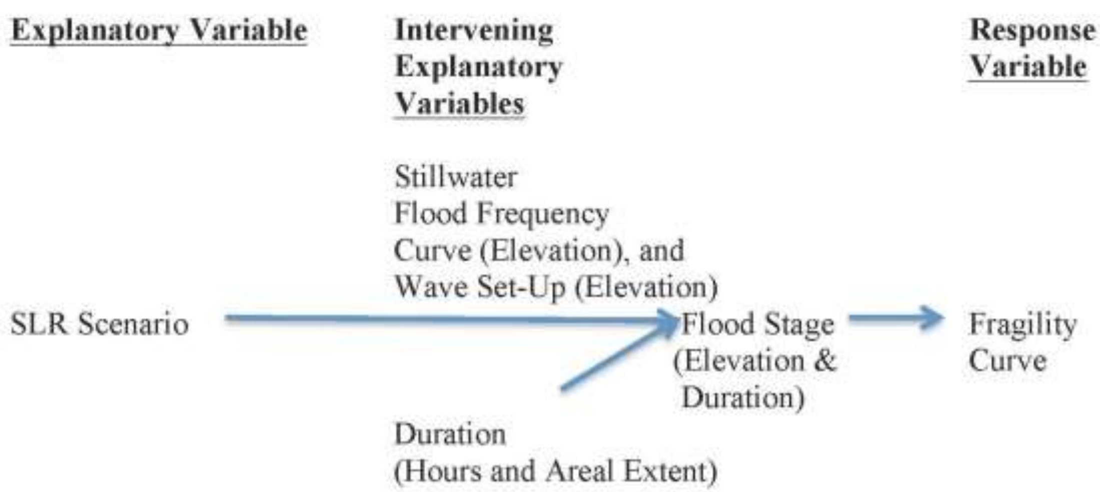

Figure 33. A Schematic of the Relationship Between the Variables

3.2.4 Data

3.2.4.1 Explanatory Variable – Sea Level Rise Scenario

ASCE notes climate model projections cannot determine probability distributions for future climate and requires judgment to determine reasonable conditions for design (ASCE, 2015). With this understanding, the author chooses to use the scenario's determined by Sea Level Rise Calculator provided at the USACE website for Responses to Climate Change (USACE, 2015b). There are four curves based on modifications to National Research Council guidance (NRC, 1987) to include recent Intergovernmental Panel on Climate Change projections for global sea level rise.

The Corps further adjusts these curves to represent the local or relative rate of change (USACE, 2013). Figure 34 provides four scenarios, based on NOAA representations of sea level rise for the Sewells Point Tide Gauge. The basic equation is $E(t_2 - t_1) = 0.000457(t_2 - t_1) + b(t_2^2 - t_1^2)$ where b is constant for each scenario. The Low curve represents the linear historic trend at rate of 4.57 mm/year as of March 26, 2015. The rates for the intermediate and high curves are a function of the b constant.

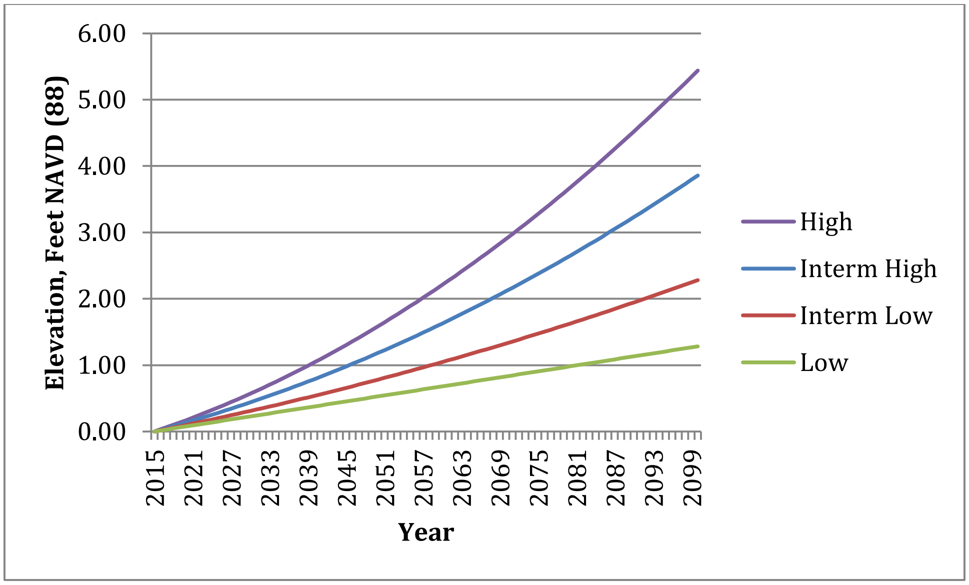

Figure 34. Estimate of Relative Sea Level Rise Projections for 2015 to 2100 (USACE, 2015b)

The benefit of the online calculator is it easily allows the user to set a start date and compute potential changes in sea level for all four curves out to the year 2100. Figures 35, 36, 37 and 38 show each of the scenarios with the stillwater flood stages superimposed to show how rising sea levels can impact future flooding levels.

However, superimposing historic stillwater levels on projected sea levels is an less than accurate representation of future conditions. This assumes that the statistical variables of stillwater levels will be similar to past records, but this is not likely. The weather in the future will be different due to uncertain changes in the climate. This means properties of weather related variables in the future should be statistically different than historic trends (ASCE, 2015).

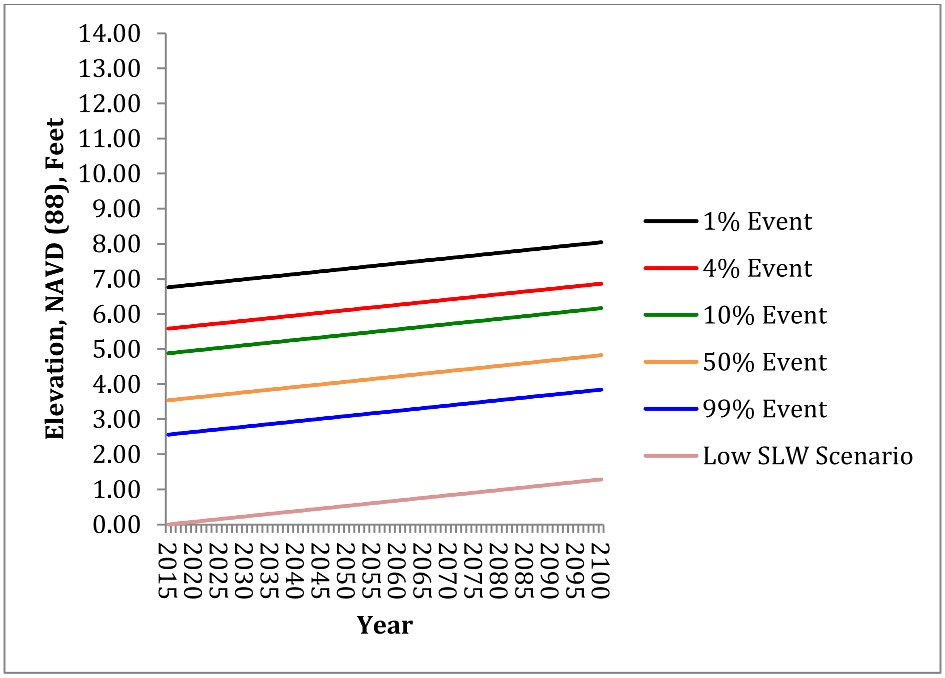

Figure 35. Stillwater Flood Stages for Low Sea Level Rise Scenario

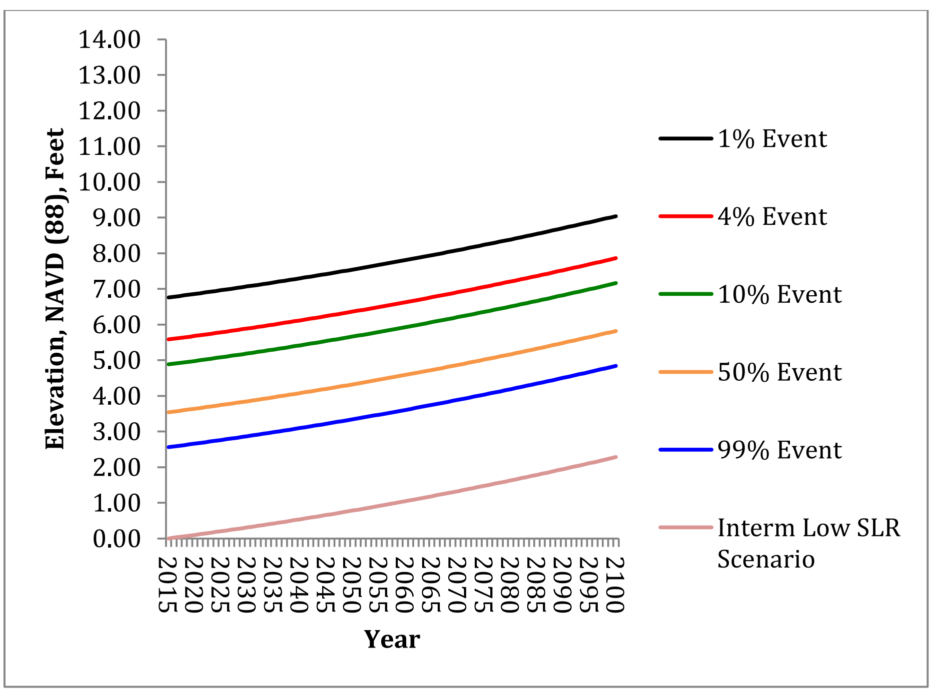

Figure 36. Stillwater Flood Stages for Intermediate Low Sea Level Rise Scenario

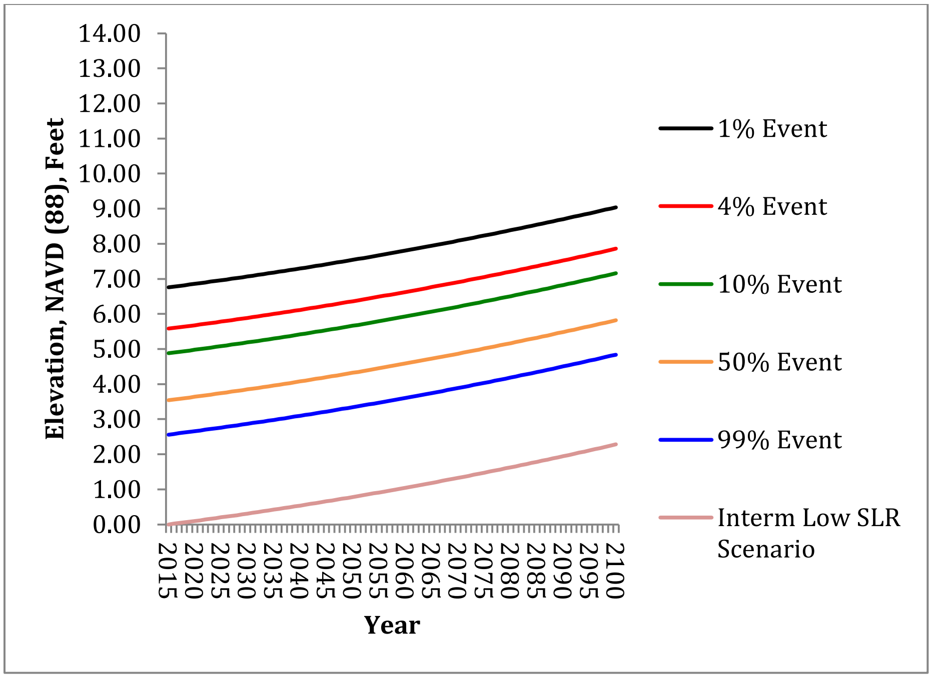

Figure 37. Stillwater Flood Stages for Intermediate High Sea Level Rise Scenario

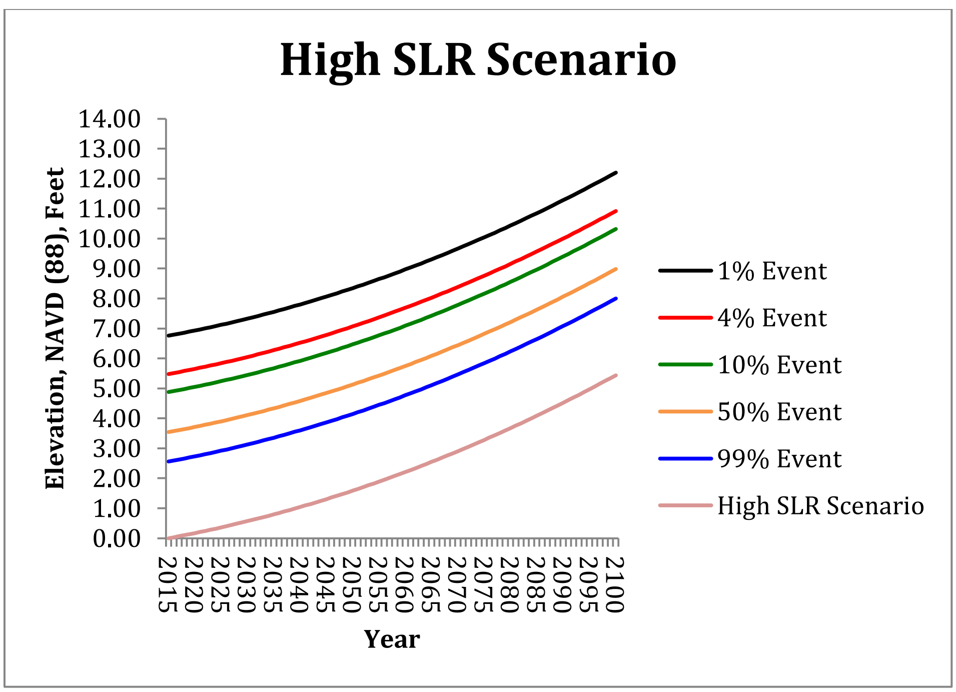

Figure 38. Stillwater Flood Stages for High Sea Level Rise Scenario

3.2.4.2 Intervening Explanatory Variables - Stillwater Level and Wave Set-Up

The National Oceanic and Atmospheric Administration (NOAA) website provides data on extreme stillwater levels for the Sewells Point, VA tide gauge available (NOAA, 2015). Figure 39 provides an annual exceedence probability curve of still water elevations with 95% confidence intervals. The datum is MHHW expressed in meters. The estimated uncertainty in the elevation is less than 0.01 meters.

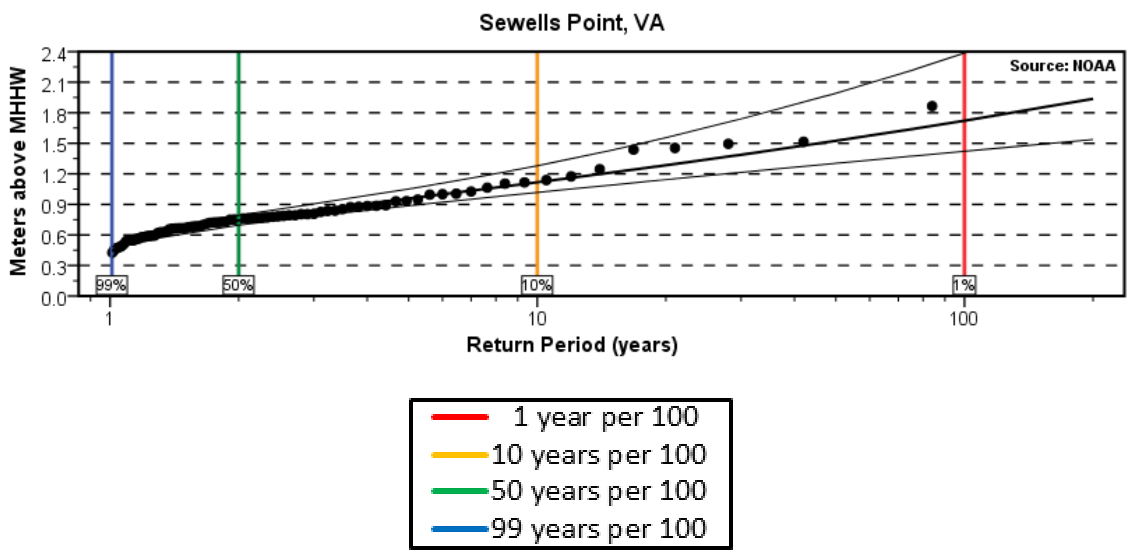

Figure 39. NOAA Exceedence Probability Curves versus Return Period, Tide Gauge 8838610, Sewells Point VA (NOAA, 2015)

Figure 40 provides a breakdown of the annual exceedence levels. Please note the vertical datum used on the ordinate is Mean Sea Level (MSL) expressed in meters. In this figure, the adjustment to convert the MSL elevations to MHHL elevations for the tide gauge is minus 0.43 meters.

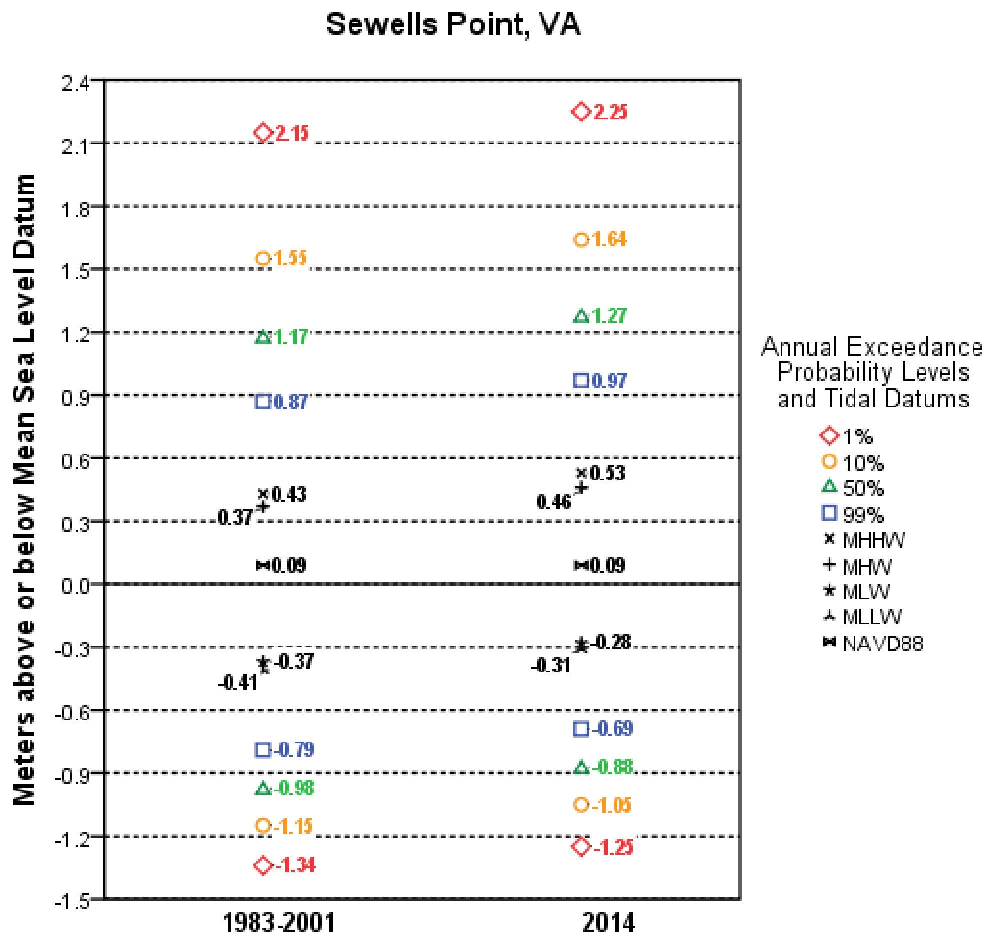

Figure 40. NOAA Tidal Datum and Exceedence Probability Levels Relative to Mean Sea Level, Meters, Tide Gauge 8838610, Sewells Point, VA (NOAA, 2015)

Table 8 converts the MSL elevations in Figure 40 to MHHW in order to estimate event probabilities shown in Table 9. It also converts elevations for the pump station structures that are in feet, NAVD (88) into meters MHHW for use in Table 9.

Table 8. Project and Storm Event Stillwater Elevations

Point of Interest	Meters Above MSL[1]	Meters Above MHHW[2]	Meters Above NAVD[3]	Feet Above NAVD (88)[4]
1% Event	2.15	1.72	2.06	6.76
4% Event	1.79	1.36	1.70	5.58
10% Event	1.55	1.15	1.49	4.88
50% Event	1.17	0.74	1.08	3.53
99% Event	0.87	0.44	0.78	2.56
MHHW	0.43	0.00	0.34	1.12
MHW	0.37	-0.06	0.28	0.92
NAVD88	0.09	-0.34	0.00	0.00
Elizabeth River SWL[4]	0.09	-0.34	0.00	0.00
Top of Existing PS 113[4]	1.00	0.57	0.91	2.97
Bottom of Existing PS 113 Control Panel[4]	1.73	1.30	1.64	5.38
Top of New PS 113[4]	2.56	2.13	2.47	8.10
Bottom of New PS 113 Control Panel[4]	3.47	3.04	3.38	11.1

1. From Figure 40, NOAA Tidal Datums and Exceedence Probability Levels Relative to Mean Sea Level (MSL), Tide Gauge 8838610, Sewells Point, VA. Need to convert to MHHW to match ordinate in Figure 39. Figure 40 does not provide a value for the 0.2% and 4% annual exceedence probability level. See Table 9 for computation of these elevations and for elevations of storms of interest.
2. MSL elevations adjusted to MHHW by subtracting 0.43 meters.
3. MHHW elevations adjusted to NAVD by adding 0.34 meters.
4. Elevations in feet, NAVD (88) for Elizabeth River and pump station structures taken from site plan in Appendix A. Elevation for bottom of existing PS 113 Control Panel measured by survey using top of PS 113 as bench mark = 2.97 feet, NAVD (88). Elevations in meters for bottom of PS Control Panel back-calculated from feet.

Table 9 uses the MHHW elevations in Table 8 to estimate annual exceedence probabilities using Figure 39. It provides storm probabilities that would match the structural elevations of the pump stations.

Table 9. Storm Event Annual Exceedence Probabilities for Stillwater Elevations

		Event Probability[2]				
Points of Interest	**MHHW Meters[1]**	**Return Period, Log X, Years**	**Return Period, 10^x, Years**	**Return Period, $1/10^x$ %**	**NAVD Meters[3]**	**NAVD Feet[4]**
Bottom of New PS 113 Control Panel	3.04	4.2000	15849	0.006	3.38	11.1
Top of new PS 113	2.13	2.6833	482	0.2	2.47	8.10
1% Event	1.72	2.0000	100	1.0	2.06	6.76
4.0% Event	1.360	1.4000	25	4.0	1.70	5.58
Bottom of PS 113 Control Panel	1.30	1.3000	20	5.0	1.37	5.38
10% Event	1.12	1.0000	10	10	1.46	4.79
50% Event	0.74					
Top of PS 113	0.57	0.0833	1	83	0.91	2.97
99% Event	0.44	-0.1333	1	136	0.78	2.56

1. Elevations for pump station structures from Table 8. Elevation for 4% event was back calculated until elevation in meters produced the appropriate return period in years in 10^x column.
2. Estimate based on the slope of the median line from Figure 39 of 1.72 – 1.12 meters over Log 100 - Log 10 of return period in log years = 0.60 meters/return period in log years. $Log\ X = 2 - (1.72 - MHHW)/0.60$. Pump station elevations equated to an event probability.
3. MHHW elevations adjusted to NAVD by adding 0.34 meters.
4. Feet = Meters/0.3048.

However, it is necessary to include wave effects in computing base flood elevations. Storms generated waves are a function of wind speed, fetch and storm duration. When the resulting wave action reaches a shoreline it causes a super elevation of the mean water level.

As waves cross deep-water there is a mass transport of water in the form of momentum. The waves cause a depression in the mean water level, $\bar{\eta}$ behind the wave, which is called wave set-down. The following equation computes the set-down where H is the wave height, k = $\frac{2\pi}{L}$ is the wave number, and h is the water depth (Basco, 2012):

$$\bar{\eta} = -\frac{H^2 k}{8 sinh 2kh} \qquad (21).$$

As a wave approaches the near shore, it begins to feel the sub-bottom at a depth to wavelength ratio of $d/_L \geq 0.5$. As the wave continues to propagate towards the shoreline, it begins to shoal and rise and continues to depress the water level behind the wave. When the wave height reaches a deep-water wave height to water depth ratio of $\kappa = \left(\frac{H}{d}\right) = 0.8$ it breaks in the surf zone. At the point the wave breaks, its momentum causes the maximum depression in the still water level behind the wave resulting in the lowest set down, $\bar{\eta}_b$.

Once the wave breaks, the momentum dissipates and carries the water up the face of the shoreline, which is called wave set-up, $\bar{\eta}_s$. The following equation computes set-up where $h_b$is the water depth at $\bar{\eta}_b$, $\mathcal{K}$ is a dimensionless number, h is the water depth as the wave approaches the shore, and h_b is the water depth at the breaker line (plunge point in Figure 41):

$$\bar{\eta}_s = \bar{\eta}_b - \mathcal{K}(h - h_b) \qquad (22).$$

$$\mathcal{K} = \left({}^{3\kappa^2}/_{8}\right)/(1 + 3\kappa^2/8) \qquad (23)$$

The maximum wave set-up, $\bar{\eta}_{max}$ occurs when the water surge roles to a stop at a depth, $h = 0$.

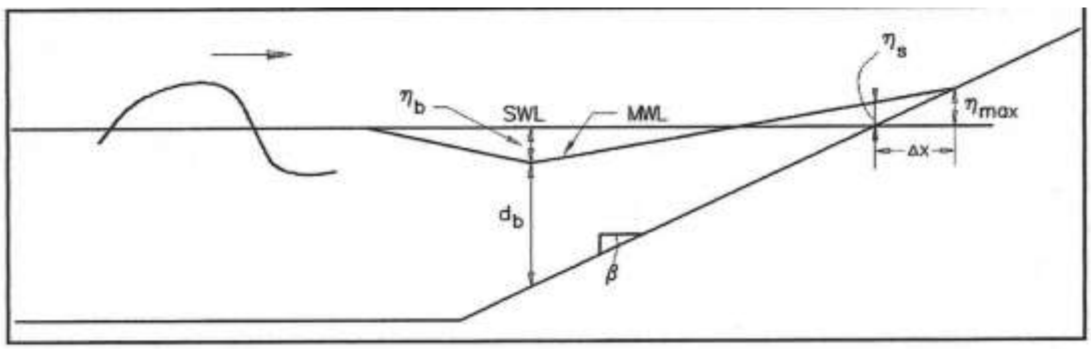

Figure 41. Definition Sketch for Wave Set-Up (USACE, 2002) (Figure II-4-7)

For this area, the FEMA flood map shown in Figure 21, shows Walnut Hill Street is within Zone AE and has a Base Flood Elevation (BFE) = 8.1 feet, NAVD (88). Zone AE means it is an area where FEMA has determined the 1% annual chance flood (1% chance of being equaled or exceeded in any given year) also known as the base flood or 100-year flood.

The author assumes the difference between the FEMA's BFE at 8.1 feet, NAVD (88) and the NOAA Stillwater level at 6.76 feet, NAVD (88), is the wave set-up at the project location for the 1% event, a difference of approximately 1.3 feet.

For the sake of simplicity, the author further assumes a semi-log, linear increase in set-up for each of the storm frequencies in Table 8 starting at zero feet at the Mean Tide Range to 1.3 feet at the 1% event. It is comparable to the level of accuracy and precision of an expert elicitation used to judge probabilities of pump failure. A reliability analysis may warrant a more detailed analysis.

Using this assumption, Table 10 presents the base flood stage elevations for the year 2015. Figures 42, 43, 44 and 45 show the base flood elevations for each of the sea level rise scenarios. Table 11 is a summary of how the base flood elevation changes over a 20-year design life (life cycle) for a typical submersible wastewater pump and over a 50-year design life for a pump station structure.

Table 10. Flood Elevations for Flood Stage Frequencies

Event, %	Return Period Years	Wave Set-Up Feet[1]	Stillwater Elevation Feet, NAVD (88)	Flood Elev. Feet, NAVD (88)
1	100	1.30	6.76	8.06[2]
4	25	0.91	5.58	6.49
10	10	0.65	4.88	5.53
50	2	0.20	3.54	3.74
99	1.01	0.00	2.56	2.56

1. Assumed linear increase in set-up from zero at Mean Tide Range to 1.3 feet at the 1% event, the difference between NOAA stillwater elevation and FEMA BFE. The slope of the line = 0.65 based on the delta changing over the Log of the Return Period in Years =100 and the Log of the Return Period of MTR =1. Wave Set-Up = 0.65(Log (Return Period) - Log 1).
2. FEMA value rounded up to 8.1 feet, NAVD (88)

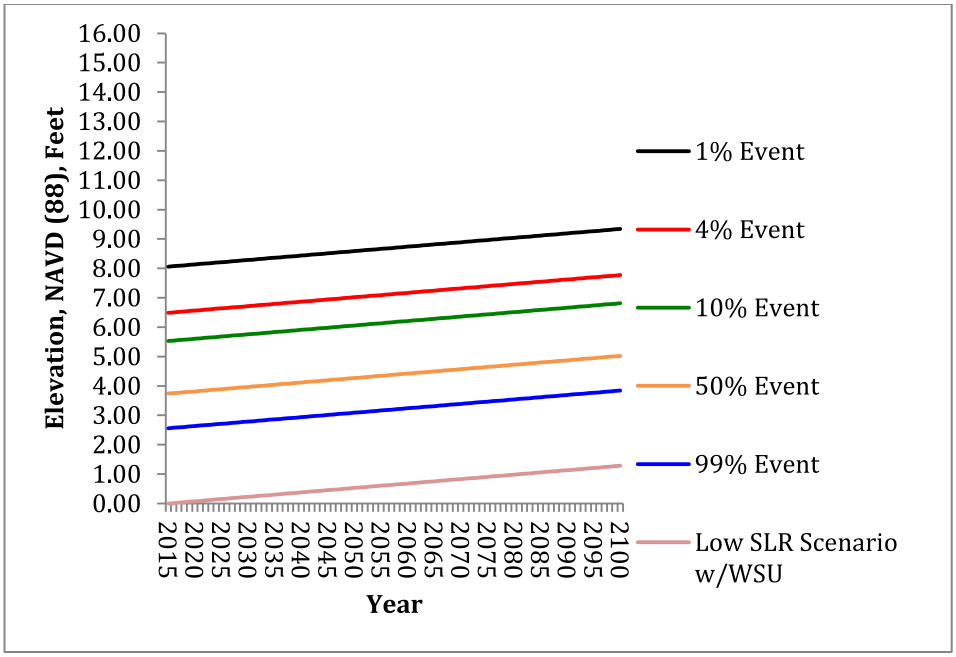

Figure 42. Low Sea Level Rise Scenario with Wave Set-Up

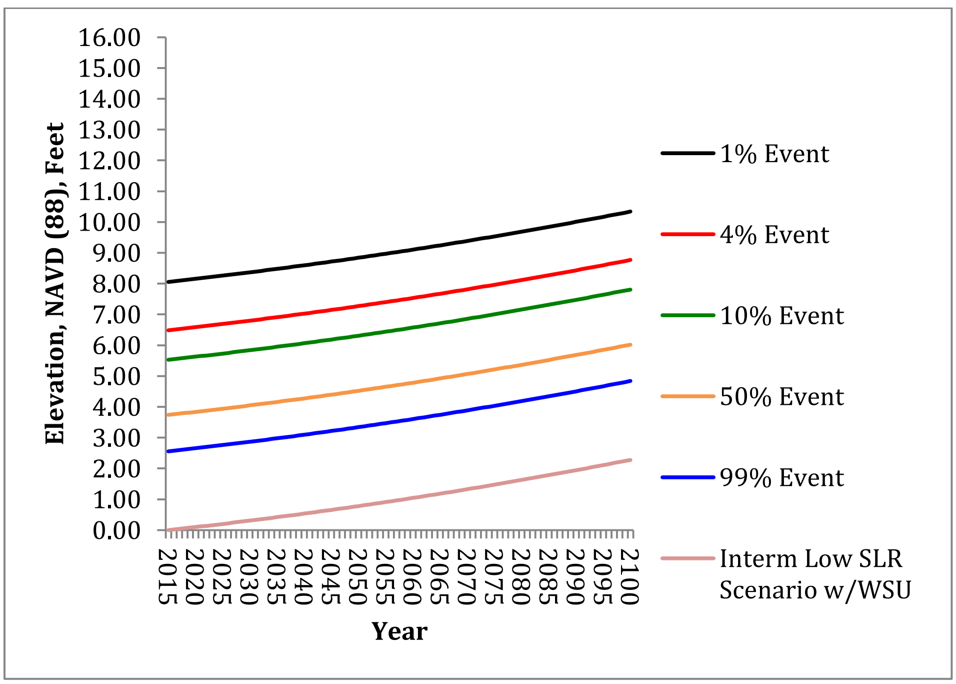

Figure 43. Intermediate-Low Sea Level Rise Scenario with Wave Set-Up

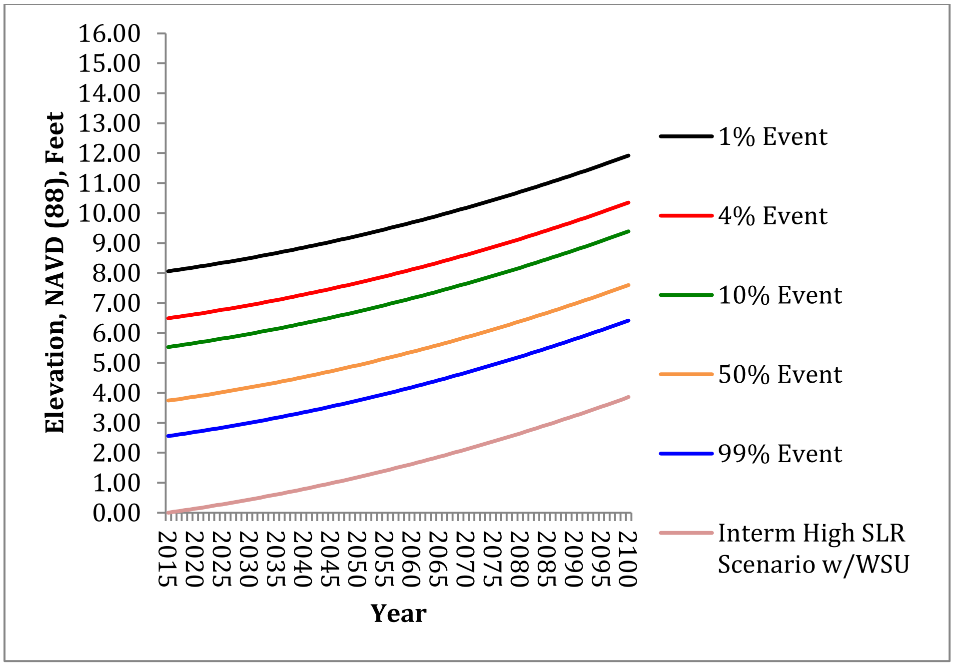

Figure 44. Intermediate-High Sea Level Rise Scenario with Wave Set-Up

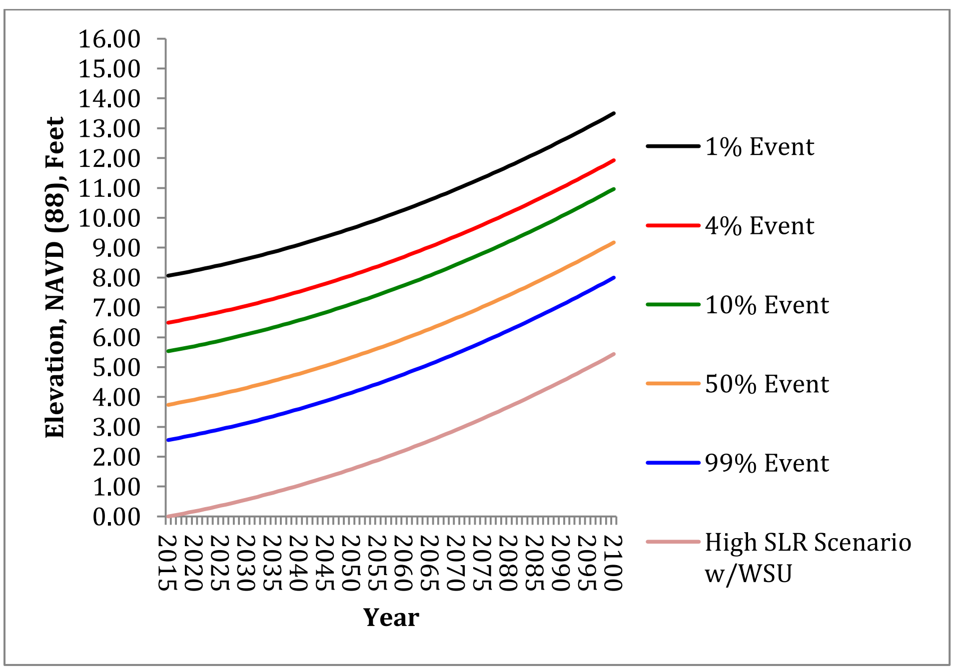

Figure 45. High Sea Level Rise Scenario with Wave Set-Up

Table 11. Summary of Changes in Flood Elevations for 20 and 50 – Year Design Life Cycles

20-Year Design Life of Pump, 2015 - 2035					
Scenario	**Storm Event w/Wave Set-Up, Feet, NAVD (88)**				
	99%	**50%**	**10%**	**4%**	**1%**
2015 BFE	2.56	3.74	5.53	6.49	8.06
2035 Low	2.86	4.04	5.83	6.79	8.36
2035 Int-Low	2.98	4.16	5.95	6.91	8.48
2035 Int-High	3.17	4.35	6.14	7.10	8.67
2035 High	3.35	4.53	6.32	7.28	8.85
50-Year Design Life of Pump Station Structure, 2015 - 2065					
Scenario	**Storm Event w/Wave Set-Up, Feet, NAVD (88)**				
	99%	**50%**	**10%**	**4%**	**1%**
2015 BFE	2.56	3.74	5.53	6.49	8.06
2065 Low	3.31	4.49	6.28	7.24	8.81
2065 Int-Low	3.74	4.92	6.71	7.67	9.24
2065 Int-High	4.42	5.60	7.39	8.35	9.92
2065 High	5.11	6.29	8.08	9.04	10.61

3.2.4.3 Intervening Explanatory Variables – Flood Stage Duration

The performance of the submersible pumps is dependent upon the duration of flooding. The proper way to assess duration is to model the infiltration and inflow within the network. The duration starts from the time the water levels in the wet well trigger the emergency alarm until the water level drops below the alarm-off elevation. It is the time it takes floodwaters to fill and drain from the network of pipes and manholes. However, the city does not have this kind of information. (See Appendix A, March 13, 2015 entry.)

In reviewing this study, the subject matter experts requested additional information (See Appendix A, July 14, 2015 entry). They judged that when the pump has no power, at some point inflow will overwhelm the capacity of the system and spills will occur. They also judged that when the pump does have power, the city's observation that grit could cause the pump motor to burn out after 48 to 72 hours operation to be a reasonable expectation

In order to better estimate probabilities that the network would have insufficient capacity and result in a spill, the experts requested an estimate of the volume of the network. In examining Table 6, the experts noted that the lowest manhole is elevation 2 feet, NAVD (88) and at the point floodwaters reach 4 feet, NAVD (88) 25% of the manholes are inundated. They qualitatively judged at this floodstage for the condition where the power is off, inflow would have a significant impact after 5-hours of continuous inundation. For the condition where the power remains on, inflow and grit would have a significant impact after 48-hours of continuous inundation.

Given these possible conditions, the experts also requested the annual probability of exceedence for flooding at elevation 4 feet, NAVD (88) for durations of 5 hours and 48 hours. Also, they requested the probable durations for such a flood for each of the floodstage frequencies from the 99 to 1% events, and for the 4% event as the sea level rises.

In order to assess durations of flooding at the site, historic tide levels for the year 1928 through 2014 are used to develop a duration frequency curve. There are a total of 746,968 hourly tidal readings. As part of this record, 1942 has only data into August, and 1943 has only data starting in September. For this analysis, these two years are merged. Therefore, even though the record covers 87 years, there are only 86 years of data. Then for each year from 1928 to 2013, the tide readings are adjusted to equate to 2014 tide levels based on the linear historic relative sea level trend at rate of 4.57 mm/year as of March 26, 2015 (NOAA, 2015). In addition, the author added 0.5-foot increments up to 3 feet to the adjusted 2014 tide levels to provide data to estimate how durations will change over time.

The number of hours of flooding at or above Elevation 4 feet, NAVD (88) ranged from 283 hours for 70 events at the 0.0-foot increment to 162,828 hours and an estimated 17,000 events at the 3.0-foot increment for the 1928 to 2014 time period. The author started the analysis with the Peak-Over-Threshold method (Kamphuis, 2010) to compute the durations for a range of annual frequencies for the 99, 50, 10, 4 and 1% events and for computing the probability of exceedence for the 5, 6, 12, 24, 48 and 72 hour flood durations. Digital sorting identified the total number of hours of flooding and each grouping representing an event, but determining the duration for each event required counting the hours by hand using the Excel count function.

However, hand counting the hours for each event proved a challenge for a large number of events at the 2.5 and 3.0-foot increments. A great many of the events had short durations and attempts to adjust the threshold levels and bin sizes to estimate durations proved outcomes were dependent on subjective choices. Instead, the author opted to use an Extreme Value Analysis from Order Data method (Kamphuis, 2010) to approximate needed values. This method required selecting the most extreme annual event, and eliminated making judgments as to what to select. However, the latter method is at best an expedient substitute for a full enumeration using the Peak-Over-Threshold method. Comparisons of the two methods at the lower increments show that the Extreme Value Analysis underestimates both the durations and probabilities of exceedence, a weakness in this assessment.

The methodology follows guidance provided by J. William Kamphuis for extreme wave heights (Kamphuis, 2010). The probability of exceedence, $Q = {}^{i - c_1}/_{N + c_2}$ where i is the ranking of the data point and N is the total number of points. The values c_1 and c_2 are constants for unbiased plotting positions based on the distribution used to compute Q. In addition, this study used the Log Normal, Gumbel and Weibull distributions to analyze the extreme values, because they are appropriate methods for ordered statistics and to generate a linear expression to extrapolate outcomes.

Using an Excel generated R-Squared regression analysis; the Weibull distribution produced the most robust relationship for interpretation and extrapolation. The linear expression for the Weibull model is duration, $D_{TR} = \gamma + \beta(\ln\{\lambda T_R\})^{1/\propto}$. This equation is resolved from the linear equation $(ln\lambda T_R)^{1/\propto} = {}^{1}/_{\beta}\, D_{TR} - {}^{\gamma}/_{\beta}$ where lambda is the number of events per year on which the analysis is based (one/year), and T_R is the return period in years.

Table 12 provides the annual probability of exceedence for flooding at elevation 4 feet, NAVD (88) for a range of durations. The annual probabilities for 5-hours or more of flooding is significant ranging from 23% in 2015 to as high as 74% in 2065. However, the probabilities at 48 to 72 hours or more of flooding are insignificant.

Table 12. Probabilities of Exceedence for Flood Durations

Probability of Exceedence for Flood Duration, % For Elevation 4+ Ft., NAVD (88)						
Year	**5-Hrs**	**6-Hrs**	**12-Hrs**	**24-Hrs**	**48-Hrs**	**72-Hrs**
2015	23.1	16.2	2.0	0.0	0.0	0.0
2035	33.7	25.6	5.2	0.2	0.0	0.0
2065	73.8	66.1	38.7	9.1	0.6	0.0

Table 13 provides the durations for flooding at or above elevation 4 feet, NAVD (88) for a range of annual frequencies from the 99 to 1% duration event, and for the 4% duration event as the sea level rises. Computations for Tables 12 and 13 are in Appendix C, Flood Duration Analysis.

Table 13. Probable Flood Durations for Range of Return Periods

Summary of Probable Annual Flood Duration Frequencies, Hours For Elevation 4+ Ft., NAVD (88)						
Year	**Increment of SLR, Ft[1]**	**99% Event**	**50% Event**	**10% Event**	**4% Event**	**1% Event**
2015	0.00	0	1	5	7	10
2035	0.61				14	
2065	1.86				39	

1. Increments based on Intermediate High Sea Level Rise Scenario

3.2.4.4 Response Variable – Fragility Curves

Expert elicitation requires standards, protocols and documentation that can withstand professional scrutiny the same as the scientific principles of data collection (Clemen & Reilly, 2001). The main difference is experts exercise judgments that are influenced by biases, which is different than collecting data in a laboratory setting.

The first step is to document and justify the expert-selection process similar to the scientific process for selecting specific data points. The second step is to provide an environment where experts can make judgments in a way that minimizes biases. This is similar to a scientist demonstrating his or her measurements are without bias.

A third step is to combine the judgments of multiple experts into one probability distribution representing the impact of an event on the pump station. This requires taking into account the relative expertise of and any redundancy within the cadre of experts. This is similar to a scientist combining results from multiple data sets to draw a conclusion.

The author used the following protocol to assemble a team of experts and to conduct the exercise (Clemen & Reilly, 2001).

- Background – Identify what variables the subject matter expert must judge and identify the skills, knowledge and abilities experts need to have. For this project, the expert is judging the performance of a pump when exposed to flooding waters. The objective of the pump station is to remove a sufficient volume of wastewater to avoid any spillage that results in consequences. Therefore, the analysis needs experts who have design and operations experience of submersible wastewater pump stations. Those with design experience should be licensed professional engineers, and those with operations experience should have a minimum of 10 years of experience or experience with city's pumps.
- Identification and Recruitment of Experts – The team should be composed of one City of Norfolk engineer from the Departments of Utilities, one engineer from HRSD, and two consulting engineers familiar with the design of local municipal, submersible wastewater systems.
- Motivating Experts – The primary motivation is both the city and the local professional engineering community are keenly aware of the challenges rising sea levels pose the region's infrastructure. Several practicing engineers voluntarily expressed an interest to participate as experts. They see is it as an opportunity to learn a new methodology that they can apply in their own practice (Baecher & Christen, 2003).
- Structuring and Decomposition – This phase is also known as knowledge exploration. Section 3.2.3, Variables describes the relationships among the relative variables. It identifies the response variable as a fragility curve needed to represent the performance of the pump as it is exposed to rising floodwaters. Section 2.2.5 Subset question e: "What is the appropriate means to demonstrate the impact on the performance of the pump stations?" provides background on pump design and performance and identifies two potential failure modes for this analysis; (1) floodwaters can cause electrical shorts in the electrical and control

system; and (2) as the depth and duration of inundation increases a pump's capacity decreases and/or the motor could burn out.

- Probability Assessment Training – As a preamble to initiating the elicitation, the author explains the purpose of the study, the basics of a risk-informed decision, and the role a fragility curve plays in the calculation. A key aspect of the training is to make experts aware of potential bias and the need for dialogue among the participants to explore possible undue influences (Plous, 1993).

  Biases are beliefs and experiences experts use to view the analysis and the information they may choose to judge the problem. Intentional biases are when an expert makes a willful decision to influence a decision to satisfy a particular agenda. Unintentional biases are cognitive biases that reflect a behavior such as the availability heuristic, the representative heuristic and anchoring. The following definitions are almost verbatim from work by Patrick Hester, PhD, Old Dominion University (Hester, 2012)

  - Availability Heuristic – It is the practice of basing probabilistic evidence on an available piece of information. For example, people estimate the likelihood of an event based on something similar they can remember. This is a particular issue when most recent experiences are fresh in people's memories and have a larger influence than older experiences.
  - Representative Heuristic – It occurs when people assume commonalities between objects. For example an expert estimated the probability for another pump and assumes the pump under study is the same and estimates similar probabilities. The problem is when this assumption causes the expert to overlook differences between the two pumps.
  - Anchoring – People anchor their judgments and base subsequent judgments on an initial value provided as part of the process. For example, the analyst provides a baseline value and people anchor probability values close to that baseline value. The analyst needs to be aware of how leading questions may anchor people when eliciting their opinion.

- Probabilistic Elicitation and Verification – The objective of this step is to perform the needed probability assessments, and to document the reasoning behind the assessments. A trained facilitator should lead the elicitation and should not be an expert in the topic to minimize introducing biases into the process. The analyst seeking the elicitation should monitor the judgments to insure they comply with the three axioms and common understandings or probability described in section 2.2.3.1 Design Principles.

- The process will use a gaming concept termed Over-Under (O/U) to judge whether a particular flood condition does or does not impact the pump systems performance. The O/U is a commonly used in sports betting. It is based on whether the gambler believes a certain statistical outcome will either be above or below some value. A common statistic is the combined score of the two competing teams.
- The gambler's objective is to judge whether the final total score will be higher or lower than the posted O/U score. The aim of the booking agency is to have a balance of bets on each side of the O/U statistic. The author is choosing this approach because getting a consensus is a challenge and betting is a way to cope with any irreconcilable differences. The split also represents where a better is indifferent and the risk attitude is neutral.
- This process will have four experts and preferably an even number to seek an even split as explained below. They will use Table 14 as a scale to judge probabilities.
- The flood stages will be divided into increments identified in Table 19. For each increment, each expert will judge, given the flood elevation (A), whether the probability for non-performance (B) is above or below a specified $P((B|A)$ from Table 14. After each "bet", the experts will be asked to explain their judgment.
- If the estimates of the experts are not balanced, then the process will repeat itself using either a higher or lower $P((B|A)$ until there is a balance of experts across the O/U.
- The facilitator will document each bet and include notes on any discussion following the betting, and the rationale for redoing the bet.
- The final step will be to review the results and judge whether it is a reasonable representation.

Table 14. Constructed Scale to Judge Performance (Pinto & Garvey, 2013), (Vick, 2002)

Definition of Non-Performance	Verbal Descriptor	Probability
Impacts the system's operational capability to the extent that the pump system shuts down and/or results in uncontrolled overflow (0.85 – 0.99).	Almost Certain	$P(B\|A) = 0.99$
	Very High Chance	$P(B\|A) = 0.90$
Impacts the system's operational capability to the extent that the performance is greatly impaired and on the verge of shutting down or causing uncontrolled overflows (0.65 – 0.85).	High Chance	$P(B\|A) =$*0.80*
	Probable	$P(B\|A) = 0.65$
Impacts the system's operational capability to the extent that the performance is significantly impaired and has the potential to shut down and/or cause overflows (0.35 – 0.65).	Even Chance	$P(B\|A) =$*0.50*
Impacts the system's operational capabilities to the extent that performance is impaired, but remains operational (0.15 – 0.35).	Possible	$P(B\|A) = 0.35$
	Low Chance	$P(B\|A) =$*0.20*
Impacts the system's operational capabilities in a way that result in a negligible impact (0.01 – 0.15).	Very Low Chance	$P(B\|A) =$*0.10*
	Almost Impossible	$P(B\|A) =$*0.02*

- Aggregation of Experts Probability Distribution – The objective of this step is to develop one fragility curve for each pump station system accounting for the two failure modes. This author assumes the failure modes are independent. Also, the process must ignore other contributing failure modes caused by major flooding such as power outages. For this study, it is necessary to judge the pumps in isolation of outside factors to develop a relative risk value to hypothetically compare the two stations.

3.3 Consequences

A consequence analysis assesses the impacts of non-performance. It consists of the identification of potential losses and the magnitude of those loses. For this study, the City of Norfolk identified three consequences; social, environmental, and cost impacts. (See Appendix A, March 5, 2015, April 23, 2015, and May 7, 2015 entries.)

The social impact is a function of the number of customers disturbed by a disruption of service, the spillage, any odor, and the recovery efforts. The scale is based on how much the impacts would extend across the service area. It is possible to impact neighboring service areas if it is necessary to divert flows into another network.

The environmental impact is a function of the extent spillage of wastewater would flow within and beyond the service area, colloquially referred to as the sewerage shed. The scale is based on the ability to recover the spillage. Once the wastewater extends into a body of water, it becomes more difficult to contain the spill.

The cost impact is a function of the number of different types of costs that the city can incur. Cost includes expenses to recover spillage and clean contaminated areas, to make repairs to the pump station and any related infrastructure, to perform any bypass pumping to a forcemain or to pump and haul spillage, and/or to pay regulatory fines. Typically, bypassing involves pumping wastewater from the wet well directly into a nearby force main. However, if the force main is damaged, the city pumps the wastewater into a truck and hauls it to waste treatment plant, colloquially referred to as “pump and haul”.

A major cleanup is defined as having to go outside the service area to recover spillage. A major repair specific to PS 113 is defined as a cost that exceeds $10,000. (See Appendix A, April 23, 2015 entry.) The scale is based on the number of different kinds of costs incurred.

Consequences within a risk equation can take the form of a mathematical “value” function defined by criterion that represents a range of performance. It provides a way to measure the impact of an event within a set of possible events. It offers a means to compare outcomes to identify those events that pose an unacceptable risk based on the possible consequences (Pinto & Garvey, 2013).

The value function is a measure because increasing values of the function represent increasing levels of consequences. The measure between the levels is a ratio or cardinal measurement scale where the levels are assigned numbers such that the differences between levels have meaning. The difference across the levels is a ratio of one level to the other levels with a definable beginning (zero) and allows comparison by multiplication and division (Pinto & Garvey, 2013)

For this particular case, the City of Norfolk wants to understand how larger events, and events on increasing sea levels impact the performance of the pump station.

Since these kinds of events tend to increasingly strain a pump's performance, the analysis needs a function that represents a monotonically increasing value over a range of evaluation criterion. The mathematical expression for a monotonically increasing value is an exponential or a linear value function given by the following equations based on an exponential constant ρ:

$$V_x(x) = 1 - e^{-(x - x_{min})/\rho} \Big/ 1 - e^{-(x_{max} - x_{min})} \; if \; \rho \neq \infty \tag{24}$$

or

$$V_x(x) = (x - x_{min}) \Big/ (x_{max} - x_{min}) \; if \; \rho = \infty \tag{25}$$

The parameter ρ represents the shape of the exponential value function and reflects whether the decision maker has a risk adverse, risk neutral or risk taking attitude (Schultz, Mitchell, Harper, & Bridges, 2010). The definitions for the three attitudes are listed below and are verbatim from the reference:

- Risk adverse behavior is described by a concave utility function and means that the decision maker would have to be compensated to voluntarily accept a lottery in a choice between a sure thing and a lottery with equal expected payoffs. This is the most common attitude toward risk encountered among individuals.

- Risk neutral behavior is described by a linear utility function. The decision maker is indifferent between a lottery and a sure thing that have equal expected payoffs. This function might be used to describe the behavior of insurers and investment banks.

- Risk seeking behavior is described by a convex utility function. This function suggests an individual would be willing to pay for the exposure to an uncertain outcome that has the same expected outcome as an alternative certain outcome. Risk seeking utility functions might be used to describe gambling behavior.

Sensitivity studies would aid public officials to choose an appropriate attitude (Schultz, Mitchell, et al., 2010). If the decision maker has a risk-adverse attitude, then ρ is a positive number and results in an opportunity cost; a higher project cost than a risk neutral position where those extra funds could be allocated to other needed infrastructure. If the decision maker has a risk-taking attitude, then ρ is a negative number. Such an attitude can be perceived by the tax payer as gambling and would be quick to blame a public agency for a bad outcome. If the decision maker is risk-neutral, then ρ is infinite and offers a mid-range method for estimating the risk of public funds.

For public works infrastructure, a public agency has a fiduciary responsibility for the use of public funds and a risk-neutral attitude is an appropriate policy decision to adopt (Schultz, Mitchell, et al., 2010). For this case, ρ is infinite and the linear expression in equation (21) for $V_x(x)$ would apply.

Since the value function for each consequence is defined by a criterion, it is referred to as a single-dimensional value function (SDVF). For this study, there are three consequences, hence three SDVF's. Assuming the criterion representing each SDVF is independent, the value function takes the form of an additive function to represent the sum of the impact of the SDVF's and the following equation applies (Pinto & Garvey, 2013):

$$V(A) = w_1(V_1) + w_2(V_2) + w_3(V_3) \qquad (26).$$

The $V(A)$ term is a measure of the overall impact of the risk event. The w_i terms are the relative weight of each consequence expressed as a fraction where the sum of the fractions equal 1, $\sum_i w_i = 1.0$. The city advised that the impact of the three consequences is a function of intensity over a time span and would be specific to characteristics of each site and pump station.

In the case of PS 113 failing and needing repair, Figure 46 represents a characterization of how the consequences would play out over a six-month period needed to respond and restore the pump station to full operations (See Appendix A, April 23, 2015, May 7, 2015 and May 20, 2105 entries). The social impacts require the most immediate response and demand political assurances to denizens that all issues will be resolved to their satisfaction. It is the perception that the city is taking appropriate action that makes the social impact the most intense of the three consequences. Concerns for environmental impacts would be part of the response to social impacts and regulatory agencies, but will play out longer than the need for immediate public assurances of appropriate actions. Concerns for cost impacts also start immediately and tend to extend over a longer period than the other two consequences.

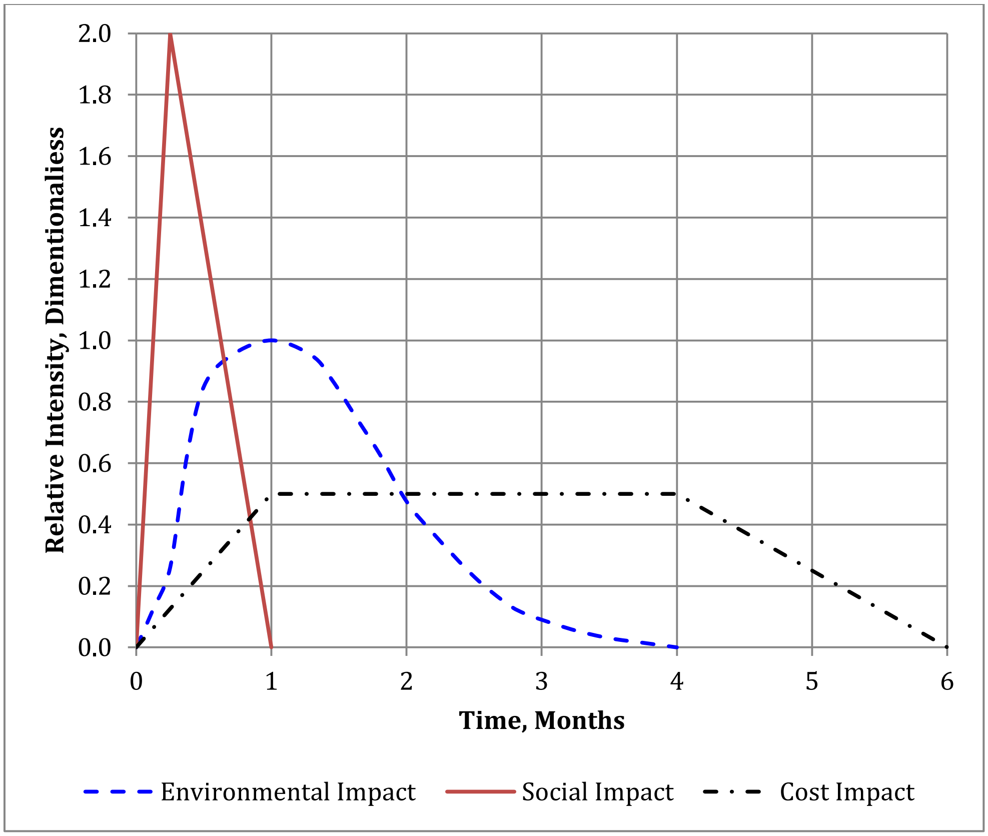

Figure 46. Intensity of Consequences Over Time

The city advises that the intensity of the social impacts would be twice that of the environmental impacts, and environmental impacts would be twice the cost impacts. (See Appendix A, May 7, 2015 and May 20, 2015 entries.) However, costs would play out over a period 1.5 times environmental impacts and 6 times that of social impacts. For simplicity, the author assumes the best way to represent weights is to use the area under the respective plots as appropriate ratio between the consequences. The area for the social impacts is 1-unit and represents the baseline for computing ratios. The area for the environmental impacts is 1.75-units and for the costs it is 3.25-units. The sum of the three areas is 6 units. Table 15 summarizes the distribution of the weights by consequence.

Table 15. Weights, w_i for Single Dimensional Value Functions

Consequences	Ratio of Areas	Weight, w_i
w_1, Social Impacts	1.0	1/6 = 0.17
w_2, Environmental Impacts	1.75 w_1	1.75/6 = 0.29
w_3, Cost Impacts	3.25 w_1	3.25/6 = 0.54
$\sum_i w_i =$	Total Area = 6	6/6 = 1.00

The three V_i terms in the $V(A)$ equation represent the value of each of the consequences. Tables 16, 17 and 18, developed specifically for these studies, provide a scale for each consequence reflecting the outcome for a monotonically increasing impact for that particular consequence (See Appendix A, April 7, 2015; April 23, 2015; May 7, 2015 and May 20 2015 entries). As with the weights, the ratio column represents the city's assessment of the differences between the levels.

Using the equation (25), $V_x(x) = {}^{x - x_{min}}/_{x_{max} - x_{min}}\ if\ \rho = \infty$, the ratios are converted to fractions in the form of a piecewise linear value function. The value $x_{min} = 1$ is for Level 1, the base level, and $V_x(x)$ equals zero, the least impact. Each succeeding level incrementally sums up the *x's* until it reaches $x_{max} = 10$ and $V_x(x)$ equals one at Level 5 to represent the worse impact.

Table 16. Constructed Scale to Judge Social Impacts, V_1 (x_1)

Scale Level (Score)	**Definition of Impact**	**Ratio of Impact from Level to Level 1, (x_1)**	**Value Function V_1 (x_1)**
5	Recover efforts impact neighboring service areas	10	9/9 = 1.00
4	Impacts the entire service area	6	5/9 = 0.55
3	Impacts extend beyond immediate block.	3	2/9 = 0.22
2	Impacts customers within the block	2	1/9 = 0.11
1	No impacts on any customers in service area	1	0/9 = 0.00

Table 17. Constructed Scale to Judge Environmental Impact, V_2(x_2)

Scale Level (Score)	**Definition of Impact**	**Ratio of Impact from Level to Level 1, (x_2)**	**Value Function V_2 (x_2)**
5	Spills within the body of water	10	9/9 = 1.00
4	Spills within the service area	6	5/9 = 0.55
3	Spills with blocks of the station	3	2/9 = 0.22
2	Spills within immediate station area	2	1/9 = 0.11
1	No spillage	1	0/9 = 0.00

Table 18. Constructed Scale to Judge Cost to Repair, V_3 (x_3)

Scale Level (Score)	Definition of Impact	Ratio of Impact from Level to Level 1, (x_3)	Value Function V_3 (x_3)
5	By-pass pumping, major repairs, major cleanup and a fine	10	9/9 = 1.00
4	By-pass pumping, major repairs, and minor cleanup	6	5/9 = 0.55
3	Major repairs and minor cleanup	3	2/9 = 0.22
2	Minor repairs and minor cleanup	2	1/9 = 0.11
1	No costs	1	0/9 = 0.00

3.4 Risk Analysis Methodology

The risk equation (20) as presented in section 3.1 Risk Informed Decision Methodology, is modified as follows to align with the use of an event tree and the approach for assessing consequences:

$$R = P_E(P_F)(V(A)) \qquad (27).$$

The equation determines a relative risk score. The analysis uses an Excel spreadsheet to record the event frequency, the estimated probabilities of non-performance within the event tree, the selected consequences for that particular step in the event tree, and calculate the risk score for a given event frequency (Figure 47).

CASE #:	1
SLR Scenario	2015
ELEVATION:	2.56 Feet, NAVD (88)
Event P	0.990
% MH Inundated	0

Hazard, P_E		Event Tree Analysis - Fragility, P_F										Consequence Analysis, V(A)				Risk Score, R
												Social Impact Weights, w_1 0.17	Environment Impact Weights, w_2 0.29	Cost Impact Weights, w_3 0.54	Additive Value Function	
Event	P =	Alternative	Event	P =	Event	P =	Event	P =	Probability of Spill for Flood Stage, P_F	Probability of Spill Occuring Over One Year, $P_L = P_E * P_F$	Social Impacts Function $V_1(x_1)$	Environment Impacts Function $V_2(x_2)$	Cost Impacts Function $V_3(x_3)$	$V(A) = \Sigma w_i * V_i(x_i)$	$R = P_E * P_F * V(A)$
Flood Stage Event	0.99	Existing Pump Station	Power Off	0.00	Insufficient Capacity	0.000	Spill	0.00	0.00E+00	0.00E+00	0.00	0.00	0.00	0.00	0.00E+00
							No Spill	1.00	0.00E+00	0.00E+00					
					Sufficient Capacity	1.000	Spill	0.00	0.00E+00	0.00E+00	0.00	0.00	0.00	0.00	0.00E+00
							No Spill	1.00	0.00E+00	0.00E+00					
			Power On	1.00	Insufficient Capacity	0.000	Spill	0.00	0.00E+00	0.00E+00	0.00	0.00	0.00	0.00	0.00E+00
							No Spill	1.00	0.00E+00	0.00E+00					
					Sufficient Capacity	1.000	Spill	0.00	0.00E+00	0.00E+00	0.00	0.00	0.00	0.00	0.00E+00
							No Spill	1.00	1.00E+00	9.90E-01					
					Total Expected Value				1.000	0.990			Totals	0.00	0.000
							Spill		0.000	0.000					
							No Spill		1.000	0.990					
		New Pump Station	Power Off	0.00	Insufficient Capacity	0.000	Spill	0.00	0.00E+00	0.00E+00	0.00	0.00	0.00	0.00	0.00E+00
							No Spill	1.00	0.00E+00	0.00E+00					
					Sufficient Capacity	1.000	Spill	0.00	0.00E+00	0.00E+00	0.00	0.00	0.00	0.00	0.00E+00
							No Spill	1.00	0.00E+00	0.00E+00					
			Power On	1.00	Insufficient Capacity	0.000	Spill	0.00	0.00E+00	0.00E+00	0.00	0.00	0.00	0.00	0.00E+00
							No Spill	1.00	0.00E+00	0.00E+00					
					Sufficient Capacity	1.000	Spill	0.00	0.00E+00	0.00E+00	0.00	0.00	0.00	0.00	0.00E+00
							No Spill	1.00	1.00E+00	9.90E-01					
					Total Expected Value				1.000	0.990			Totals	0.00	0.000
							Spill		0.000	0.000					
							No Spill		1.000	0.990					

Figure 47. Decision Tree Analysis EXCEL Spread Sheet

As noted in section 2.2.3.2 Tolerable Risk, in order to perform a risk analysis, it is necessary to define performance standards. As stated in the Section 9VAC25-790-380, specified equipment must be above the Base Flood Elevation. The existing pump station does not meet this requirement. The new pump station does meet the 2015 BFE at elevation 8.1 feet, NAVD (88) and has set the bottom of the electrical control panel at elevation 11.10 feet, NAVD (88). This elevation is also higher than the projected 2065 BFE for the High SLR Scenario shown in Table 11.

Table 19 provides a list of the number of cases needed to assess the risk over the range of events in 2015 and demonstrate change in the 4% event over the 50-year design cycle. The analysis will use the Intermediate High sea level rise scenarios for 2035 and 2065, because this scenario is a reasonable representation of the potential change in sea levels over the next 50 years and the change across all four scenarios is not significant except for the outlying years. Each case is listed in increasing increments of flood stage to aid in judging probabilities across the scenarios in a consistent manner.

Table 19. Study Elevations for the Cases in the Decision Tree Analysis

Decision Tree Analysis Case No.	Flood Stage, Ft NAVD (88)	Flood Frequency, %	SLR Scenario
1	2.56	99	2015
2	3.74	50	2015
3	5.53	10	2015
4	6.49	4	2015
5	7.10	4	2035 Inter High
6	8.06	1	2015 BFE
7	8.35	4	2065 Inter High

The expert elicitation uses the following steps to assess risk and how it changes by the year 2035, the 20-year design life cycle for the pump; and by 2065, the 50-year design life cycles for the pump and pump station, respectively.

1. The subject matter experts first assessed the new pump station. They repeated the process for the existing pump station.
2. The experts judged impacts to the pump station starting with Case 1 representing the minimum flood elevation of the seven flood events and up through Case 7, the maximum flood elevation of the events. There are two key failure points. The first is when there is no power and the flood stage is 4 feet, NAVD (88) or higher and the duration is at least 5 hours. At this flood stage, the duration may be long enough to possibly impact the system's capacity. The second is when flood elevations are about one foot higher than the bottom of the control panel causing electrical components to short out. Flood stages do reach the control panel for the existing pump station, but do not reach the control panel for the new pump station.
3. The experts used the Over-Under (O/U) gaming concept described in section 3.2.4.3 Response Variable – Fragility for the Probabilistic Elicitation and Verification process. The objective of this step was to perform the needed probability assessments, and to document the reasoning behind the assessments.
4. The experts used Table 14 to judge P_F probabilities for the POWER OFF, INSUFFICIENT CAPACITY and SPILL events. The flood stages are divided into increments as identified in Table 19. For each increment, each expert judged, given the flood elevation (A), whether the probability for non-performance (B) was above or below a specified $P((B|A)$ from Table 14.
    a. Each initial estimate started with a probability of 50% and the judgment as to whether the probability was over/under. Starting at this midpoint tends to minimizes biases (Pinto, 2015). After each "bet", the experts were asked to explain their judgment.

b. If the estimates of the experts were not balanced, then the process repeated itself using either a higher or lower $P((B|A)$ until there was a balance of experts across the O/U.

5. The experts repeated the above process and used Table 20 to judge three consequences. The table combines Tables 16, 17 and 18 into one to provide a simpler scale to aid the experts. The numbers 1 through 5 are the Scale Levels in the tables, which are equated to the appropriate V_i values in the Excel spreadsheet.
6. The facilitator documented each bet and included notes on any discussion following the betting, and the rationale for redoing the bet. The final step was to review the results and judge whether it is a reasonable representation.
7. For each alternative, the analysis developed a risk score for each case. Each case showed how the risk changes with increasing flood levels that will be summarized in a graph.

Table 20. Constructed Scale for Consequences

<table>
<tr><td colspan="5">Social Impacts of Spill - The social impact is a function of the number of customers disturbed by a disruption of service, the spillage, any odor, and the recovery efforts. The scale is based on how much the impacts would extend across the service area. It is possible to impact neighboring service areas if it is necessary to divert flows into another network.</td></tr>
<tr><td>No impacts on any customers in service area</td><td>Impacts customers within the block</td><td>Impacts extend beyond immediate block</td><td>Impacts the entire service area</td><td>Recovery efforts impact neighboring service areas</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td colspan="5">Environmental Impacts of Spill -The environmental impact is a function of the extent spillage of wastewater would flow within and beyond the service area, colloquially referred to as the sewerage shed. The scale is based on the ability to recover the spillage. Once the wastewater extends into a body of water, it becomes more difficult to contain the spill.</td></tr>
<tr><td>No impacts on any customers in service area</td><td>Impacts customers within the block</td><td>Impacts extend beyond immediate block</td><td>Impacts the entire service area</td><td>Recovery efforts impact neighboring service areas</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td colspan="5">Cost Impacts of Spill - The cost impact is a function of the number of different types of costs that the city can incur. Cost includes expenses to recover spillage and clean contaminated areas, to make repairs to the pump station and any related infrastructure, to perform any bypass pumping to a forcemain or to pump and haul spillage, and/or regulatory fines. Typically, bypassing involves pumping wastewater from the wet well directly into a nearby force main. However, if the force main is damaged, the city pumps the wastewater into a truck and hauls it to waste treatment plant, colloquially referred to as “pump and haul”.

A major cleanup is defined as having to go outside the service area to recover spillage. A major repair specific to PS 113 is defined as a cost that exceeds $10,000. The scale is based on the number of different kinds of costs incurred.</td></tr>
<tr><td>No impacts on any customers in service area</td><td>Impacts customers within the block</td><td>Impacts extend beyond immediate block</td><td>Impacts the entire service area</td><td>Recovery efforts impact neighboring service areas</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
</table>

The spreadsheet in Figure 47 produces three graphics for the existing and new pump station:

- Probability of Failure Over Lifetime, P_L versus Time showing how fragility changes from 2015 to 2065 and whether at some point it exceeds the performance objective.
- Probability of Failure, P_F versus Flood Stage showing how fragility changes across the 99, 50, 10, 4 and 1% events and whether it demonstrates a traditional generalized exposure versus effect correlation as shown in Figure 18.
- Relative Risk versus Time showing any reduction of risk from 2015 to 2065 by building the new pump station.

These three graphics enable the city to compare the fragility of the new pump station against the existing pump station. Also, the city can gauge how much relative risk they can buy down for the amount invested in the new pump station option. It will also inform the city how the risk will change over the life cycle of the new pump station. This will aid them in judging whether there is some tipping point where the city needs to make new investments in resilience.

3.5 Expert Elicitation

The following people volunteered to participate on the expert elicitation team: Michael Barbachem, P.E., Whitman, Requardt & Associates, LLP; Melvin Hopkins, P.E., City of Norfolk, Department of Utilities; H. Ali Mahan, P.E., O'Brien & Gere; and Robert J. Martz, P E., Hampton Roads Sanitation District. The team first met on July 14, 2015, with Barbachem, Mahan and Martz attending.

The team received an overview of the study, a training session on the elicitation process and presentation on available data. Given, that only three of the four invited members participated, the team opted to address any imbalances in the O/U estimates on an ad-hoc basis.

Once the process started, the team quickly rejected data suggested to judge the probabilities pertaining to INSUFFICIENT CAPACITY. As noted in section 3.2.4.3 Intervening Explanatory Variable, the subject matter experts requested different information (See Appendix A, July 14, 2015 entry). They judged that when the pump has no power, at some point inflow will overwhelm the capacity of the system and spills will occur. They also judged that when the pump does have power, the city's observation that grit could cause the pump motor to burn out after 48 to 72 hours operation to be a reasonable expectation.

The extra information the experts requested was an estimate of the volume of the network, the probability that durations of flooding at elevation 4 feet, NAVD (88) would exceed 5 hours (POWER OFF – INSUFFICIENT CAPACITY) and 48 hours (POWER ON – INSUFFICIENT CAPACITY), and the probable durations for such a flood for each of the flood stage frequencies from the 99 to 1% events, and for the 4% event as the sea level rises.

The team reconvened on August 14, 2015, but again only Barbachem, Mahan, and Martz attended. (See Appendix A, August 14, 2015). In order to judge the probabilities that the network had insufficient capacity with the power off, they took the following steps to construct Table 21 below:

1. Assumed the network is filled with water below elevation 2 feet, NAVD (88), the elevation of the lowest manhole and approximate elevation of local watertable.
2. Converted the design capacity of 60,000 gpd average flow to 2,500 gph (42 gpm).
3. For each case in Table 19, listed the flood frequency, year, flood stage elevation and storm duration from Table 11 (Table 21, Columns 1, 2 and 3; and from Table 13 (Table 21, Column 4).
4. Assumed for each flood stage that after 5 hours without power, the network would fill up to that elevation and estimated the available capacity above that elevation using the capacities for each of the flood stage frequencies in Table 7 (Table 21, Columns 5 and 7).
5. The experts divided the 2,500 gph rate into the available capacities estimated in step (4) to compute the hours it would take for the network to fill-up from floodwaters (Table 21, Columns 6 and 8).
6. Compared the time from step (5) against the durations presented in Table 13.
7. If the flood duration was greater than the time it took to fill the available capacity, then the experts used this factor to consider the likelihood that the system had an insufficient capacity.

Table 21. Available Network Capacity versus Storm Frequency Flood Stage with Power Off

Flood Data				Existing PS 113		New PS 113	
Storm Frequency, %	Year	Flood Elev., Feet NAVD (88)[1]	Flood Duration, Hours[2]	Available Capacity, Gallons[3]	Time to Fill Network w/Power-Off Hours[4]	Available Capacity, Gallons[3]	Time to Fill Network w/Power-Off Hours[4]
99	2015	2.56	0	23,200	9	25,800	10
50	2015	3.74	1	13,400	5	15,600	6
10	2015	5.53	5	4,200	2	5,400	2
4	2015	6.49	7	2,100	1	3,700	1
4	2035	7.10	14	1,000	0	350	0
1	2015	8.06	10	55	0	72	0
4	2065	8.36	39	0	0	0	0

1. From Table 11, Summary of Changes in Flood Elevations for 20 and 50-Year Design Life Cycles
2. From Table 13, Probable Durations for Range of Flood Stage Frequencies
3. Estimated based on data in Table 7.
4. Based on Time to Fill Network Capacity/Average Hourly Flow[5] = 2,500 gph.
5. Average Hourly Flow = 310 gpd/unit x 194 units = 60,140 gpd/24 hours = 2,506 gph

For judging the probabilities that the network had insufficient capacity with the power on, they first assumed the probability would be the inverse with the power off. However, they quickly judged this an inaccurate assumption, because as floodwaters increased, probability for insufficient capacity decreased.

Instead, the experts assumed a continuous operation of the pump would handle the inflow. They also assumed that capacity would diminish with increasing flood stages. They advised modeling would be necessary to adequately judge impacts, but used their experience to estimate probabilities. Also, the maximum duration of any event was 39 hours, less than the 48 hours where grit could cause problems.

Also, the experts used the data from Table 6 to understand the areal extent of the flooding by the number of manholes inundated.as the flood levels increased. In addition, they took the data from Table 12 for the annual probability of exceedence for flooding at elevation 4 feet, NAVD (88) to understand how long the area would stay flooded. Plus, they used the annual probabilities that the storm could last 5 or more hours with the pump off to judge a point where the network would have insufficient capacity; and 48 or more hours with the pump on to help judge a point where the pump starts to have enough grit to impact performance. (See section 3.2.4.3 Intervening Explanatory Variables – Flood Stage Duration)

As a final step, the experts combined all this information and created an informal aid during the exercise. The information is captured in Table 22.

Table 22. Summary of Data for the Cases in Decision Tree Analysis

Decision Tree Analysis Case No.[1]	Flood Stage, Ft NAVD (88)[1]	Flood Frequency, % P_E[1]	SLR Scenario[1]	Flood Duration Above Elev. 4 Ft, Hours[2]	Prob. of Exceed. of Flood Duration 5 Hours, %[3]	Prob. of Exceed. of Flood Duration 48 Hours, %[3]	Percent of MH's Inundated[4] %	Existing PS, Time to Backfill Network, Hours[5]	New PS, Time to Backfill Network, Hours[5]
1	2.56	99	2015	0	23.1	0	8	9	10
2	3.74	50	2015	1	23.1	0	21	5	6
3	5.53	10	2015	5	23.1	0	50	2	2
4	6.49	4	2015	7	23.1	0	62* *Causes existing PS control panel to short out at 6.38 ft	1	1
5	7.10	4	2035 Inter. High	14	33.7	0	71	0	0
6	8.06	1	2015 BFE	10	23.1	0	96	0	0
7	8.35	4	2065 Inter. High	39	73.8	0.6	100	0	0

1. From Table 19, Study Elevations for the Cases in the Decision Tree Analysis
2. From Table 13, Probable Durations for Range of Flood Stage Frequences
3. From Table 12, Probabilities of Exceedence for Flood Durations
4. From Table 6, Manholes within Sewerage Service Area
5. From Table 21, Available Network Capacity versus Storm Frequency Flood Stage with Power Off

Appendix D, Decision Event Tree Analysis has the tally sheets of the individual judgments (termed Trials). There were 19 probability estimates for each case, seven cases per pump station and two pump stations. That adds up to 133 judgments per pump station for a total of 266 estimates.

As noted, only three of the invited experts participated. For judging the pump's performance, the team added a third term, Even (E) to the Over (O) and Under (U) terms. As a resolution to seeking a balanced O/U bet, the experts accepted two E's as long as the O or U accepted the E estimate, or estimates were balanced by one O, one U and one E and all experts accepted the E estimate.

Flood levels for Cases 1, 2, and 3, the lower elevations occurring in 2015, required the most discussion. As the flood levels reached elevation 6 feet, NAVD (88), it was obvious the impacts to the network and the low-lying neighborhood would be significantly detrimental. At the higher flood elevations, the exercise became more academic as flooding would be so extensive and disruptive to the community at large.

For judging POWER OFF, INSUFFICIENT CAPACITY and SPILL, each Trial (T) estimate started with a probability of 50% (Table 14). Of the 266 T- estimates only 16 judgments (6%) required up to four Trials. Of the 16, only 12 judgments (4.5%) had a mixed response that required discussion to resolve balancing the estimate. All of these mixed T-estimates were within the first three cases. Case 2 for both the new and existing pump station had the most discussion and accounted for 8 of the 12 judgments.

The experts included estimates for confidence intervals (CI) for each judgment. All three experts were consistent and in agreement. For all estimates at probabilities of less than10% or greater than 95%, the CI is 0.01. For those estimates from 10% to 95%, the CI is 0.05. The exercise did not estimate a confidence level.

For judging the Consequences, the T-estimates were based on a constructed scale (Table 20). There was a total of 168 T-estimates. The experts discussed the possible outcomes and came to a unanimous agreement on all of the estimated scale numbers.

The decision event tree computations are in Appendix D, Decision Event Tree Analysis. The results show that the probability of a spill increases as the flood stages increase reflective of an exposure – effect correlation (Figure 17). Figure 48 shows a comparison between the new and existing pump stations for the year 2015. At a probability of 50%, it would take a flood at least one-foot higher for the new pump station to have that probability. The limits plotted at the 0.01 and 0.10% fragility levels are performance standards discussed in section 3.6 Performance Standards.

A key improvement is the control panel for the new station is six feet higher than the existing pump station (City of Norfolk, 2014). However, it is the network capacity that has a significant influence on the overall systems vulnerability. The new pump station and associated piping minimally improves the network capacity above elevation 2 feet, NAVD (88). As the flood stage approaches the base flood elevation, the probability of a spill is high.

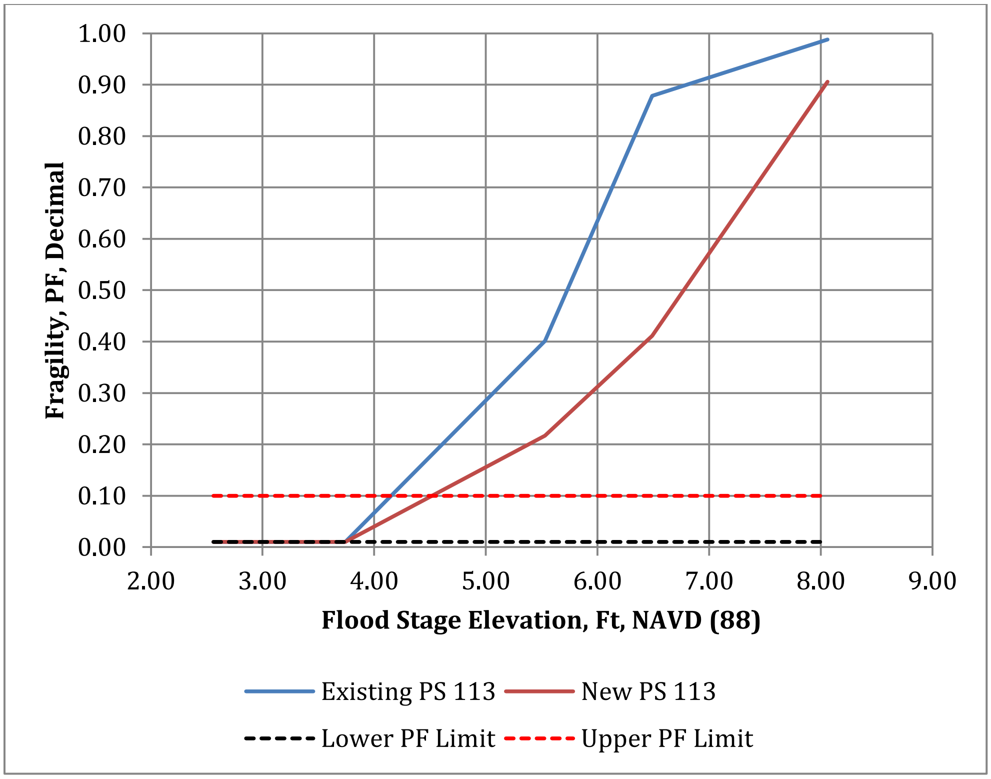

Figure 48. Probability of Spill, P_F versus Food Stage in 2015, Cases 1, 2, 3, 4 and 6

At the critical 4% flood event shown in Figure 49, the new pump station cuts the probability of a spill by more than half from 88 percent to 41%. Also, it shows that by 2035, the existing pump station would be ineffective in preventing a spill; but the new station could still operate. However, by 2065, the new station would be near ineffective; but it is a moot point because the whole area would be stressed by storms on an additional 1.8 feet of sea level. As noted for Figure 48, the limits plotted at the 0.01 and 0.1% fragility levels are performance standards discussed in section 3.6 Performance Standards.

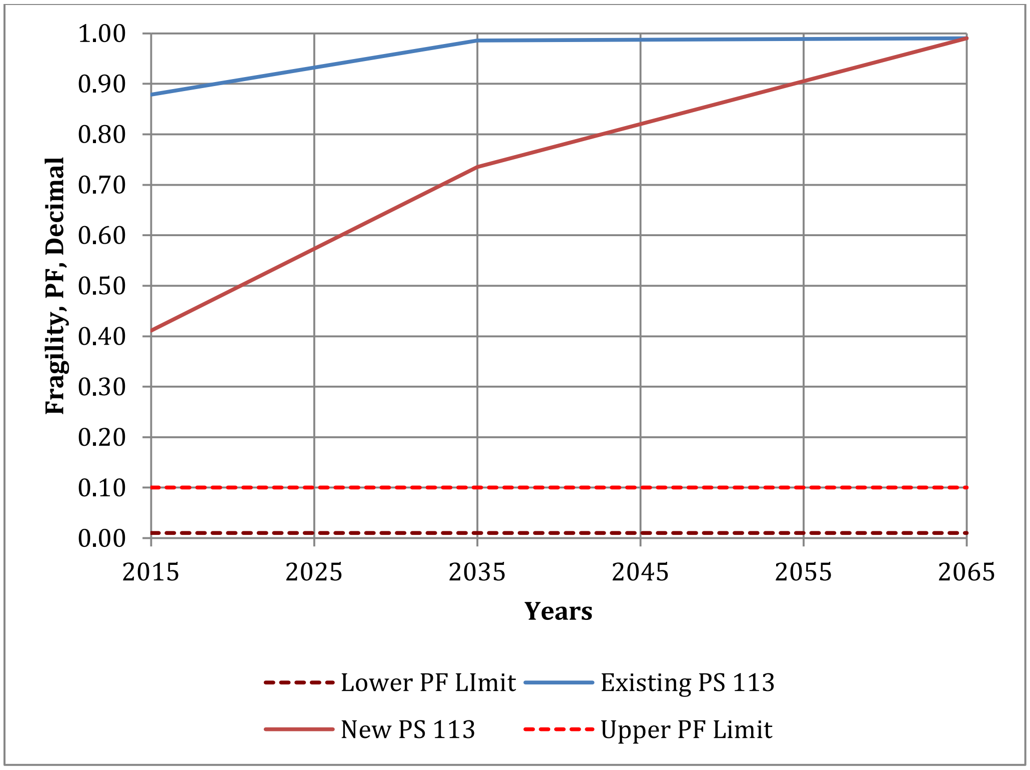

Figure 49. Probability of Spill, P_F for 4% Flood Event versus Time, Cases 4, 5 and 7

Risk computations show that the investment in the new pump station reduces possible consequences. Figure 50 shows that the new pump station cuts the relative risk by nearly five-fold over the existing condition at the critical 4% event. The risk remains proportional out to 2035, the 20-year design life cycle of the new pumps. However, by 2065, the 50-year design life cycle of the new pump station, risk to the new pump station increases sevenfold and there is minimal difference between the existing and new pump station.

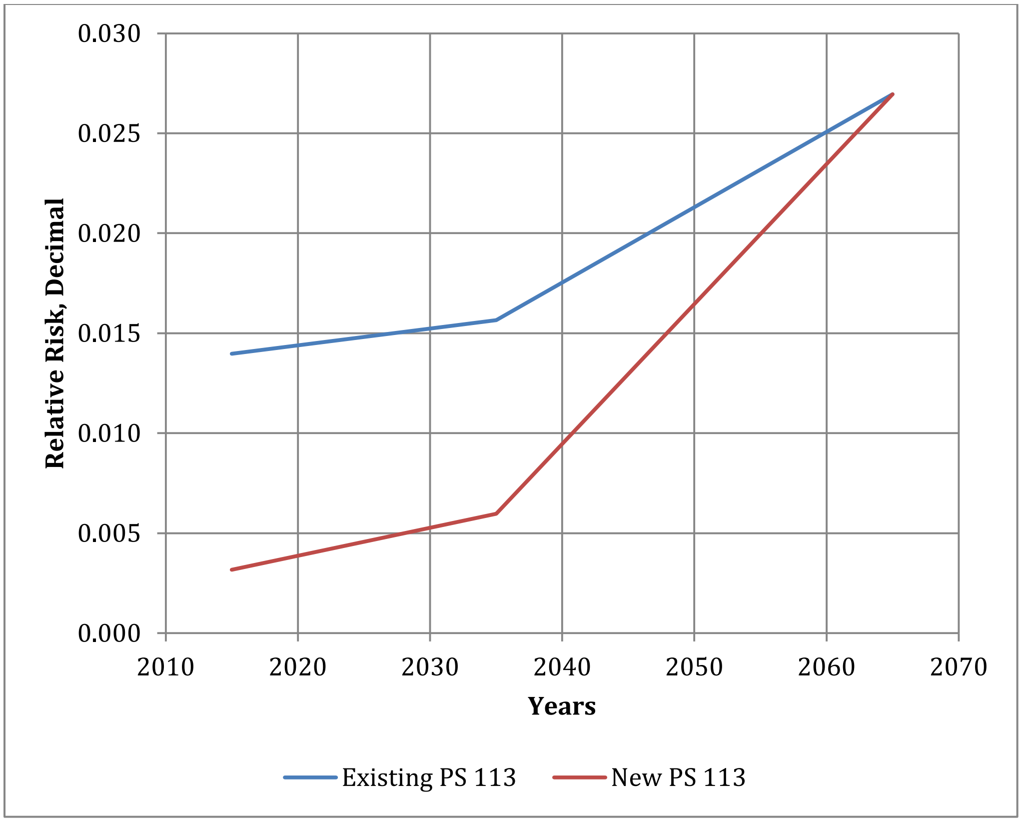

Figure 50. Relative Risk Score, R versus Time for 4% Flood Event, Cases 4, 5 and 7

These risk levels should remain consistent into the future. Since the area is developed, there is minimal concern that future growth will increase possible consequences and increase risk. However, what is evident is any improvements are limited by the overall impact rising seas will have on the region as a whole. In the absence of any actions to keep rising seas at bay, future investments in wastewater collection systems in low-lying areas will need to consider a shorter replacement life cycle than traditionally planned in programing capital improvements.

3.6 Performance Standards

As noted in section 2.2.3.2 Tolerable Risk, for consequences that do not involve loss of life, society may accept higher levels of risk based on how much loss they are willing to tolerate. The literature review indicates a 10^{-4} annual risk of casualty is an appropriate level of societal risk for urban areas where the risk is voluntarily accepted. However, the consequences as a result of a wastewater spill generally do not involve a loss of human life. Based on Figure 20 in section 2.2.3.2 Tolerable Risk, an upper limit for *involuntarily* accepted annual risk of casualty for a fatality of one (or less) is 10^{-3}. Given that the *voluntarily* accepted annual risk of casualty noted above is 10^{-4}, it is reasonable to assume an annual risk of non-casualty at an order of magnitude higher (10^{-3}) is tolerable for assessing the pump station.

Also, in order to assess risk, it is essential to define a performance level for the pump to remain operational. The requirements in the State Water Control Board, Chapter 790, Sewage Collection and Treatment Regulations, Section 9VAC25-790-380 states the pump station must remain operational for the 4% exceedence event. It implies zero probability for failure or no risk. However, every structure has a potential for failure due to uncertainty because of a lack of a full understanding of the problem, an uncertain future, imperfections in manufactured components, and variations in design and construction quality.

The literature lacks guidance specific to acceptable performance levels. The ideal design standard for a level or reliability would be a probability of non-performance at P_F

= 0.01. However, it is the author's opinion such a level is difficult to achieve for designing public works infrastructure, because each project is unique and there is a lack of reliability based data for a wide range of infrastructure. The author suggests designing facilities to fall within a band where 0.01 is a lower limit and an increase in order of magnitude to $P_F = 0.10$ as a practical upper limit. Designers could justify even higher upper limits to lower life cycle costs if the city considers the relative risk as low as reasonably practical.

Figures 48 and 49 plot these limits against the fragility curves. Figure 48 shows that the performance for both pumps falls outside the performance standards before floodwaters reach elevation 5 feet, NAVD (88). Figure 49 shows neither pump currently meet a $P_F = 0.10$ performance standard at the 4% flood event.

The analysis demonstrates the investment in the new pump station reduces the relative risk due to coastal flooding in the near term. However, the risk for the new pump station at the 4% exceedence event is 0.003 and the probability for a spill is 0.4; both numbers are higher than the ideal standard.

3.7 Conclusions and Recommendations

In the absence of information on the existing pump station and network, the study can best estimate the relative risk. Based on expert elicitation, the annual risk to the existing pump station in 2015 is 0.014 and to the new pump station it is 0.003.

Investment in a new pump station reduces the relative risk three-fold. This ratio remains proportional out to 2035, the design life cycle of the pump. However, over the 50-year design life of the new pump station, the relative risk to the new pump station increases sevenfold, mainly because the whole neighborhood will be stressed by storms onto a 1.8 foot increase in sea level.

Short-term efforts to reduce infiltration and inflow by waterproofing manholes, the pipe network and service laterals; and modifications to storm drains to prevent backflow into the streets would help. However, continued long-term efforts to improve wastewater infrastructure seem less practical given the region's increasing vulnerability to flooding. Capital improvements to keep rising sea levels at bay may be a more prudent approach to reduce exposure to high flood levels that impact the system's performance and cause the consequences.

The study's strength is it offers a way to frame the socio-technical problems common with public works infrastructure within systems engineering concepts. It applies systems thinking in the form of a hierarchy to tailor an analysis compatible with the complexity of a problem situation. The result is a step-by-step outline for engineers to choose a design approach in line with the problem's degree of complexity.

The study's weakness is the use of expert elicitation may be the least precise and accurate approach to judge performance. The use of expert elicitation has its role and is best when there is insufficient information about a project and a lack of resources to invest in new data. Given that the great bulk of public works infrastructure lacks the data needed to support reliability based assessments, elicitation will play a dominant role in aiding engineers to gauge performance.

Another weakness is the lack of a model of the network that feeds the pump station. It would have enabled sensitivity analyses to aid the experts in assessing potential impacts to network capacity and possible spills. Also, for pump stations without backup generators, it would be prudent to weigh the potential for loss of commercial power for extended periods of time.

A third weakness is the use of the Extreme Value Analysis from Ordered Data method to compute to compute the durations for a range of annual frequencies for the 99, 50, 10, 4 and 1% events and for computing the probability of exceedence for the 5, 6, 12, 24, 48 and 72 hour flood durations. This method is at best an expedient approximation and in this study under estimates durations and frequencies. Future studies should consider a full enumeration using the Peak-Over-Threshold method.

Fortunately, the construction of the new pump station offers the City of Norfolk a research opportunity to better understand the performance of submersible wastewater pumps exposed to coastal flooding. Both the university and city should pursue a grant to model the impacts of flooding on the sewerage system's capacity. The sewerage shed is a good candidate because it is (1) small and in close proximity to a HRSD wastewater plant, (2) the shed is already fully developed and consequences will remain relatively constant over time, (3) it is frequently flooded, and (4) the new station has SCADA to provide data to assess impacts.

In summary, this study provides a decision framework for the Director of Utilities to use to comprehend impacts on the existing PS 113 and the proposed new station. In addition, it provides the Department of Utilities a means to demonstrate how well investing in these improvements reduces the risk over the life cycle of the pump station. Also, the decision tree analysis is adaptable to other pump stations and the city could conduct assessments in-house staff.

For ODU, it creates research expertise in methodologies to assess the impact of rising sea levels on infrastructure. The case study provides a conceptual approach for the College of Engineering to develop a library of fragility curves for a range of regional infrastructure. In addition, building this knowledge within ASCE’s concepts for critical infrastructure enhances the capability of the university’s Coastal Engineering Research Center established by David R. Basco, Ph.D., P. E.

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APPENDIX A: Project Journal, Photographs and Drawings

Part 1: Project Journal

April 25, 2014: I had a brief conversation with Kristen Lentz, PE, Director of Utilities, City of Norfolk. As a follow-on to earlier discussions about my degree progress, I asked if she had projects that I could study and if so, would she be my sponsor and serve on a doctoral committee? She said yes and yes. She said the city had applied for FEMA grants to modify four low-lying pump stations to project against frequent flooding. FEMA rejected the applications stating the risk was too low. We agreed to meet to discuss.

May 23, 2014: I met with the City of Norfolk, Kristen Lentz, PE, Director of Utilities, Eric Tucker, Assistant Director of Utilities, and Ken Turner, PE, Engineering Manager. The city provided the following information:

- Copies of Commonwealth of VA, Hazard Mitigation Grant Program (HMGP) Pre-Application Form DR-4092-VA for Flood Damage Mitigation of Wastewater Pump Stations 109, 112, 113, and 114 located in the Larchmont Neighborhood (City of Norfolk, 2013b)
- PS 113 Flood Control Site Improvements Study, City of Norfolk, Department of Utilities, Draft: June 14, 2011, by O'Brien & Gere. The existing station does not have a backup generator (O'Brien & Gere, 2011).

The pre-applications noted flooding damages existing pump stations and listed such corrective actions as elevating control panels, installing new submersible pumps, raising wet well elevations, and installing watertight hatches.

I asked some questions pertaining to primary stakeholders and Turner referenced an HRSD assessment by Brown and Caldwell. The POC is Richard Stear. I noted that my research committee would need to review to assess whether it has sufficient rigor for a doctoral project. Turner will be the City's POC.

June 2, 2014: I ran into Benjamin J. McFarlane, ACIP at the MTS Tech Surge workshop at ODU. Asked if he was aware of any information on local I&I studies. He referred me to Whitney Katchmark, PE.

June 2, 2014: Via email, I requested from Turner, for any long-term records on PS 113 pumping rates during a full range of weather conditions.

June 3, 2014: Turner responded for PS 113 and the other stations, only have monitoring for alarm conditions. He advised there is no information on the flow rate, pump run time, wet well level or anything for this station. Also, he noted, as the city replaces pumps, the new pumps with large volume flows will include SCADA packages to capture data.

In response, I requested any information on the pump station specifications, and design calculations for sizing the pump to serve its network.

June 3, 2014: I emailed Katchmark. She responded via email referring me to Mike C. Morgan, PE, CDM-Smith who's doing a regional study for HRSD.

June 4, 2014: Turner responded yes and that he will get back to me.

June 5, 2014: Dr. David Basco, PE and I visited PS 113. He pointed out a gated stormwater outlet located at the edge of the Lafayette River that drains from the catch basin next to the pump station. He said his neighbor, RADM Kevin Slates, takes it upon himself to close the gate during storms.

June 11, 2014: Dr. Gary Schafran had given me Jay Bernas, PE, Chief of Planning & Analysis, HRSD. In attempting to call Bernas, I reached Bruce Husselbee, PE. Bernas is on vacation this week. Husselbee noted he just received direction to incorporate SLR into project design. He expects to contract with one of his large IDC's on board, HRD or CDM-Smith, to develop guidance. I asked him to consider inviting CEE to sit in and listen to get a real world experience on the issue.

June 12, 2014: I called Michael C. Morgan, PE, CDM-Smith. He explained HRSD in partnership with jurisdictions is doing a regional study. It is a hydraulic model of fluid flow and includes rainfall I&I. Phillip L. Hubbard, PE is the POC at HRSD. As for Norfolk, the segment in question is solely theirs and is the owner of the data. He referenced a study by Greeley & Hansen.

June 12, 2014: I sent a follow-up email to Turner on June 3rd request for information and mentioned Greeley & Hansen study.

June 16, 2014: I met Chris Guvernator, PE, O'Brien & Gere at the ODU CEE Alumni tour of new engineering building. His firm did the PS 113 study, which I have a copy of the report from the city. He offered information.

June 19, 2014: I called Jay Bernas, PE left a voice message and sent a follow-on email. I called to see if HRSD is studying the impacts of infiltration rates on its network and if that information is available to ODU?

June 20, 23, and 24, 2014: As follow-up to our June 16 discussion, I exchanged emails with Chris Guvernator requesting information on network and pump station. I followed up with more emails, June 23, 24 with clarification.

June 23, 2014: I received a call back from Robert Martz, PE, HRSD, 460-7009 about my request for information about the Inflow & Infiltration studies. We chatted briefly as I was about to enter the Chiropractor's office. He said they are just starting a study and are waiting on data from the jurisdictions for their portion of the network. I asked if he had any information about infiltration rates for pipes underwater, partially underwater, and above water. He said they did not have that kind of information. However, he could give us information about lines underwater in Tidewater and for lines above groundwater in Williamsburg. I begged off to go to my appointment, but asked if I can call him back and we agreed to early tomorrow morning.

June 26, 2014: I met with my advisor Dr. Schafran to discuss research proposal. The current concept is in the right direction. May need to narrow scope to just the pump stations. Examining the network may be too much for a research project scope. Also, the schedule is ambitious. He will be on vacation for the month of July. So I am to continue to flush out the proposal, consult with other committee members as needed, and meet in August to review and discuss when to present to the committee.

June 26, 2014: Martz and I chatted. He said Infiltration & Infiltration rates come from the jurisdictions. He will set up a meeting with CDM (Gary St. John, PE) to find the needed information. He also noted that Bruce Husselbee has tasked him with developing the SLR guidance for HRSD and would like to link in with what ODU is doing. We agreed to share. I referred him to HRPDC, Whitney Katchmark as a starting point and to get copies of Ben McFarlane's reports. I sent him a list of local, state, and Federal references with links.

June 27, 2014: I met with Dr. Schafran. I had sent ahead a copy of the Module 3: Project Problem Statement. He had a few questions for clarification. He thinks the schedule is optimistic. I asked him how this will work. He said with the PhD program, it's usually the advisor and the student. However, for the DEng, we may need to invite the full committee for advisor meetings. He will be on vacation during July. I am too draft a proposal and get back to him in August.

July 17, 2014: I returned July 14 call and email from Michael Morgan, CDM Smith. He called per request from Phil Hubbard and Rob Martz. I left a message and email that I will call him Thursday at 11 AM.

He sent ahead the following paper, A Collaboration Approach to Modeling the Hampton Roads Regional Wastewater Collection System, by Michael C. Morgan, Phillip L. Hubbard, Robert J. Martz, Charles J. Moore and Dr. Ing. Matthias Wittenberg. They presented the paper at a conference in 2012. I requested information on when and where so I can reference the work.

The paper provides information on dry and wet well input to the Regional Hydraulic Model HRSD is developing. Ken Turner is the POC with Norfolk and Rick Underhill is the POC with Greeley & Hansen who did the work. See June 12 entries.

HRSD should have and will provide what input information the city submitted for PS 113 such as service area, flow parameters, the transfer of rainfall data into infiltration rates, and pump details.

I inquired if the jurisdictions followed HRSD design guidance or something else, such as the Health Department. He said they size there lines to HRSD pump stations per HRSD standards, but did not know if they used local, state or HRSD standards to design the rest of their system.

We discussed how to assess flood impacts. I discussed the development of the fragility curve using expert solicitation in the absence of any operations data.

I emailed him the same information on sea levels I had sent to Martz on June 26.

July 17, 2014: In an email, Chris Guvernator provided the following information on the calculations for the PS 113 replacement station. Based on the information he has, it is expected to pump 120 gallons per minute. Over a standard day, it is expected to pump approximately 60,000 gallons per day (gpd). He also attached PDF files of the PS 113 vicinity contour map and section view.

Aug 12, 2014: In an email, Michael Morgan provided the following information for the existing Norfolk Pump Station 113 that HRSD received from Norfolk's consultant (Rick Underhill, Greeley and Hansen).

Norfolk Pump Station 113

Number of Pumps: 2 (constant speed type)
Design Pressure: 65 ft
Firm Capacity: 150 gpm
Wet well Top elevation: 2.24 ft NAVD 88
Cross-sectional area of wet well: 28.27 square ft
Lowest overflow point for the pump station service area: pump station wet well

Pump curve for each of the two pumps:

Total Head	Pump Flow
46 feet	500 gpm
65 feet	150 gpm
74 feet	50 gpm

With regard to the paper he previously sent on July 17, below is the reference information:

Morgan, M; Hubbard, P; Martz, R; Moore, C; Wittenberg, M. (2012), A Collaborative Approach to Modeling the Hampton Roads Regional Wastewater Collection System. *Proceedings of the 2012 Water Environment Federation Collection Systems Conference*; St. Louis, Missouri.

October 23-24, 2014: I exchanged emails with Chris Guvernator who is now with the City of Norfolk, Department of Public Works. He provided the following feedback to questions.

1. What design standards did you follow? Does the city have its own standards? Did they reference HRSD standards and/or state standards (9VAC25-790) or something else?

The pump station was designed in accordance with the Virginia Sewage Collection and Treatment (SCAT) regulations, which I think you referenced correctly. The station was also designed in accordance with the Consent Order for the Hampton Roads Area, which includes an Attachment called "Exhibit A – Regional Design Guidelines" that further governs the design.

2. Do you have a designated design life for the pump system; one for the pump itself (or what is a typical service life for the pump itself)?

Generally, a pump is planned for replacement at the 20-year mark. Some municipalities will program in a 10-year life, but it depends on how hard the pump works, characteristics of the sewage and flow rates at the station. It also depends on whether they are following the recommended maintenance program.

3. Can you please provide the pump specifications? I assume you cannot specify a proprietary pump. Can you advise as to what pumps that meet the specification?

The pump specifications are incomplete, and won't be finalized until the City gives the go-ahead to bid the project. There is only one pump manufacturer included on its approved products list, last updated 08-27-2014, which is Fairbanks Morse. But they have other pumps in service, like Flygt and Clow/Yeomans. You could see if the standard manufacturer's technical specification will work. That will be close to what the City will eventually use. I have attached one for Flygt. See if that is what you are looking for. I can get you others if you want. I can also get you in touch with a manufacturer's rep for more detailed questions and info.

I also asked him if he knew what types of pumps are in the existing PS 113. He referred me to Leticia Quejada, Department of Utilities, who is the PM for the PS 113 project.

October 28, 2014: I sent an email to Leticia Quejada, Department of Utilities requesting information on the type of pumps (manufacturer and model) that are in the existing PS 113. She provided a prompt response with a fact sheet about the pumps. The systems model is a Hydro-O-Matic (Vertical), SPDF 500 with 5 HP, 1150 RPM, 3-Phase, 60 Hertz motor; and a 2"x4" submersible grinder pump.

February 24, 2015: I met with Dr. Christopher Krus, PE, Assistant City Engineer, Department of Utilities, City of Norfolk. I had provided him a copy of the draft report dated February 23, 2014. He went over his comments. He also forwarded an email before the meeting that included three items; (1) A fact sheet on the Hydro-O-Matic (Vertical), SPDF 500 with 5 HP previously provided by Leticia Quejada on October 28th, (2) Yeomans pump characteristics Curve No. 3501, Speed 1750 RPM, and

(3) Manufacturer's literature for a Pentair, Hydromatic Models HPGF/HPGFH Submersible Sewage Grinder Pump as an example of comparable pump in the existing PS 113. He noted that the manufacturer cut sheet for the Hydromatic model does not use the same model number, and that these names/numbers change with various attachments (including horizontal discharge, rails, etc.). He suggested either using the city's fact sheet or contacting the manufacturer for the exact information. He also provided an aerial photograph the site from the city's Geographical Information Systems website. The website is available at the following reference (City of Norfolk, 2015).

We also met H. Leonard Matthews, Jr. PE with the city and discussed the proposed analysis for assessing consequences. They agreed with three consequences, one for environmental impacts, one for costs to repair, and one for social impacts. After the meeting, Krus forwarded a copy of the December 19, 2014 Consent Order, a Commonwealth of Virginia, State Water Control Board Enforcement Action, Order by Consent issued to the city and other local jurisdictions for the purpose of resolving certain violations of State Water Control law and regulations.

March 5, 2015: I called Carey Canty, Operations Division, Department of Utilities, city of Norfolk, 757-823-1028. We first talked about failure modes. Other than power supply disruptions, he advised typical failures caused by flooding are (1) electrical shorts in the Quasar electrical junction box, (green box at grade level), (2) electrical shorts in the control panel when water levels are about one foot above the bottom of the panel, (3) the pump running continuously for 2 to 3 days overloading the pump motor, and (4) dirt and sand chokes the pump, slowing it down and driving up the amperage burning out the motor.

When the pump shuts down, the most common emergency response is to by-pass the pump. Typically, the crew sets-up a temporary pump to divert wastewater from the wet well directly to the force main. When it is flooding, then the crew must walk in and whether they can reach the pump and set-up depends on the flood level. Another method is to "pump and haul", i.e. pump the wastewater to a truck to haul out it away. The only time they need to "pump and haul" is if the force main is broken. This has not happened at PS 113, but it has happened at other stations.

He said the longest time they had to by-pass a pump was one week. The number of days depended on how long it took the electrician to get parts to make repairs.

March 13, 2015: I met with Leticia Quejada and Mel Hopkins, Department of Utilities to go over some questions on data. (1) The site plan provided by O'Brien & Gere via email (see July 17, 2014 entry and included in Appendix A) shows the top of the manhole at elevation 2.97 feet, NAVD (88) and the HRSD Regional Hydraulic Model data provided by the city from a Greeley & Hansen shows the top of the wet well at elevation 2.24 feet, NAVD (88).

They confirmed that the elevation on the site is correct and that the difference between the two elevations is the thickness of the manhole cap. (2) The design life cycle for the pump is 20 years and for the pump station it is 50 years. (3) Quejada confirmed using the

Yeoman pump characteristic curve for the PS 113. (4) For pump characteristic curves, contact Susan Stallnaker, O'Brien & Gere for the new pump station, and Rick Underhill, Greeley & Hansen the existing pump. (5)

We discussed how best to represent the duration of flooding. Hopkins explained that the duration is called the response time. The duration starts from the time the water levels in the wet well trigger the emergency alarm until the water level drops below the alarm-off elevation. It is the time it takes floodwaters to drain from the entire network of pipes and manholes. The city does not calculate the time it takes to drain the system.

April 7, 2015: I met with Mel Hopkins to go over report and discuss proposed consequences. He explained that the consequences have a temporal component; they change from the time of the event until impacts are mitigated. He will review the report and proposed consequence tables and we scheduled a follow-up meeting for April 13, 2015.

April 13, 2015: I met with Mel Hopkins to review the report and respond to questions. We scheduled a follow-up meeting for April 23, 2015.

April 23, 2015: I met with Mel Hopkins to go over the consequence tables. We identified and agreed on three outcomes: environmental, cost and social impacts. The environmental impact is a function of the extent spillage of wastewater would extend within and beyond the service area, colloquially referred to as the sewage shed. The scale is based on the ability to recover the sewage. Once the spillage extends into a body of water, it becomes far more difficult to contain the spill.

Cost impact is a function of the number of different types of costs that the city can incur. Cost includes expenses to recover spillage and clean contaminated areas, to make repairs to the pump station and any related infrastructure, to perform any bypass pumping to a forcemain or to pump and haul spillage, and/or regulatory fines. A major cleanup is defined as having to go outside the sewage shed to recover spillage. A major repair is defined as costs that exceed $10,000. The scale is based on the amount of different kinds of costs incurred.

Social impact is a function of the number of customers disturbed by disruption of service, the spillage, and recovery efforts. The scale is based on the areal extent of the impacts. It is possible to impact neighboring service areas if it is necessary to divert flows into another network.

We scheduled a follow-up meeting to test the Event Tree Analysis spreadsheet for May 7, 2015.

May 7, 2015: I met with Mel Hopkins to once again go over the consequence tables. Mr. Hopkins is satisfied with the ratios for the three consequences in Tables 13, 14 and 15. However, he advised that intensity of the consequences varies over the response time and revisited weights in Table 12.

Mr. Hopkins assumes that if PS 113 would fail, the response would take about 6 months to restore order. He drafted a sketch of the intensity of the three consequences and how they play out over a six-month response period. The intensity of the social impacts would be twice that of environmental impacts, and environmental impacts would be twice the cost impacts. I suggested the best way to represent weights is to use the area under the respective plots to define appropriate ratios between the consequences.

In describing the sketch, he advised that the social impact is the most intense because it requires politics to assure the citizens that all issues will be resolved to their satisfaction. It is the perception that the city is taking the appropriate actions that makes the social impact the most intense of the three consequences. Concerns for environmental impacts would be part of the response to social impacts and regulatory agencies, but will play out longer than the need for immediate public assurances of appropriate actions. Concerns for cost impacts also start immediately and tend to extend over a longer period than the other two consequences. However, costs would play out over a period 1.5 times environmental impacts and 6 times that of social impacts.

May 20, 2015: I met with Hopkins to test risk analysis EXCEL spreadsheets. The risk outcomes are different than expected. Also, in assessing consequences, we decided to make minor adjustments to the Constructed Scale to Judge Cost to Repair. I will revisit the math used to compute risk and seek a second opinion as to whether the outcomes are appropriate.

July 9, 2015: I stopped by the city to pick up a set of plans and specifications from Leticia Quejada (City of Norfolk, 2014).

July 14, 2015: Initiated the Expert Elicitation. The following people volunteered to participate on the expert elicitation team: Michael Barbachem, P. E., Whitman, Requardt & Associates, LLP; Melvin Hopkins, P. E., City of Norfolk, Department of Utilities; H. Ali Mahan, P. E., O'Brien & Gere; and Robert J. Martz, P.E., Hampton Roads Sanitation District. However, only Barbachem, Mahan and Martz attended.

The team received an overview of the study, a training session on the elicitation process and presentation on available data. Given, that only three members showed, the team opted to address any imbalances in the O/U estimates on an ad-hoc basis.

Once the process started, the team quickly rejected data suggested to judge the probability that the system was insufficient. The subject matter experts requested different information. They judged that when the pump has no power, at some point inflow will overwhelm the capacity of the system and spills will occur. They also judged that when the pump does have power, the city's observation that grit could cause the pump motor to burn after 48 to 72 hours operation to be a reasonable expectation.

In order to better estimate probabilities that the network would have insufficient capacity and result in a spill, the experts requested an estimate of the volume of the network. In examining Table 6, the experts noted that the lowest manhole is elevation 2.02 feet, NAVD (88) and at the point floodwaters reach 4 feet, NAVD (88) 25% of the manholes are inundated. They qualitatively judged at this flood stage for the condition where the power is off, inflow would have a significant impact after 5-hours of continuous inundation. For the condition where the power remains on, inflow and grit could have a significant impact after 48-hours of continuous inundation.

Given these possible conditions, the experts also requested the annual probability of exceedence for flooding at elevation 4 feet, NAVD (88) for durations of 5 hours and 48 hours. Also, they requested the probable durations for such a flood for each of the flood stage frequencies from the 99 to 1% events, and for the 4% event as the sea level rises.

Martz noted a discrepancy between the top of pump station manhole at elevation 2.97 feet, NAVD (88) and what was shown in HRSD data as 2.24 feet, NAVD (88). I advised that based on a discussion with the city (see March 13, 2015 entry) that elevation 2.97 was the top of manhole and elevation 2.24 was the top of the wet well. The difference is the thickness of the manhole cap. Martz advised that elevation 2.24 should be the correct elevation. The contract plans provided by the city on July 9, 2015 do not indicate an elevation and contour lines were unclear. A profile of the existing manhole shown in a draft O'Brien and Gere report identifies the elevation as 2.73 feet, NAVD (88) (O'Brien & Gere, 2011).

Following this session, I opted to accept the city's original interpretation and chose to accept the city's interpretation because the spread was insignificant. The key elevation this impacts is the bottom of the existing pump station control panel. I used the manhole as a benchmark to determine the base of the panel at elevation 5.38 feet, NAVD. It could be at elevation 5.14 feet, NAVD (88) or as low as elevation 4.65 feet, NAVD. Based on city input (see March 5, 2015 entry) electrical shorts occur at flood levels one foot above the bottom of the panel. This means these shorts could occur at elevation 6.14 feet, NAVD (88) or as low as 5.65 feet, NAVD (88). However, the discrepancy has a minimal impact on the estimate of failure probabilities, because all three possible elevations stay within the flood stage for Case 4 shown in Table 22. If the lower elevations were below elevation 5.53 feet, NAVD (88), then it would have impacted probabilities for Case 3.

August 14, 2015: The team of experts reconvened to perform the elicitation and completed it in about 5 hours. Again, only three members showed up: Barbachem, Mahan and Martz. The team received an overview of the new data and opted to address any imbalances in the O/U estimates with the following guidelines. For judging the pump's performance, the team added a third term, Even (E) to the Over (O) and Under (U) terms. As a resolution to seeking a balanced O/U bet, the experts accepted two E's as long as the O or U accepted the E estimate, or estimates were balanced by one O, one U and one E and all experts accepted the E estimate.

The team also took Table 19 and expanded it to summarize available information to create Table 22. They added columns for flood durations from Table 13, probabilities of exceeding the 5-hour and 48-hour durations from Table 12, percentage of manholes inundated from Table 6, and times to backfill the network from Table 21.

Flood levels at the lower elevations required the most discussion. As the flood levels exceeded elevation 6 feet, NAVD (88), it was obvious the impacts to the network and the low-lying neighborhood would be significantly detrimental. At the higher flood elevations, the exercise became more academic as flooding would be so extensive and disruptive to the community at large.

September 29, 2015: In responding to comments provided by Dr. Schafran on the draft Final Report, I realized an error in the Sewage Network Volume calculations. As noted in the July 14, 2015 entry, there is discussion of the discrepancy of the top of the existing pump station wet well. I should have used an elevation for the underside of the wet well manhole instead of the one for the top of the manhole. I do not know the thickness of the manhole cover. However, the difference is only a few inches and would have reduced the volume by a matter of 20-30 gallons, much less than 0.03% of the total volume.

November 3, 2015: In response to my November 2, 2015 email request, Leticia Quejada responded that the city has only one submersible pump station, PS 42, with a backup generator.

APPENDIX A (Continued)

Part 2: Photographs and Drawings

Figure 51. Areal View of the Site (See Appendix A, February 23, 2015 entry)

Figure 52. Existing Pump Station Location on Walnut Hill Street at the corner of Sylvan Street

Figure 53. New Pump Station Location on Walnut Hill Street at the corner of Rolfe Avenue

Figure 54. Flooding of Walnut Hill Street, October 4, 2015

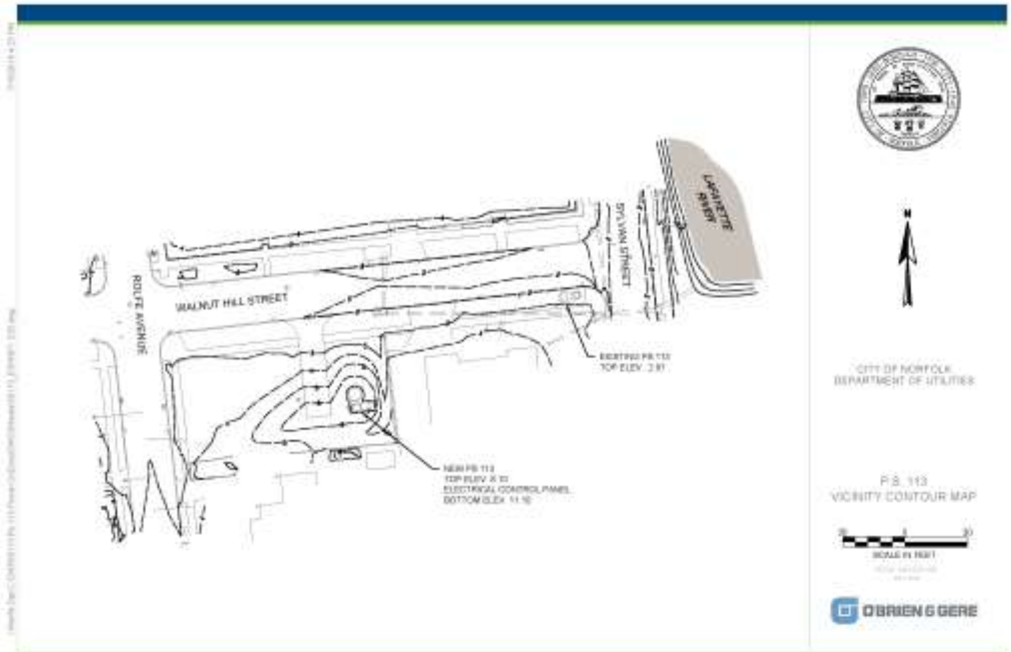


Figure 55. Site Plan (See Appendix A, July 17, 2014 entry)

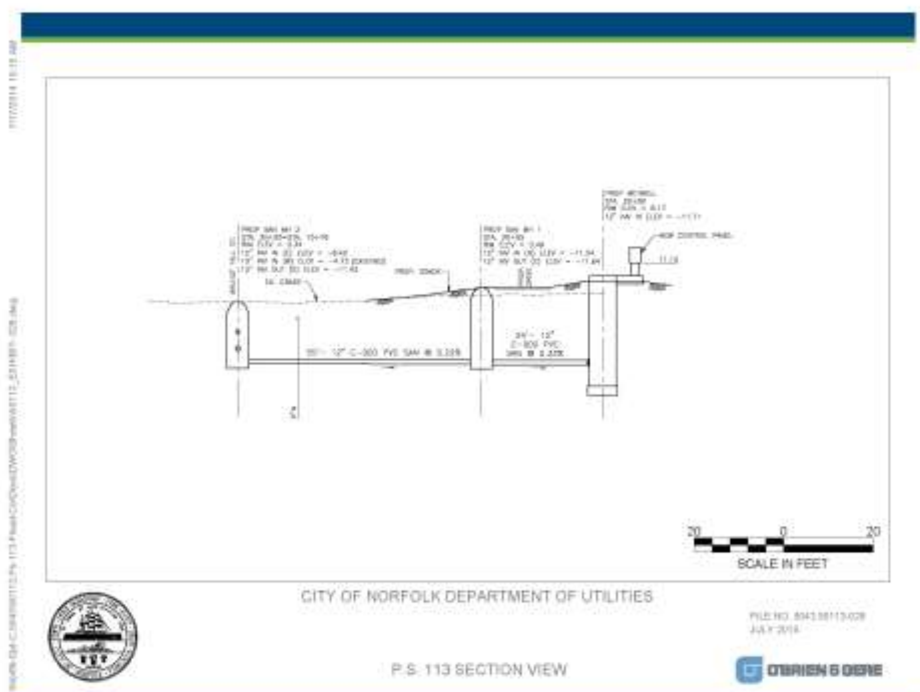


Figure 56. Cross Section of New Pump Station (See Appendix A, July 17, 2014 entry)

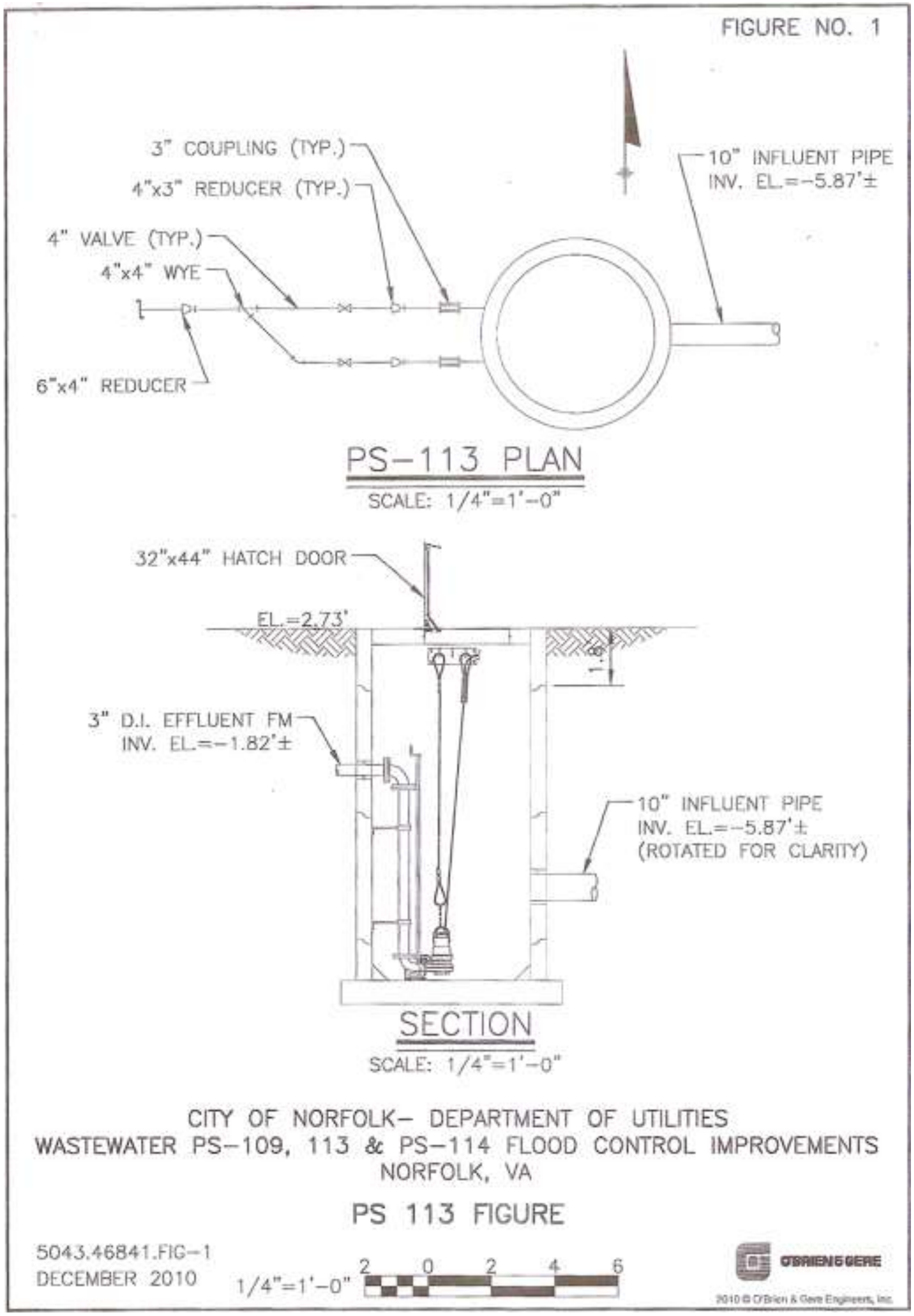


Figure 57. Existing Wet Well Cross Section (O'Brien & Gere, 2011)

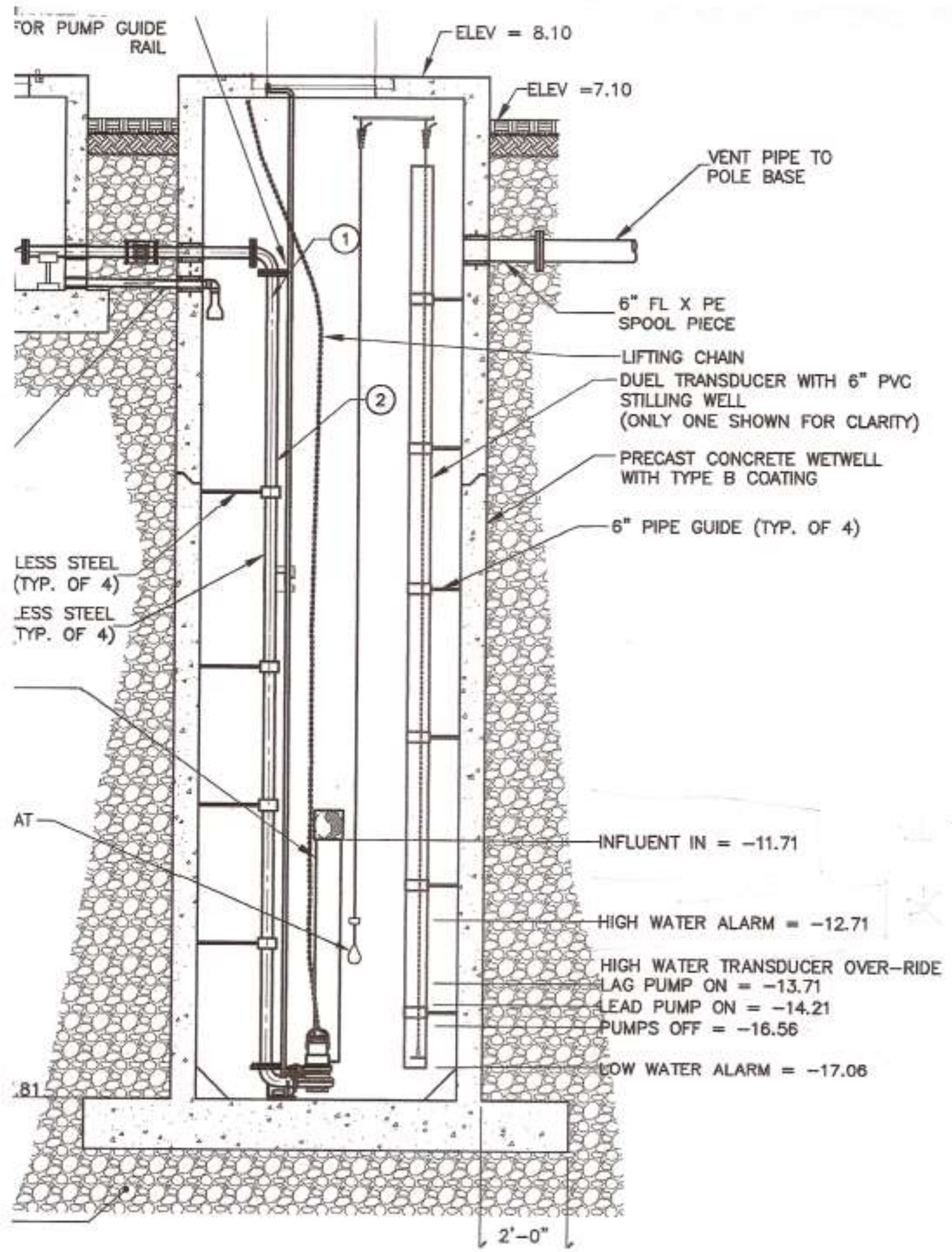


Figure A8. New Wet Well Cross Section (City of Norfolk, 2014)

APPENDIX B: SLR Rise Curves and Storm Event Elevations

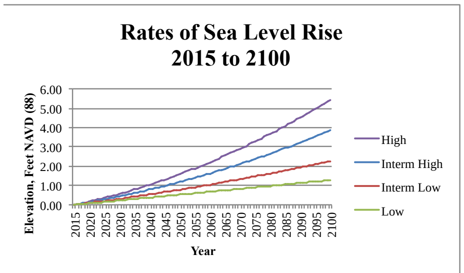
Ref: USACE ER 1110-2-8162, Incorporating Sea Level Change in Civil Works Projects

Equation = $E(t_2 - t_1) = 0.00457(t_2 - t_1) + b(t_2^2 - t_1^2)$

Rate as of March 26, 2015 is 0.00457 mm/year, NOAA

Start year (B3) =	**1992**
Current year (B4) =	**2015**
t_1 = B4 - B3	**23**

Constant Value, *b*	
Low, *b* =	0.0000000
Inter Low, *b* =	0.0000271
Inter High, *b* =	0.0000700
High, *b* =	0.0001130



Pump Design Life = 20 Years
Pump Station Structure Design Life = 50 years

Change in Sea Level Over Design Life					
Year	**Design Life**	**Low**	**Inter Low**	**Inter High**	**High**
2015		0	0	0	0
2035	**Pump**	0.3018	0.4200	0.6070	0.7945
2065	**Pump Stat**	0.7546	1.1842	1.8643	2.5459

Figure 34. Stillwater Level Sea Level Rise Scenarios

Future Year	**t_2 = Col D -B3**	**Low**	**Inter Low**	**Inter High**	**High**
2015	23	0.0000	0.0000	0.0000	0.0000
2016	24	0.0151	0.0193	0.0260	0.0326
2017	25	0.0302	0.0388	0.0524	0.0660
2018	26	0.0453	0.0584	0.0793	0.1001
2019	27	0.0604	0.0783	0.1066	0.1350
2020	28	0.0755	0.0983	0.1344	0.1706
2021	29	0.0906	0.1185	0.1627	0.2070
2022	30	0.1056	0.1389	0.1914	0.2441
2023	31	0.1207	0.1594	0.2206	0.2820
2024	32	0.1358	0.1801	0.2503	0.3206
2025	33	0.1509	0.2010	0.2804	0.3599
2026	34	0.1660	0.2221	0.3110	0.4000
2027	35	0.1811	0.2434	0.3420	0.4408
2028	36	0.1962	0.2648	0.3735	0.4824
2029	37	0.2113	0.2865	0.4055	0.5248
2030	38	0.2264	0.3083	0.4379	0.5679
2031	39	0.2415	0.3303	0.4708	0.6117
2032	40	0.2566	0.3524	0.5042	0.6563
2033	41	0.2717	0.3748	0.5380	0.7016
2034	42	0.2868	0.3973	0.5723	0.7476
2035	43	0.3018	0.4200	0.6070	0.7945
2036	44	0.3169	0.4429	0.6422	0.8420
2037	45	0.3320	0.4659	0.6779	0.8903
2038	46	0.3471	0.4892	0.7140	0.9394
2039	47	0.3622	0.5126	0.7506	0.9892
2040	48	0.3773	0.5362	0.7876	1.0397
2041	49	0.3924	0.5599	0.8252	1.0910
2042	50	0.4075	0.5839	0.8631	1.1430
2043	51	0.4226	0.6080	0.9016	1.1958
2044	52	0.4377	0.6323	0.9405	1.2494
2045	53	0.4528	0.6568	0.9799	1.3036
2046	54	0.4679	0.6815	1.0197	1.3587
2047	55	0.4830	0.7063	1.0600	1.4144
2048	56	0.4981	0.7314	1.1007	1.4709
2049	57	0.5131	0.7566	1.1419	1.5282
2050	58	0.5282	0.7820	1.1836	1.5862
2051	59	0.5433	0.8075	1.2258	1.6450
2052	60	0.5584	0.8333	1.2684	1.7045
2053	61	0.5735	0.8592	1.3114	1.7647
2054	62	0.5886	0.8853	1.3550	1.8257
2055	63	0.6037	0.9116	1.3989	1.8875
2056	64	0.6188	0.9380	1.4434	1.9499
2057	65	0.6339	0.9647	1.4883	2.0132
2058	66	0.6490	0.9915	1.5337	2.0771
2059	67	0.6641	1.0185	1.5795	2.1419
2060	68	0.6792	1.0457	1.6258	2.2073
2061	69	0.6943	1.0730	1.6726	2.2736
2062	70	0.7093	1.1005	1.7198	2.3405
2063	71	0.7244	1.1283	1.7675	2.4082
2064	72	0.7395	1.1561	1.8157	2.4767
2065	73	0.7546	1.1842	1.8643	2.5459
2066	74	0.7697	1.2125	1.9133	2.6159
2067	75	0.7848	1.2409	1.9629	2.6866
2068	76	0.7999	1.2695	2.0129	2.7580
2069	77	0.8150	1.2983	2.0633	2.8302
2070	78	0.8301	1.3272	2.1143	2.9031
2071	79	0.8452	1.3564	2.1657	2.9768
2072	80	0.8603	1.3857	2.2175	3.0512
2073	81	0.8754	1.4152	2.2698	3.1264
2074	82	0.8905	1.4449	2.3226	3.2023
2075	83	0.9055	1.4748	2.3758	3.2790
2076	84	0.9206	1.5048	2.4295	3.3564
2077	85	0.9357	1.5350	2.4837	3.4346
2078	86	0.9508	1.5654	2.5383	3.5135
2079	87	0.9659	1.5960	2.5934	3.5931
2080	88	0.9810	1.6267	2.6489	3.6735
2081	89	0.9961	1.6577	2.7050	3.7547
2082	90	1.0112	1.6888	2.7614	3.8366
2083	91	1.0263	1.7201	2.8184	3.9192
2084	92	1.0414	1.7515	2.8758	4.0026
2085	93	1.0565	1.7832	2.9336	4.0867
2086	94	1.0716	1.8150	2.9919	4.1716
2087	95	1.0867	1.8470	3.0507	4.2572
2088	96	1.1018	1.8792	3.1100	4.3436
2089	97	1.1168	1.9116	3.1697	4.4307
2090	98	1.1319	1.9441	3.2299	4.5186
2091	99	1.1470	1.9769	3.2905	4.6072
2092	100	1.1621	2.0098	3.3516	4.6965
2093	101	1.1772	2.0428	3.4131	4.7866
2094	102	1.1923	2.0761	3.4752	4.8775
2095	103	1.2074	2.1095	3.5376	4.9691
2096	104	1.2225	2.1432	3.6006	5.0614
2097	105	1.2376	2.1770	3.6640	5.1545
2098	106	1.2527	2.2109	3.7279	5.2484
2099	107	1.2678	2.2451	3.7922	5.3429
2100	108	1.2829	2.2794	3.8570	5.4383

Figure 35. Stillwater Level Flood Stages for Low (Historic) Sea Level Rise Scenario							
		Storm Event/Storm Elevation, Feet NAVD (88)					
Time	$E(\Delta t = t_2 - t_1)$	99%	50%	10%	4%	1%	0.20%
Year	SWL, Ft=	2.56	3.54	4.88	5.58	6.76	8.14
2015	0.00	2.56	3.54	4.88	5.58	6.76	8.14
2016	0.02	2.58	3.56	4.90	5.60	6.78	8.16
2017	0.03	2.59	3.57	4.91	5.61	6.79	8.17
2018	0.05	2.61	3.59	4.93	5.63	6.81	8.19
2019	0.06	2.62	3.60	4.94	5.64	6.82	8.20
2020	0.08	2.64	3.62	4.96	5.66	6.84	8.22
2021	0.09	2.65	3.63	4.97	5.67	6.85	8.23
2022	0.11	2.67	3.65	4.99	5.69	6.87	8.25
2023	0.12	2.68	3.66	5.00	5.70	6.88	8.26
2024	0.14	2.70	3.68	5.02	5.72	6.90	8.28
2025	0.15	2.71	3.69	5.03	5.73	6.91	8.29
2026	0.17	2.73	3.71	5.05	5.75	6.93	8.31
2027	0.18	2.74	3.72	5.06	5.76	6.94	8.32
2028	0.20	2.76	3.74	5.08	5.78	6.96	8.34
2029	0.21	2.77	3.75	5.09	5.79	6.97	8.35
2030	0.23	2.79	3.77	5.11	5.81	6.99	8.37
2031	0.24	2.80	3.78	5.12	5.82	7.00	8.38
2032	0.26	2.82	3.80	5.14	5.84	7.02	8.40
2033	0.27	2.83	3.81	5.15	5.85	7.03	8.41
2034	0.29	2.85	3.83	5.17	5.87	7.05	8.43
2035	0.30	2.86	3.84	5.18	5.88	7.06	8.44
2036	0.32	2.88	3.86	5.20	5.90	7.08	8.46
2037	0.33	2.89	3.87	5.21	5.91	7.09	8.47
2038	0.35	2.91	3.89	5.23	5.93	7.11	8.49
2039	0.36	2.92	3.90	5.24	5.94	7.12	8.50
2040	0.38	2.94	3.92	5.26	5.96	7.14	8.52
2041	0.39	2.95	3.93	5.27	5.97	7.15	8.53
2042	0.41	2.97	3.95	5.29	5.99	7.17	8.55
2043	0.42	2.98	3.96	5.30	6.00	7.18	8.56
2044	0.44	3.00	3.98	5.32	6.02	7.20	8.58
2045	0.45	3.01	3.99	5.33	6.03	7.21	8.59
2046	0.47	3.03	4.01	5.35	6.05	7.23	8.61
2047	0.48	3.04	4.02	5.36	6.06	7.24	8.62
2048	0.50	3.06	4.04	5.38	6.08	7.26	8.64
2049	0.51	3.07	4.05	5.39	6.09	7.27	8.65
2050	0.53	3.09	4.07	5.41	6.11	7.29	8.67
2051	0.54	3.10	4.08	5.42	6.12	7.30	8.68
2052	0.56	3.12	4.10	5.44	6.14	7.32	8.70
2053	0.57	3.13	4.11	5.45	6.15	7.33	8.71
2054	0.59	3.15	4.13	5.47	6.17	7.35	8.73
2055	0.60	3.16	4.14	5.48	6.18	7.36	8.74
2056	0.62	3.18	4.16	5.50	6.20	7.38	8.76
2057	0.63	3.19	4.17	5.51	6.21	7.39	8.77
2058	0.65	3.21	4.19	5.53	6.23	7.41	8.79
2059	0.66	3.22	4.20	5.54	6.24	7.42	8.80
2060	0.68	3.24	4.22	5.56	6.26	7.44	8.82
2061	0.69	3.25	4.23	5.57	6.27	7.45	8.83
2062	0.71	3.27	4.25	5.59	6.29	7.47	8.85
2063	0.72	3.28	4.26	5.60	6.30	7.48	8.86
2064	0.74	3.30	4.28	5.62	6.32	7.50	8.88
2065	0.75	3.31	4.29	5.63	6.33	7.51	8.89
2066	0.77	3.33	4.31	5.65	6.35	7.53	8.91
2067	0.78	3.34	4.32	5.66	6.36	7.54	8.92
2068	0.80	3.36	4.34	5.68	6.38	7.56	8.94
2069	0.81	3.37	4.35	5.69	6.39	7.57	8.95
2070	0.83	3.39	4.37	5.71	6.41	7.59	8.97
2071	0.85	3.41	4.39	5.73	6.43	7.61	8.99
2072	0.86	3.42	4.40	5.74	6.44	7.62	9.00
2073	0.88	3.44	4.42	5.76	6.46	7.64	9.02
2074	0.89	3.45	4.43	5.77	6.47	7.65	9.03
2075	0.91	3.47	4.45	5.79	6.49	7.67	9.05
2076	0.92	3.48	4.46	5.80	6.50	7.68	9.06
2077	0.94	3.50	4.48	5.82	6.52	7.70	9.08
2078	0.95	3.51	4.49	5.83	6.53	7.71	9.09
2079	0.97	3.53	4.51	5.85	6.55	7.73	9.11
2080	0.98	3.54	4.52	5.86	6.56	7.74	9.12
2081	1.00	3.56	4.54	5.88	6.58	7.76	9.14
2082	1.01	3.57	4.55	5.89	6.59	7.77	9.15
2083	1.03	3.59	4.57	5.91	6.61	7.79	9.17
2084	1.04	3.60	4.58	5.92	6.62	7.80	9.18
2085	1.06	3.62	4.60	5.94	6.64	7.82	9.20
2086	1.07	3.63	4.61	5.95	6.65	7.83	9.21
2087	1.09	3.65	4.63	5.97	6.67	7.85	9.23
2088	1.10	3.66	4.64	5.98	6.68	7.86	9.24
2089	1.12	3.68	4.66	6.00	6.70	7.88	9.26
2090	1.13	3.69	4.67	6.01	6.71	7.89	9.27
2091	1.15	3.71	4.69	6.03	6.73	7.91	9.29
2092	1.16	3.72	4.70	6.04	6.74	7.92	9.30
2093	1.18	3.74	4.72	6.06	6.76	7.94	9.32
2094	1.19	3.75	4.73	6.07	6.77	7.95	9.33
2095	1.21	3.77	4.75	6.09	6.79	7.97	9.35
2096	1.22	3.78	4.76	6.10	6.80	7.98	9.36
2097	1.24	3.80	4.78	6.12	6.82	8.00	9.38
2098	1.25	3.81	4.79	6.13	6.83	8.01	9.39
2099	1.27	3.83	4.81	6.15	6.85	8.03	9.41
2100	1.28	3.84	4.82	6.16	6.86	8.04	9.42

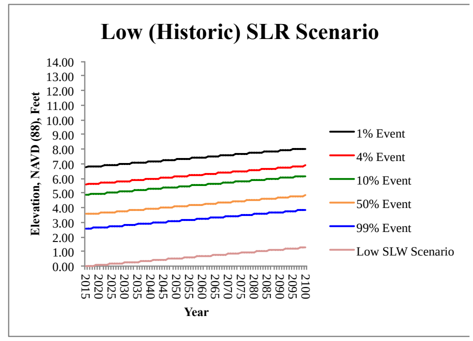


Figure 36. Stillwater Level Flood Stages for Intermediate-Low Scenario							
		Storm Event, %/Feet, NAVD (88)					
Time	**E($\Delta t = t_2 - t_1$)**	**99%**	**50%**	**10%**	**4%**	**1%**	**0.20%**
Year	**SWL, Ft=**	**2.56**	**3.54**	**4.88**	**5.58**	**6.76**	**8.14**
2015	0.00	2.56	3.54	4.88	5.58	6.76	8.14
2016	0.02	2.58	3.56	4.90	5.60	6.78	8.16
2017	0.04	2.60	3.58	4.92	5.62	6.80	8.18
2018	0.06	2.62	3.60	4.94	5.64	6.82	8.20
2019	0.08	2.64	3.62	4.96	5.66	6.84	8.22
2020	0.10	2.66	3.64	4.98	5.68	6.86	8.24
2021	0.12	2.68	3.66	5.00	5.70	6.88	8.26
2022	0.14	2.70	3.68	5.02	5.72	6.90	8.28
2023	0.16	2.72	3.70	5.04	5.74	6.92	8.30
2024	0.18	2.74	3.72	5.06	5.76	6.94	8.32
2025	0.20	2.76	3.74	5.08	5.78	6.96	8.34
2026	0.22	2.78	3.76	5.10	5.80	6.98	8.36
2027	0.24	2.80	3.78	5.12	5.82	7.00	8.38
2028	0.26	2.82	3.80	5.14	5.84	7.02	8.40
2029	0.29	2.85	3.83	5.17	5.87	7.05	8.43
2030	0.31	2.87	3.85	5.19	5.89	7.07	8.45
2031	0.33	2.89	3.87	5.21	5.91	7.09	8.47
2032	0.35	2.91	3.89	5.23	5.93	7.11	8.49
2033	0.37	2.93	3.91	5.25	5.95	7.13	8.51
2034	0.40	2.96	3.94	5.28	5.98	7.16	8.54
2035	0.42	2.98	3.96	5.30	6.00	7.18	8.56
2036	0.44	3.00	3.98	5.32	6.02	7.20	8.58
2037	0.47	3.03	4.01	5.35	6.05	7.23	8.61
2038	0.49	3.05	4.03	5.37	6.07	7.25	8.63
2039	0.51	3.07	4.05	5.39	6.09	7.27	8.65
2040	0.54	3.10	4.08	5.42	6.12	7.30	8.68
2041	0.56	3.12	4.10	5.44	6.14	7.32	8.70
2042	0.58	3.14	4.12	5.46	6.16	7.34	8.72
2043	0.61	3.17	4.15	5.49	6.19	7.37	8.75
2044	0.63	3.19	4.17	5.51	6.21	7.39	8.77
2045	0.66	3.22	4.20	5.54	6.24	7.42	8.80
2046	0.68	3.24	4.22	5.56	6.26	7.44	8.82
2047	0.71	3.27	4.25	5.59	6.29	7.47	8.85
2048	0.73	3.29	4.27	5.61	6.31	7.49	8.87
2049	0.76	3.32	4.30	5.64	6.34	7.52	8.90
2050	0.78	3.34	4.32	5.66	6.36	7.54	8.92
2051	0.81	3.37	4.35	5.69	6.39	7.57	8.95
2052	0.83	3.39	4.37	5.71	6.41	7.59	8.97
2053	0.86	3.42	4.40	5.74	6.44	7.62	9.00
2054	0.89	3.45	4.43	5.77	6.47	7.65	9.03
2055	0.91	3.47	4.45	5.79	6.49	7.67	9.05
2056	0.94	3.50	4.48	5.82	6.52	7.70	9.08
2057	0.96	3.52	4.50	5.84	6.54	7.72	9.10
2058	0.99	3.55	4.53	5.87	6.57	7.75	9.13
2059	1.02	3.58	4.56	5.90	6.60	7.78	9.16
2060	1.05	3.61	4.59	5.93	6.63	7.81	9.19
2061	1.07	3.63	4.61	5.95	6.65	7.83	9.21
2062	1.10	3.66	4.64	5.98	6.68	7.86	9.24
2063	1.13	3.69	4.67	6.01	6.71	7.89	9.27
2064	1.16	3.72	4.70	6.04	6.74	7.92	9.30
2065	1.18	3.74	4.72	6.06	6.76	7.94	9.32
2066	1.21	3.77	4.75	6.09	6.79	7.97	9.35
2067	1.24	3.80	4.78	6.12	6.82	8.00	9.38
2068	1.27	3.83	4.81	6.15	6.85	8.03	9.41
2069	1.30	3.86	4.84	6.18	6.88	8.06	9.44
2070	1.33	3.89	4.87	6.21	6.91	8.09	9.47
2071	1.36	3.92	4.90	6.24	6.94	8.12	9.50
2072	1.39	3.95	4.93	6.27	6.97	8.15	9.53
2073	1.42	3.98	4.96	6.30	7.00	8.18	9.56
2074	1.44	4.00	4.98	6.32	7.02	8.20	9.58
2075	1.47	4.03	5.01	6.35	7.05	8.23	9.61
2076	1.50	4.06	5.04	6.38	7.08	8.26	9.64
2077	1.54	4.10	5.08	6.42	7.12	8.30	9.68
2078	1.57	4.13	5.11	6.45	7.15	8.33	9.71
2079	1.60	4.16	5.14	6.48	7.18	8.36	9.74
2080	1.63	4.19	5.17	6.51	7.21	8.39	9.77
2081	1.66	4.22	5.20	6.54	7.24	8.42	9.80
2082	1.69	4.25	5.23	6.57	7.27	8.45	9.83
2083	1.72	4.28	5.26	6.60	7.30	8.48	9.86
2084	1.75	4.31	5.29	6.63	7.33	8.51	9.89
2085	1.78	4.34	5.32	6.66	7.36	8.54	9.92
2086	1.82	4.38	5.36	6.70	7.40	8.58	9.96
2087	1.85	4.41	5.39	6.73	7.43	8.61	9.99
2088	1.88	4.44	5.42	6.76	7.46	8.64	10.02
2089	1.91	4.47	5.45	6.79	7.49	8.67	10.05
2090	1.94	4.50	5.48	6.82	7.52	8.70	10.08
2091	1.98	4.54	5.52	6.86	7.56	8.74	10.12
2092	2.01	4.57	5.55	6.89	7.59	8.77	10.15
2093	2.04	4.60	5.58	6.92	7.62	8.80	10.18
2094	2.08	4.64	5.62	6.96	7.66	8.84	10.22
2095	2.11	4.67	5.65	6.99	7.69	8.87	10.25
2096	2.14	4.70	5.68	7.02	7.72	8.90	10.28
2097	2.18	4.74	5.72	7.06	7.76	8.94	10.32
2098	2.21	4.77	5.75	7.09	7.79	8.97	10.35
2099	2.25	4.81	5.79	7.13	7.83	9.01	10.39
2100	2.28	4.84	5.82	7.16	7.86	9.04	10.42

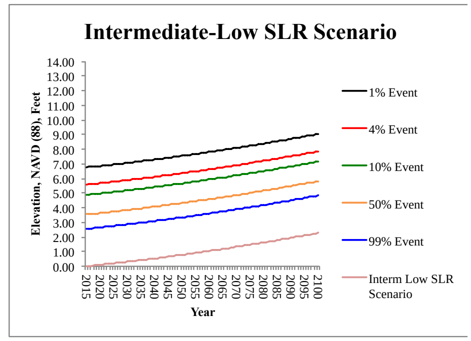


Figure 37. Stillwater Level Intermediate-High Scenario							
Time	$E(\Delta t=t_2-t_1)$	99%	50%	10%	4%	1%	0.20%
Year	SWL, Ft=	2.56	3.54	4.88	5.58	6.76	8.14
2015	0.00	2.56	3.54	4.88	5.58	6.76	8.14
2016	0.03	2.59	3.57	4.91	5.61	6.79	8.17
2017	0.05	2.61	3.59	4.93	5.63	6.81	8.19
2018	0.08	2.64	3.62	4.96	5.66	6.84	8.22
2019	0.11	2.67	3.65	4.99	5.69	6.87	8.25
2020	0.13	2.69	3.67	5.01	5.71	6.89	8.27
2021	0.16	2.72	3.70	5.04	5.74	6.92	8.30
2022	0.19	2.75	3.73	5.07	5.77	6.95	8.33
2023	0.22	2.78	3.76	5.10	5.80	6.98	8.36
2024	0.25	2.81	3.79	5.13	5.83	7.01	8.39
2025	0.28	2.84	3.82	5.16	5.86	7.04	8.42
2026	0.31	2.87	3.85	5.19	5.89	7.07	8.45
2027	0.34	2.90	3.88	5.22	5.92	7.10	8.48
2028	0.37	2.93	3.91	5.25	5.95	7.13	8.51
2029	0.41	2.97	3.95	5.29	5.99	7.17	8.55
2030	0.44	3.00	3.98	5.32	6.02	7.20	8.58
2031	0.47	3.03	4.01	5.35	6.05	7.23	8.61
2032	0.50	3.06	4.04	5.38	6.08	7.26	8.64
2033	0.54	3.10	4.08	5.42	6.12	7.30	8.68
2034	0.57	3.13	4.11	5.45	6.15	7.33	8.71
2035	0.61	3.17	4.15	5.49	6.19	7.37	8.75
2036	0.64	3.20	4.18	5.52	6.22	7.40	8.78
2037	0.68	3.24	4.22	5.56	6.26	7.44	8.82
2038	0.71	3.27	4.25	5.59	6.29	7.47	8.85
2039	0.75	3.31	4.29	5.63	6.33	7.51	8.89
2040	0.79	3.35	4.33	5.67	6.37	7.55	8.93
2041	0.83	3.39	4.37	5.71	6.41	7.59	8.97
2042	0.86	3.42	4.40	5.74	6.44	7.62	9.00
2043	0.90	3.46	4.44	5.78	6.48	7.66	9.04
2044	0.94	3.50	4.48	5.82	6.52	7.70	9.08
2045	0.98	3.54	4.52	5.86	6.56	7.74	9.12
2046	1.02	3.58	4.56	5.90	6.60	7.78	9.16
2047	1.06	3.62	4.60	5.94	6.64	7.82	9.20
2048	1.10	3.66	4.64	5.98	6.68	7.86	9.24
2049	1.14	3.70	4.68	6.02	6.72	7.90	9.28
2050	1.18	3.74	4.72	6.06	6.76	7.94	9.32
2051	1.23	3.79	4.77	6.11	6.81	7.99	9.37
2052	1.27	3.83	4.81	6.15	6.85	8.03	9.41
2053	1.31	3.87	4.85	6.19	6.89	8.07	9.45
2054	1.35	3.91	4.89	6.23	6.93	8.11	9.49
2055	1.40	3.96	4.94	6.28	6.98	8.16	9.54
2056	1.44	4.00	4.98	6.32	7.02	8.20	9.58
2057	1.49	4.05	5.03	6.37	7.07	8.25	9.63
2058	1.53	4.09	5.07	6.41	7.11	8.29	9.67
2059	1.58	4.14	5.12	6.46	7.16	8.34	9.72
2060	1.63	4.19	5.17	6.51	7.21	8.39	9.77
2061	1.67	4.23	5.21	6.55	7.25	8.43	9.81
2062	1.72	4.28	5.26	6.60	7.30	8.48	9.86
2063	1.77	4.33	5.31	6.65	7.35	8.53	9.91
2064	1.82	4.38	5.36	6.70	7.40	8.58	9.96
2065	1.86	4.42	5.40	6.74	7.44	8.62	10.00
2066	1.91	4.47	5.45	6.79	7.49	8.67	10.05
2067	1.96	4.52	5.50	6.84	7.54	8.72	10.10
2068	2.01	4.57	5.55	6.89	7.59	8.77	10.15
2069	2.06	4.62	5.60	6.94	7.64	8.82	10.20
2070	2.11	4.67	5.65	6.99	7.69	8.87	10.25
2071	2.17	4.73	5.71	7.05	7.75	8.93	10.31
2072	2.22	4.78	5.76	7.10	7.80	8.98	10.36
2073	2.27	4.83	5.81	7.15	7.85	9.03	10.41
2074	2.32	4.88	5.86	7.20	7.90	9.08	10.46
2075	2.38	4.94	5.92	7.26	7.96	9.14	10.52
2076	2.43	4.99	5.97	7.31	8.01	9.19	10.57
2077	2.48	5.04	6.02	7.36	8.06	9.24	10.62
2078	2.54	5.10	6.08	7.42	8.12	9.30	10.68
2079	2.59	5.15	6.13	7.47	8.17	9.35	10.73
2080	2.65	5.21	6.19	7.53	8.23	9.41	10.79
2081	2.70	5.26	6.24	7.58	8.28	9.46	10.84
2082	2.76	5.32	6.30	7.64	8.34	9.52	10.90
2083	2.82	5.38	6.36	7.70	8.40	9.58	10.96
2084	2.88	5.44	6.42	7.76	8.46	9.64	11.02
2085	2.93	5.49	6.47	7.81	8.51	9.69	11.07
2086	2.99	5.55	6.53	7.87	8.57	9.75	11.13
2087	3.05	5.61	6.59	7.93	8.63	9.81	11.19
2088	3.11	5.67	6.65	7.99	8.69	9.87	11.25
2089	3.17	5.73	6.71	8.05	8.75	9.93	11.31
2090	3.23	5.79	6.77	8.11	8.81	9.99	11.37
2091	3.29	5.85	6.83	8.17	8.87	10.05	11.43
2092	3.35	5.91	6.89	8.23	8.93	10.11	11.49
2093	3.41	5.97	6.95	8.29	8.99	10.17	11.55
2094	3.48	6.04	7.02	8.36	9.06	10.24	11.62
2095	3.54	6.10	7.08	8.42	9.12	10.30	11.68
2096	3.60	6.16	7.14	8.48	9.18	10.36	11.74
2097	3.66	6.22	7.20	8.54	9.24	10.42	11.80
2098	3.73	6.29	7.27	8.61	9.31	10.49	11.87
2099	3.79	6.35	7.33	8.67	9.37	10.55	11.93
2100	3.86	6.42	7.40	8.74	9.44	10.62	12.00

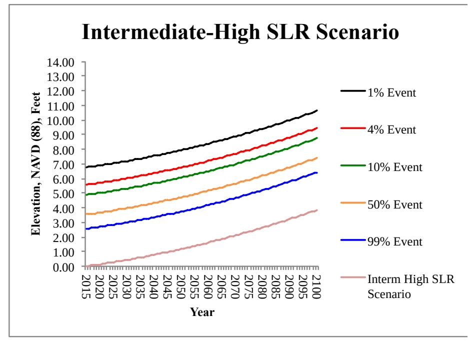


Figure 38. Stillwater Level Flood Stages for High Sea Level Rise Scenario							
		Storm Event/Storm Elevation Feet, NAVD (88)					
Time	E($\Delta t=t_2-t_1$)	99%	50%	10%	4%	1%	0.20%
Year	SWL, Ft=	2.56	3.54	4.88	5.48	6.76	8.14
2015	0.00	2.56	3.54	4.88	5.48	6.76	8.14
2016	0.03	2.59	3.57	4.91	5.51	6.79	8.17
2017	0.07	2.63	3.61	4.95	5.55	6.83	8.21
2018	0.10	2.66	3.64	4.98	5.58	6.86	8.24
2019	0.14	2.70	3.68	5.02	5.62	6.90	8.28
2020	0.17	2.73	3.71	5.05	5.65	6.93	8.31
2021	0.21	2.77	3.75	5.09	5.69	6.97	8.35
2022	0.24	2.80	3.78	5.12	5.72	7.00	8.38
2023	0.28	2.84	3.82	5.16	5.76	7.04	8.42
2024	0.32	2.88	3.86	5.20	5.80	7.08	8.46
2025	0.36	2.92	3.90	5.24	5.84	7.12	8.50
2026	0.40	2.96	3.94	5.28	5.88	7.16	8.54
2027	0.44	3.00	3.98	5.32	5.92	7.20	8.58
2028	0.48	3.04	4.02	5.36	5.96	7.24	8.62
2029	0.52	3.08	4.06	5.40	6.00	7.28	8.66
2030	0.57	3.13	4.11	5.45	6.05	7.33	8.71
2031	0.61	3.17	4.15	5.49	6.09	7.37	8.75
2032	0.66	3.22	4.20	5.54	6.14	7.42	8.80
2033	0.70	3.26	4.24	5.58	6.18	7.46	8.84
2034	0.75	3.31	4.29	5.63	6.23	7.51	8.89
2035	0.79	3.35	4.33	5.67	6.27	7.55	8.93
2036	0.84	3.40	4.38	5.72	6.32	7.60	8.98
2037	0.89	3.45	4.43	5.77	6.37	7.65	9.03
2038	0.94	3.50	4.48	5.82	6.42	7.70	9.08
2039	0.99	3.55	4.53	5.87	6.47	7.75	9.13
2040	1.04	3.60	4.58	5.92	6.52	7.80	9.18
2041	1.09	3.65	4.63	5.97	6.57	7.85	9.23
2042	1.14	3.70	4.68	6.02	6.62	7.90	9.28
2043	1.20	3.76	4.74	6.08	6.68	7.96	9.34
2044	1.25	3.81	4.79	6.13	6.73	8.01	9.39
2045	1.30	3.86	4.84	6.18	6.78	8.06	9.44
2046	1.36	3.92	4.90	6.24	6.84	8.12	9.50
2047	1.41	3.97	4.95	6.29	6.89	8.17	9.55
2048	1.47	4.03	5.01	6.35	6.95	8.23	9.61
2049	1.53	4.09	5.07	6.41	7.01	8.29	9.67
2050	1.59	4.15	5.13	6.47	7.07	8.35	9.73
2051	1.64	4.20	5.18	6.52	7.12	8.40	9.78
2052	1.70	4.26	5.24	6.58	7.18	8.46	9.84
2053	1.76	4.32	5.30	6.64	7.24	8.52	9.90
2054	1.83	4.39	5.37	6.71	7.31	8.59	9.97
2055	1.89	4.45	5.43	6.77	7.37	8.65	10.03
2056	1.95	4.51	5.49	6.83	7.43	8.71	10.09
2057	2.01	4.57	5.55	6.89	7.49	8.77	10.15
2058	2.08	4.64	5.62	6.96	7.56	8.84	10.22
2059	2.14	4.70	5.68	7.02	7.62	8.90	10.28
2060	2.21	4.77	5.75	7.09	7.69	8.97	10.35
2061	2.27	4.83	5.81	7.15	7.75	9.03	10.41
2062	2.34	4.90	5.88	7.22	7.82	9.10	10.48
2063	2.41	4.97	5.95	7.29	7.89	9.17	10.55
2064	2.48	5.04	6.02	7.36	7.96	9.24	10.62
2065	2.55	5.11	6.09	7.43	8.03	9.31	10.69
2066	2.62	5.18	6.16	7.50	8.10	9.38	10.76
2067	2.69	5.25	6.23	7.57	8.17	9.45	10.83
2068	2.76	5.32	6.30	7.64	8.24	9.52	10.90
2069	2.83	5.39	6.37	7.71	8.31	9.59	10.97
2070	2.90	5.46	6.44	7.78	8.38	9.66	11.04
2071	2.98	5.54	6.52	7.86	8.46	9.74	11.12
2072	3.05	5.61	6.59	7.93	8.53	9.81	11.19
2073	3.13	5.69	6.67	8.01	8.61	9.89	11.27
2074	3.20	5.76	6.74	8.08	8.68	9.96	11.34
2075	3.28	5.84	6.82	8.16	8.76	10.04	11.42
2076	3.36	5.92	6.90	8.24	8.84	10.12	11.50
2077	3.43	5.99	6.97	8.31	8.91	10.19	11.57
2078	3.51	6.07	7.05	8.39	8.99	10.27	11.65
2079	3.59	6.15	7.13	8.47	9.07	10.35	11.73
2080	3.67	6.23	7.21	8.55	9.15	10.43	11.81
2081	3.75	6.31	7.29	8.63	9.23	10.51	11.89
2082	3.84	6.40	7.38	8.72	9.32	10.60	11.98
2083	3.92	6.48	7.46	8.80	9.40	10.68	12.06
2084	4.00	6.56	7.54	8.88	9.48	10.76	12.14
2085	4.09	6.65	7.63	8.97	9.57	10.85	12.23
2086	4.17	6.73	7.71	9.05	9.65	10.93	12.31
2087	4.26	6.82	7.80	9.14	9.74	11.02	12.40
2088	4.34	6.90	7.88	9.22	9.82	11.10	12.48
2089	4.43	6.99	7.97	9.31	9.91	11.19	12.57
2090	4.52	7.08	8.06	9.40	10.00	11.28	12.66
2091	4.61	7.17	8.15	9.49	10.09	11.37	12.75
2092	4.70	7.26	8.24	9.58	10.18	11.46	12.84
2093	4.79	7.35	8.33	9.67	10.27	11.55	12.93
2094	4.88	7.44	8.42	9.76	10.36	11.64	13.02
2095	4.97	7.53	8.51	9.85	10.45	11.73	13.11
2096	5.06	7.62	8.60	9.94	10.54	11.82	13.20
2097	5.15	7.71	8.69	10.03	10.63	11.91	13.29
2098	5.25	7.81	8.79	10.13	10.73	12.01	13.39
2099	5.34	7.90	8.88	10.22	10.82	12.10	13.48
2100	5.44	8.00	8.98	10.32	10.92	12.20	13.58

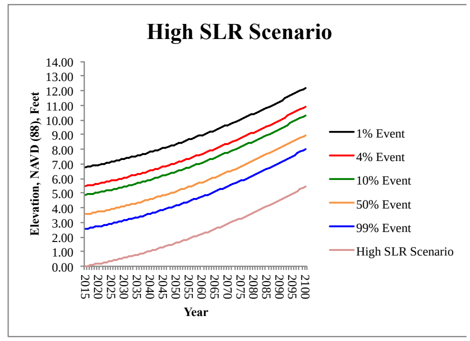
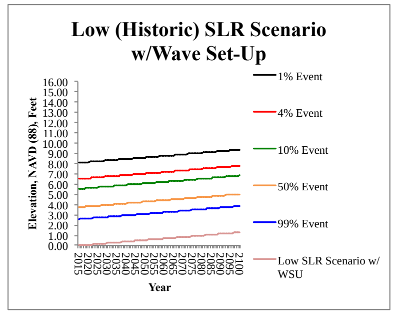


Figure 42. Wave Set-Up Flood Stages for Low (Historic) Sea Level Rise Scenario

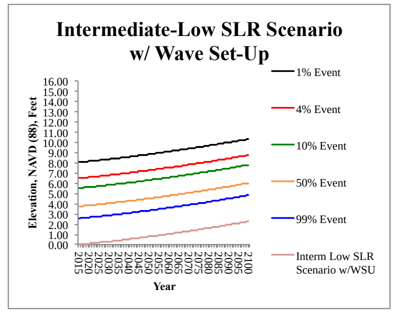
	$E(\Delta t=t_2-t_1)$	99%	50%	10%	4%	1%	0.20%
	SWL, Ft=	2.56	3.54	4.88	5.58	6.76	8.14
Time, Year	WSU, Ft=	0.00	0.20	0.65	0.91	1.30	1.75
2015	0.00	2.56	3.74	5.53	6.49	8.06	9.89
2016	0.02	2.58	3.76	5.55	6.51	8.08	9.91
2017	0.03	2.59	3.77	5.56	6.52	8.09	9.92
2018	0.05	2.61	3.79	5.58	6.54	8.11	9.94
2019	0.06	2.62	3.80	5.59	6.55	8.12	9.95
2020	0.08	2.64	3.82	5.61	6.57	8.14	9.97
2021	0.09	2.65	3.83	5.62	6.58	8.15	9.98
2022	0.11	2.67	3.85	5.64	6.60	8.17	10.00
2023	0.12	2.68	3.86	5.65	6.61	8.18	10.01
2024	0.14	2.70	3.88	5.67	6.63	8.20	10.03
2025	0.15	2.71	3.89	5.68	6.64	8.21	10.04
2026	0.17	2.73	3.91	5.70	6.66	8.23	10.06
2027	0.18	2.74	3.92	5.71	6.67	8.24	10.07
2028	0.20	2.76	3.94	5.73	6.69	8.26	10.09
2029	0.21	2.77	3.95	5.74	6.70	8.27	10.10
2030	0.23	2.79	3.97	5.76	6.72	8.29	10.12
2031	0.24	2.80	3.98	5.77	6.73	8.30	10.13
2032	0.26	2.82	4.00	5.79	6.75	8.32	10.15
2033	0.27	2.83	4.01	5.80	6.76	8.33	10.16
2034	0.29	2.85	4.03	5.82	6.78	8.35	10.18
2035	0.30	2.86	4.04	5.83	6.79	8.36	10.19
2036	0.32	2.88	4.06	5.85	6.81	8.38	10.21
2037	0.33	2.89	4.07	5.86	6.82	8.39	10.22
2038	0.35	2.91	4.09	5.88	6.84	8.41	10.24
2039	0.36	2.92	4.10	5.89	6.85	8.42	10.25
2040	0.38	2.94	4.12	5.91	6.87	8.44	10.27
2041	0.39	2.95	4.13	5.92	6.88	8.45	10.28
2042	0.41	2.97	4.15	5.94	6.90	8.47	10.30
2043	0.42	2.98	4.16	5.95	6.91	8.48	10.31
2044	0.44	3.00	4.18	5.97	6.93	8.50	10.33
2045	0.45	3.01	4.19	5.98	6.94	8.51	10.34
2046	0.47	3.03	4.21	6.00	6.96	8.53	10.36
2047	0.48	3.04	4.22	6.01	6.97	8.54	10.37
2048	0.50	3.06	4.24	6.03	6.99	8.56	10.39
2049	0.51	3.07	4.25	6.04	7.00	8.57	10.40
2050	0.53	3.09	4.27	6.06	7.02	8.59	10.42
2051	0.54	3.10	4.28	6.07	7.03	8.60	10.43
2052	0.56	3.12	4.30	6.09	7.05	8.62	10.45
2053	0.57	3.13	4.31	6.10	7.06	8.63	10.46
2054	0.59	3.15	4.33	6.12	7.08	8.65	10.48
2055	0.60	3.16	4.34	6.13	7.09	8.66	10.49
2056	0.62	3.18	4.36	6.15	7.11	8.68	10.51
2057	0.63	3.19	4.37	6.16	7.12	8.69	10.52
2058	0.65	3.21	4.39	6.18	7.14	8.71	10.54
2059	0.66	3.22	4.40	6.19	7.15	8.72	10.55
2060	0.68	3.24	4.42	6.21	7.17	8.74	10.57
2061	0.69	3.25	4.43	6.22	7.18	8.75	10.58
2062	0.71	3.27	4.45	6.24	7.20	8.77	10.60
2063	0.72	3.28	4.46	6.25	7.21	8.78	10.61
2064	0.74	3.30	4.48	6.27	7.23	8.80	10.63
2065	0.75	3.31	4.49	6.28	7.24	8.81	10.64
2066	0.77	3.33	4.51	6.30	7.26	8.83	10.66
2067	0.78	3.34	4.52	6.31	7.27	8.84	10.67
2068	0.80	3.36	4.54	6.33	7.29	8.86	10.69
2069	0.81	3.37	4.55	6.34	7.30	8.87	10.70
2070	0.83	3.39	4.57	6.36	7.32	8.89	10.72
2071	0.85	3.41	4.59	6.38	7.34	8.91	10.74
2072	0.86	3.42	4.60	6.39	7.35	8.92	10.75
2073	0.88	3.44	4.62	6.41	7.37	8.94	10.77
2074	0.89	3.45	4.63	6.42	7.38	8.95	10.78
2075	0.91	3.47	4.65	6.44	7.40	8.97	10.80
2076	0.92	3.48	4.66	6.45	7.41	8.98	10.81
2077	0.94	3.50	4.68	6.47	7.43	9.00	10.83
2078	0.95	3.51	4.69	6.48	7.44	9.01	10.84
2079	0.97	3.53	4.71	6.50	7.46	9.03	10.86
2080	0.98	3.54	4.72	6.51	7.47	9.04	10.87
2081	1.00	3.56	4.74	6.53	7.49	9.06	10.89
2082	1.01	3.57	4.75	6.54	7.50	9.07	10.90
2083	1.03	3.59	4.77	6.56	7.52	9.09	10.92
2084	1.04	3.60	4.78	6.57	7.53	9.10	10.93
2085	1.06	3.62	4.80	6.59	7.55	9.12	10.95
2086	1.07	3.63	4.81	6.60	7.56	9.13	10.96
2087	1.09	3.65	4.83	6.62	7.58	9.15	10.98
2088	1.10	3.66	4.84	6.63	7.59	9.16	10.99
2089	1.12	3.68	4.86	6.65	7.61	9.18	11.01
2090	1.13	3.69	4.87	6.66	7.62	9.19	11.02
2091	1.15	3.71	4.89	6.68	7.64	9.21	11.04
2092	1.16	3.72	4.90	6.69	7.65	9.22	11.05
2093	1.18	3.74	4.92	6.71	7.67	9.24	11.07
2094	1.19	3.75	4.93	6.72	7.68	9.25	11.08
2095	1.21	3.77	4.95	6.74	7.70	9.27	11.10
2096	1.22	3.78	4.96	6.75	7.71	9.28	11.11
2097	1.24	3.80	4.98	6.77	7.73	9.30	11.13
2098	1.25	3.81	4.99	6.78	7.74	9.31	11.14
2099	1.27	3.83	5.01	6.80	7.76	9.33	11.16
2100	1.28	3.84	5.02	6.81	7.77	9.34	11.17

Table8



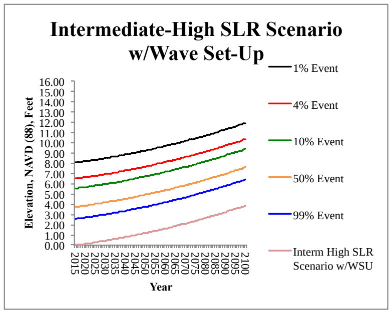
	Flood Requency Events for Event Tree Analysis, Ft. NAVD (88)					
Year	99%	50%	10%	4%	1%	0.20%
2015	2.56	3.74	5.53	6.49	8.06	9.89
2025 L	2.71	3.89	5.68	6.64	8.21	10.04
2035 L	2.86	4.04	5.83	6.79	8.36	10.19
2045 L	3.01	4.19	5.98	6.94	8.51	10.34
2055 L	3.16	4.34	6.13	7.09	8.66	10.49
2065 L	3.31	4.49	6.28	7.24	8.81	10.64

Figure 43. Wave Set-Up Flood Stages for Intermediate-Low Scenario							
		Storm Event, %/Feet, NAVD (88)					
	E(Δt=t_2-t_1)	99%	50%	10%	4%	1%	0.20%
	SWL, Ft=	2.56	3.54	4.88	5.58	6.76	8.14
Time, Year	WSU, Ft=	0.00	0.20	0.65	0.91	1.30	1.75
2015	0.00	2.56	3.74	5.53	6.49	8.06	9.89
2016	0.02	2.58	3.76	5.55	6.51	8.08	9.91
2017	0.04	2.60	3.78	5.57	6.53	8.10	9.93
2018	0.06	2.62	3.80	5.59	6.55	8.12	9.95
2019	0.08	2.64	3.82	5.61	6.57	8.14	9.97
2020	0.10	2.66	3.84	5.63	6.59	8.16	9.99
2021	0.12	2.68	3.86	5.65	6.61	8.18	10.01
2022	0.14	2.70	3.88	5.67	6.63	8.20	10.03
2023	0.16	2.72	3.90	5.69	6.65	8.22	10.05
2024	0.18	2.74	3.92	5.71	6.67	8.24	10.07
2025	0.20	2.76	3.94	5.73	6.69	8.26	10.09
2026	0.22	2.78	3.96	5.75	6.71	8.28	10.11
2027	0.24	2.80	3.98	5.77	6.73	8.30	10.13
2028	0.26	2.82	4.00	5.79	6.75	8.32	10.15
2029	0.29	2.85	4.03	5.82	6.78	8.35	10.18
2030	0.31	2.87	4.05	5.84	6.80	8.37	10.20
2031	0.33	2.89	4.07	5.86	6.82	8.39	10.22
2032	0.35	2.91	4.09	5.88	6.84	8.41	10.24
2033	0.37	2.93	4.11	5.90	6.86	8.43	10.26
2034	0.40	2.96	4.14	5.93	6.89	8.46	10.29
2035	0.42	2.98	4.16	5.95	6.91	8.48	10.31
2036	0.44	3.00	4.18	5.97	6.93	8.50	10.33
2037	0.47	3.03	4.21	6.00	6.96	8.53	10.36
2038	0.49	3.05	4.23	6.02	6.98	8.55	10.38
2039	0.51	3.07	4.25	6.04	7.00	8.57	10.40
2040	0.54	3.10	4.28	6.07	7.03	8.60	10.43
2041	0.56	3.12	4.30	6.09	7.05	8.62	10.45
2042	0.58	3.14	4.32	6.11	7.07	8.64	10.47
2043	0.61	3.17	4.35	6.14	7.10	8.67	10.50
2044	0.63	3.19	4.37	6.16	7.12	8.69	10.52
2045	0.66	3.22	4.40	6.19	7.15	8.72	10.55
2046	0.68	3.24	4.42	6.21	7.17	8.74	10.57
2047	0.71	3.27	4.45	6.24	7.20	8.77	10.60
2048	0.73	3.29	4.47	6.26	7.22	8.79	10.62
2049	0.76	3.32	4.50	6.29	7.25	8.82	10.65
2050	0.78	3.34	4.52	6.31	7.27	8.84	10.67
2051	0.81	3.37	4.55	6.34	7.30	8.87	10.70
2052	0.83	3.39	4.57	6.36	7.32	8.89	10.72
2053	0.86	3.42	4.60	6.39	7.35	8.92	10.75
2054	0.89	3.45	4.63	6.42	7.38	8.95	10.78
2055	0.91	3.47	4.65	6.44	7.40	8.97	10.80
2056	0.94	3.50	4.68	6.47	7.43	9.00	10.83
2057	0.96	3.52	4.70	6.49	7.45	9.02	10.85
2058	0.99	3.55	4.73	6.52	7.48	9.05	10.88
2059	1.02	3.58	4.76	6.55	7.51	9.08	10.91
2060	1.05	3.61	4.79	6.58	7.54	9.11	10.94
2061	1.07	3.63	4.81	6.60	7.56	9.13	10.96
2062	1.10	3.66	4.84	6.63	7.59	9.16	10.99
2063	1.13	3.69	4.87	6.66	7.62	9.19	11.02
2064	1.16	3.72	4.90	6.69	7.65	9.22	11.05
2065	1.18	3.74	4.92	6.71	7.67	9.24	11.07
2066	1.21	3.77	4.95	6.74	7.70	9.27	11.10
2067	1.24	3.80	4.98	6.77	7.73	9.30	11.13
2068	1.27	3.83	5.01	6.80	7.76	9.33	11.16
2069	1.30	3.86	5.04	6.83	7.79	9.36	11.19
2070	1.33	3.89	5.07	6.86	7.82	9.39	11.22
2071	1.36	3.92	5.10	6.89	7.85	9.42	11.25
2072	1.39	3.95	5.13	6.92	7.88	9.45	11.28
2073	1.42	3.98	5.16	6.95	7.91	9.48	11.31
2074	1.44	4.00	5.18	6.97	7.93	9.50	11.33
2075	1.47	4.03	5.21	7.00	7.96	9.53	11.36
2076	1.50	4.06	5.24	7.03	7.99	9.56	11.39
2077	1.54	4.10	5.28	7.07	8.03	9.60	11.43
2078	1.57	4.13	5.31	7.10	8.06	9.63	11.46
2079	1.60	4.16	5.34	7.13	8.09	9.66	11.49
2080	1.63	4.19	5.37	7.16	8.12	9.69	11.52
2081	1.66	4.22	5.40	7.19	8.15	9.72	11.55
2082	1.69	4.25	5.43	7.22	8.18	9.75	11.58
2083	1.72	4.28	5.46	7.25	8.21	9.78	11.61
2084	1.75	4.31	5.49	7.28	8.24	9.81	11.64
2085	1.78	4.34	5.52	7.31	8.27	9.84	11.67
2086	1.82	4.38	5.56	7.35	8.31	9.88	11.71
2087	1.85	4.41	5.59	7.38	8.34	9.91	11.74
2088	1.88	4.44	5.62	7.41	8.37	9.94	11.77
2089	1.91	4.47	5.65	7.44	8.40	9.97	11.80
2090	1.94	4.50	5.68	7.47	8.43	10.00	11.83
2091	1.98	4.54	5.72	7.51	8.47	10.04	11.87
2092	2.01	4.57	5.75	7.54	8.50	10.07	11.90
2093	2.04	4.60	5.78	7.57	8.53	10.10	11.93
2094	2.08	4.64	5.82	7.61	8.57	10.14	11.97
2095	2.11	4.67	5.85	7.64	8.60	10.17	12.00
2096	2.14	4.70	5.88	7.67	8.63	10.20	12.03
2097	2.18	4.74	5.92	7.71	8.67	10.24	12.07
2098	2.21	4.77	5.95	7.74	8.70	10.27	12.10
2099	2.25	4.81	5.99	7.78	8.74	10.31	12.14
2100	2.28	4.84	6.02	7.81	8.77	10.34	12.17



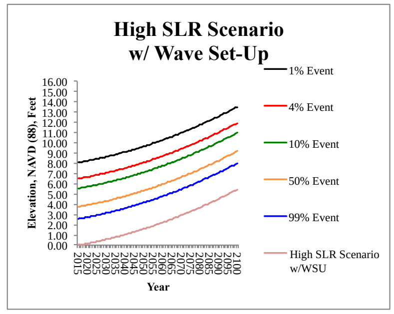
	Flood Frequency Events for Event Tree Analysis, Ft. NAVD (88)					
Year	99%	50%	10%	4%	1%	0.20%
2015	2.56	3.74	5.53	6.49	8.06	9.89
2025 IL	2.76	3.94	5.73	6.69	8.26	10.09
2035 IL	2.98	4.16	5.95	6.91	8.48	10.31
2045 IL	3.22	4.40	6.19	7.15	8.72	10.55
2055 IL	3.47	4.65	6.44	7.40	8.97	10.80
2065 IL	3.74	4.92	6.71	7.67	9.24	11.07

Figure 44. Wave Set-Up Intermediate-High Scenario							
		Storm Event, %/Feet, NAVD (88)					
	$E(\Delta t = t_2 - t_1)$	99%	50%	10%	4%	1%	0.20%
	SWL, Ft=	2.56	3.54	4.88	5.58	6.76	8.14
Time, Year	WSU, Ft=	0.00	0.20	0.65	0.91	1.30	1.75
2015	0.00	2.56	3.74	5.53	6.49	8.06	9.89
2016	0.03	2.59	3.77	5.56	6.52	8.09	9.92
2017	0.05	2.61	3.79	5.58	6.54	8.11	9.94
2018	0.08	2.64	3.82	5.61	6.57	8.14	9.97
2019	0.11	2.67	3.85	5.64	6.60	8.17	10.00
2020	0.13	2.69	3.87	5.66	6.62	8.19	10.02
2021	0.16	2.72	3.90	5.69	6.65	8.22	10.05
2022	0.19	2.75	3.93	5.72	6.68	8.25	10.08
2023	0.22	2.78	3.96	5.75	6.71	8.28	10.11
2024	0.25	2.81	3.99	5.78	6.74	8.31	10.14
2025	0.28	2.84	4.02	5.81	6.77	8.34	10.17
2026	0.31	2.87	4.05	5.84	6.80	8.37	10.20
2027	0.34	2.90	4.08	5.87	6.83	8.40	10.23
2028	0.37	2.93	4.11	5.90	6.86	8.43	10.26
2029	0.41	2.97	4.15	5.94	6.90	8.47	10.30
2030	0.44	3.00	4.18	5.97	6.93	8.50	10.33
2031	0.47	3.03	4.21	6.00	6.96	8.53	10.36
2032	0.50	3.06	4.24	6.03	6.99	8.56	10.39
2033	0.54	3.10	4.28	6.07	7.03	8.60	10.43
2034	0.57	3.13	4.31	6.10	7.06	8.63	10.46
2035	0.61	3.17	4.35	6.14	7.10	8.67	10.50
2036	0.64	3.20	4.38	6.17	7.13	8.70	10.53
2037	0.68	3.24	4.42	6.21	7.17	8.74	10.57
2038	0.71	3.27	4.45	6.24	7.20	8.77	10.60
2039	0.75	3.31	4.49	6.28	7.24	8.81	10.64
2040	0.79	3.35	4.53	6.32	7.28	8.85	10.68
2041	0.83	3.39	4.57	6.36	7.32	8.89	10.72
2042	0.86	3.42	4.60	6.39	7.35	8.92	10.75
2043	0.90	3.46	4.64	6.43	7.39	8.96	10.79
2044	0.94	3.50	4.68	6.47	7.43	9.00	10.83
2045	0.98	3.54	4.72	6.51	7.47	9.04	10.87
2046	1.02	3.58	4.76	6.55	7.51	9.08	10.91
2047	1.06	3.62	4.80	6.59	7.55	9.12	10.95
2048	1.10	3.66	4.84	6.63	7.59	9.16	10.99
2049	1.14	3.70	4.88	6.67	7.63	9.20	11.03
2050	1.18	3.74	4.92	6.71	7.67	9.24	11.07
2051	1.23	3.79	4.97	6.76	7.72	9.29	11.12
2052	1.27	3.83	5.01	6.80	7.76	9.33	11.16
2053	1.31	3.87	5.05	6.84	7.80	9.37	11.20
2054	1.35	3.91	5.09	6.88	7.84	9.41	11.24
2055	1.40	3.96	5.14	6.93	7.89	9.46	11.29
2056	1.44	4.00	5.18	6.97	7.93	9.50	11.33
2057	1.49	4.05	5.23	7.02	7.98	9.55	11.38
2058	1.53	4.09	5.27	7.06	8.02	9.59	11.42
2059	1.58	4.14	5.32	7.11	8.07	9.64	11.47
2060	1.63	4.19	5.37	7.16	8.12	9.69	11.52
2061	1.67	4.23	5.41	7.20	8.16	9.73	11.56
2062	1.72	4.28	5.46	7.25	8.21	9.78	11.61
2063	1.77	4.33	5.51	7.30	8.26	9.83	11.66
2064	1.82	4.38	5.56	7.35	8.31	9.88	11.71
2065	1.86	4.42	5.60	7.39	8.35	9.92	11.75
2066	1.91	4.47	5.65	7.44	8.40	9.97	11.80
2067	1.96	4.52	5.70	7.49	8.45	10.02	11.85
2068	2.01	4.57	5.75	7.54	8.50	10.07	11.90
2069	2.06	4.62	5.80	7.59	8.55	10.12	11.95
2070	2.11	4.67	5.85	7.64	8.60	10.17	12.00
2071	2.17	4.73	5.91	7.70	8.66	10.23	12.06
2072	2.22	4.78	5.96	7.75	8.71	10.28	12.11
2073	2.27	4.83	6.01	7.80	8.76	10.33	12.16
2074	2.32	4.88	6.06	7.85	8.81	10.38	12.21
2075	2.38	4.94	6.12	7.91	8.87	10.44	12.27
2076	2.43	4.99	6.17	7.96	8.92	10.49	12.32
2077	2.48	5.04	6.22	8.01	8.97	10.54	12.37
2078	2.54	5.10	6.28	8.07	9.03	10.60	12.43
2079	2.59	5.15	6.33	8.12	9.08	10.65	12.48
2080	2.65	5.21	6.39	8.18	9.14	10.71	12.54
2081	2.70	5.26	6.44	8.23	9.19	10.76	12.59
2082	2.76	5.32	6.50	8.29	9.25	10.82	12.65
2083	2.82	5.38	6.56	8.35	9.31	10.88	12.71
2084	2.88	5.44	6.62	8.41	9.37	10.94	12.77
2085	2.93	5.49	6.67	8.46	9.42	10.99	12.82
2086	2.99	5.55	6.73	8.52	9.48	11.05	12.88
2087	3.05	5.61	6.79	8.58	9.54	11.11	12.94
2088	3.11	5.67	6.85	8.64	9.60	11.17	13.00
2089	3.17	5.73	6.91	8.70	9.66	11.23	13.06
2090	3.23	5.79	6.97	8.76	9.72	11.29	13.12
2091	3.29	5.85	7.03	8.82	9.78	11.35	13.18
2092	3.35	5.91	7.09	8.88	9.84	11.41	13.24
2093	3.41	5.97	7.15	8.94	9.90	11.47	13.30
2094	3.48	6.04	7.22	9.01	9.97	11.54	13.37
2095	3.54	6.10	7.28	9.07	10.03	11.60	13.43
2096	3.60	6.16	7.34	9.13	10.09	11.66	13.49
2097	3.66	6.22	7.40	9.19	10.15	11.72	13.55
2098	3.73	6.29	7.47	9.26	10.22	11.79	13.62
2099	3.79	6.35	7.53	9.32	10.28	11.85	13.68
2100	3.86	6.42	7.60	9.39	10.35	11.92	13.75



	Flood Requency Events for Event Tree Analysis, Ft. NAVD (88)					
Year	99%	50%	10%	4%	1%	0.20%
2015	2.56	3.74	5.53	6.49	8.06	9.89
2025 IH	2.84	4.02	5.81	6.77	8.34	10.17
2035 IH	3.17	4.35	6.14	7.10	8.67	10.50
2045 IH	3.54	4.72	6.51	7.47	9.04	10.87
2055 IH	3.96	5.14	6.93	7.89	9.46	11.29
2065 IH	4.42	5.60	7.39	8.35	9.92	11.75

Figure 45. Wave Set-Upl Flood Stages for High Sea Level Rise Scenario							
		Storm Event, %/Feet, NAVD (88)					
	$E(\Delta t = t_2 - t_1)$	99%	50%	10%	4%	1%	0.20%
	SWL, Ft=	2.56	3.54	4.88	5.58	6.76	8.14
Time, Year	WSU, Ft=	0.00	0.20	0.65	0.91	1.30	1.75
2015	0.00	2.56	3.74	5.53	6.49	8.06	9.89
2016	0.03	2.59	3.77	5.56	6.52	8.09	9.92
2017	0.07	2.63	3.81	5.60	6.56	8.13	9.96
2018	0.10	2.66	3.84	5.63	6.59	8.16	9.99
2019	0.14	2.70	3.88	5.67	6.63	8.20	10.03
2020	0.17	2.73	3.91	5.70	6.66	8.23	10.06
2021	0.21	2.77	3.95	5.74	6.70	8.27	10.10
2022	0.24	2.80	3.98	5.77	6.73	8.30	10.13
2023	0.28	2.84	4.02	5.81	6.77	8.34	10.17
2024	0.32	2.88	4.06	5.85	6.81	8.38	10.21
2025	0.36	2.92	4.10	5.89	6.85	8.42	10.25
2026	0.40	2.96	4.14	5.93	6.89	8.46	10.29
2027	0.44	3.00	4.18	5.97	6.93	8.50	10.33
2028	0.48	3.04	4.22	6.01	6.97	8.54	10.37
2029	0.52	3.08	4.26	6.05	7.01	8.58	10.41
2030	0.57	3.13	4.31	6.10	7.06	8.63	10.46
2031	0.61	3.17	4.35	6.14	7.10	8.67	10.50
2032	0.66	3.22	4.40	6.19	7.15	8.72	10.55
2033	0.70	3.26	4.44	6.23	7.19	8.76	10.59
2034	0.75	3.31	4.49	6.28	7.24	8.81	10.64
2035	0.79	3.35	4.53	6.32	7.28	8.85	10.68
2036	0.84	3.40	4.58	6.37	7.33	8.90	10.73
2037	0.89	3.45	4.63	6.42	7.38	8.95	10.78
2038	0.94	3.50	4.68	6.47	7.43	9.00	10.83
2039	0.99	3.55	4.73	6.52	7.48	9.05	10.88
2040	1.04	3.60	4.78	6.57	7.53	9.10	10.93
2041	1.09	3.65	4.83	6.62	7.58	9.15	10.98
2042	1.14	3.70	4.88	6.67	7.63	9.20	11.03
2043	1.20	3.76	4.94	6.73	7.69	9.26	11.09
2044	1.25	3.81	4.99	6.78	7.74	9.31	11.14
2045	1.30	3.86	5.04	6.83	7.79	9.36	11.19
2046	1.36	3.92	5.10	6.89	7.85	9.42	11.25
2047	1.41	3.97	5.15	6.94	7.90	9.47	11.30
2048	1.47	4.03	5.21	7.00	7.96	9.53	11.36
2049	1.53	4.09	5.27	7.06	8.02	9.59	11.42
2050	1.59	4.15	5.33	7.12	8.08	9.65	11.48
2051	1.64	4.20	5.38	7.17	8.13	9.70	11.53
2052	1.70	4.26	5.44	7.23	8.19	9.76	11.59
2053	1.76	4.32	5.50	7.29	8.25	9.82	11.65
2054	1.83	4.39	5.57	7.36	8.32	9.89	11.72
2055	1.89	4.45	5.63	7.42	8.38	9.95	11.78
2056	1.95	4.51	5.69	7.48	8.44	10.01	11.84
2057	2.01	4.57	5.75	7.54	8.50	10.07	11.90
2058	2.08	4.64	5.82	7.61	8.57	10.14	11.97
2059	2.14	4.70	5.88	7.67	8.63	10.20	12.03
2060	2.21	4.77	5.95	7.74	8.70	10.27	12.10
2061	2.27	4.83	6.01	7.80	8.76	10.33	12.16
2062	2.34	4.90	6.08	7.87	8.83	10.40	12.23
2063	2.41	4.97	6.15	7.94	8.90	10.47	12.30
2064	2.48	5.04	6.22	8.01	8.97	10.54	12.37
2065	2.55	5.11	6.29	8.08	9.04	10.61	12.44
2066	2.62	5.18	6.36	8.15	9.11	10.68	12.51
2067	2.69	5.25	6.43	8.22	9.18	10.75	12.58
2068	2.76	5.32	6.50	8.29	9.25	10.82	12.65
2069	2.83	5.39	6.57	8.36	9.32	10.89	12.72
2070	2.90	5.46	6.64	8.43	9.39	10.96	12.79
2071	2.98	5.54	6.72	8.51	9.47	11.04	12.87
2072	3.05	5.61	6.79	8.58	9.54	11.11	12.94
2073	3.13	5.69	6.87	8.66	9.62	11.19	13.02
2074	3.20	5.76	6.94	8.73	9.69	11.26	13.09
2075	3.28	5.84	7.02	8.81	9.77	11.34	13.17
2076	3.36	5.92	7.10	8.89	9.85	11.42	13.25
2077	3.43	5.99	7.17	8.96	9.92	11.49	13.32
2078	3.51	6.07	7.25	9.04	10.00	11.57	13.40
2079	3.59	6.15	7.33	9.12	10.08	11.65	13.48
2080	3.67	6.23	7.41	9.20	10.16	11.73	13.56
2081	3.75	6.31	7.49	9.28	10.24	11.81	13.64
2082	3.84	6.40	7.58	9.37	10.33	11.90	13.73
2083	3.92	6.48	7.66	9.45	10.41	11.98	13.81
2084	4.00	6.56	7.74	9.53	10.49	12.06	13.89
2085	4.09	6.65	7.83	9.62	10.58	12.15	13.98
2086	4.17	6.73	7.91	9.70	10.66	12.23	14.06
2087	4.26	6.82	8.00	9.79	10.75	12.32	14.15
2088	4.34	6.90	8.08	9.87	10.83	12.40	14.23
2089	4.43	6.99	8.17	9.96	10.92	12.49	14.32
2090	4.52	7.08	8.26	10.05	11.01	12.58	14.41
2091	4.61	7.17	8.35	10.14	11.10	12.67	14.50
2092	4.70	7.26	8.44	10.23	11.19	12.76	14.59
2093	4.79	7.35	8.53	10.32	11.28	12.85	14.68
2094	4.88	7.44	8.62	10.41	11.37	12.94	14.77
2095	4.97	7.53	8.71	10.50	11.46	13.03	14.86
2096	5.06	7.62	8.80	10.59	11.55	13.12	14.95
2097	5.15	7.71	8.89	10.68	11.64	13.21	15.04
2098	5.25	7.81	8.99	10.78	11.74	13.31	15.14
2099	5.34	7.90	9.08	10.87	11.83	13.40	15.23
2100	5.44	8.00	9.18	10.97	11.93	13.50	15.33



	Flood Requency Events for Event Tree Analysis, Ft. NAVD (88)					
Year	99%	50%	10%	4%	1%	0.20%
2015	2.56	3.74	5.53	6.49	8.06	9.89
2025 H	2.92	4.10	5.89	6.85	8.42	10.25
2035 H	3.35	4.53	6.32	7.28	8.85	10.68
2045 H	3.86	5.04	6.83	7.79	9.36	11.19
2055 H	4.45	5.63	7.42	8.38	9.95	11.78
2065 H	5.11	6.29	8.08	9.04	10.61	12.44

APPENDIX C: Flood Duration Analysis

Page 212 - Summary of Events – Provides recommended values for durations for a range of Return Periods, Tables 12 and 13 in body of report.

Page 213 - Current Year + SLR = 0.0 Feet – Extreme Value Analysis for 2014

Page 214 - Current Year + SLR = 0.5 Feet – Extreme Value Analysis for 2014 plus 0.05 feet of SLR.

Page 215 - Current Year + SLR = 1.0 Feet – Extreme Value Analysis for 2014 plus 1.0 feet of SLR.

Page 216 - Current Year + SLR = 1.5 Feet – Extreme Value Analysis for 2014 plus 1.5 feet of SLR.

Page 217 - Current Year + SLR = 2.0 Feet – Extreme Value Analysis for 2014 plus 2.0 feet of SLR.

Page 218 - Current Year + SLR = 2.5 Feet – Extreme Value Analysis for 2014 plus 2.5 feet of SLR.

Page 219 - Current Year + SLR = 2.5 Feet, Adjusted – Extreme Value Analysis for 2014 plus 2.5 feet of SLR with an adjusted α. The results for the 2.5-foot increment were odd compared to the other increments. The Weibull α in the Weibull distribution analysis was reduced from 1.8 to 1.4 to align the 99 and 50% durations with those for the 2.0 and 3.0-foot increments.

Page 220 - Current Year + SLR = 3.0 Feet – Extreme Value Analysis for 2014 plus 3.0 feet of SLR.

Page 221 - Longest Annual Duration – This is the summary of the longest (most extreme) event for each year. The data is from the Summary of Annual Events, 1928 – 2014 spreadsheet. It is used to cut and paste the data into respective current year + SLR spreadsheets.

Summary of Results - Tables 1 and 2 provide results from Current Year plus sea level rise increments in the following sheets based on both a Gumbel and Weibull Distribution Analysis. The results for the Weibull are for the alpha with the highest R-Squared value, except for 1.0 foot increment.The results for the 2.5 foot increment were odd compared to the other increments. The α was reduced from 1.8 to 1.4 to better align the calculated durations with those for the increments. The Weibull analysis had the higher R^2 values for all increments except at 3.0 feet, which was slightly less. Therefore, the author chose to use the Weibull results for the duration frequency analysis. Table 3 provides the inverse of the return period for 5, 6, 12, 24, 48 and 72 hours of flooding in percent of probable annual exceedence. Converting the percent to decimel format provides the probability of exceedence needed to assess the probability the pump will fail

Table 1 - Summary of Gumbel D_{TR}

	TR, % =	99	50	10	4	1	0.2
	TR, Years =	1	2	10	25	100	500
Increment of SLR, Ft =	0.0	-6	1	5	9	18	25
	0.5	-6	3	7	12	23	31
	1.0	-7	6	13	20	37	48
	1.5	-8	9	17	27	48	63
	2.0	4	13	34	45	63	84
	2.5	0	26	38	52	84	106
	3.0	7	46	65	86	135	168

Table 2 - Summary of Weibull Calcuated D_{TR}

	TR, % =	99	50	10	4	1	0.2
	TR, Years =	1	2	10	25	100	500
Increment of SLR, Ft =	0.0	0	1	5	7	10	13
	0.5	0	3	10	15	21	28
	1.0	-7	6	13	20	37	48
	1.5	3	9	23	31	44	58
	2.0	4	13	34	45	63	84
	2.5	4	17	48	65	91	122
	3.0	7	27	73	100	140	186

Table 3 - Summary of Durations, D_{TR} for range of T_R, %

	D_{TR} , Hours =	5	6	12	24	48	72
Increment of SLR, Ft =	0.0	11.8	7.30	0.424	0.001	0.000	0.000
	0.5	37.9	30.3	7.87	0.532	0.002	0.000
	1.0	65.8	56.8	23.3	3.9	0.111	0.003
	1.5	87.7	78.1	39.4	9.9	0.637	0.041
	2.0	94.3	87.0	54.9	21.7	3.39	0.529
	2.5	98.0	93.5	68.0	36.1	10.2	2.85
	3.0	102	101	95.2	86.2	69.9	56.5

Table 4 - Probability of Exceedence for Durations for Range of Scenarios

SLR Scenarios	Sea Level Stage E(Δt=t2-t1), Feet[1]	Probability of Exceedence for 5-Hr Flood Duration, %	Probability of Exceedence for 6-Hr Flood Duration, %	Probability of Exceedence for 12-Hr Flood Duration, %	Probability of Exceedence for 24-Hr Flood Duration, %	Probability of Exceedence for 48-Hr Flood Duration, %	Probability of Exceedence for 72-Hr Flood Duration, %
2015	0.00	23.1	16.2	2.0	0.029	0.000	0.000
2035 Low	0.30	27.8	20.3	3.2	0.073	0.000	0.000
2035 Int Low	0.42	30.0	22.2	3.9	0.106	0.000	0.000
2035 Int High	0.61	33.7	25.6	5.2	0.188	0.000	0.000
2035 High	0.79	37.9	29.5	7.0	0.335	0.001	0.000
2065 Low	0.75	36.9	28.6	6.6	0.297	0.001	0.000
2065 Int Low	1.18	48.3	39.6	13.1	1.12	0.009	0.000
2065 Int High	1.86	73.8	66.1	38.7	9.10	0.622	0.044
2065 High	2.55	113	111	115	74.6	45.4	27.3

1. Increments of SLR from SLR Curve with Flood Levels Excel

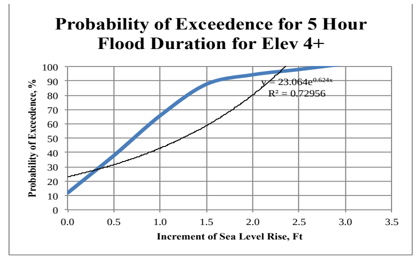
Table 12 (in body of report). Probability of Exceedence for Flood Duration, %

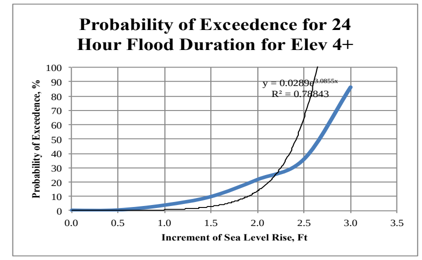
Year	5-Hours	6-Hours	12-Hours	24-Hours	48-Hours	72-Hours
2015	23.1	16.2	2.0	0.0	0.0	0.0
2035	33.7	25.6	5.2	0.2	0.0	0.0
2065	73.8	66.1	38.7	9.1	0.6	0.0

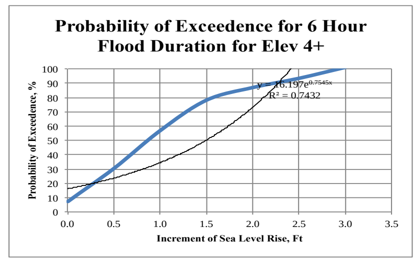
Table 13 (in body of report). Probable Flood Durations for a Range of Return Periods, %

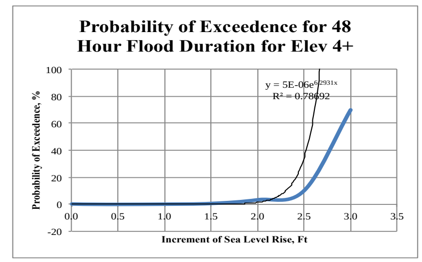
Year	Increment of SLR, Ft.[1]	99% Event	50% Event	10% Event	4% Event[2]	1% Event
2015	0.00	0	1	5	7	10
2035	0.61				14	
2065	1.86				39	

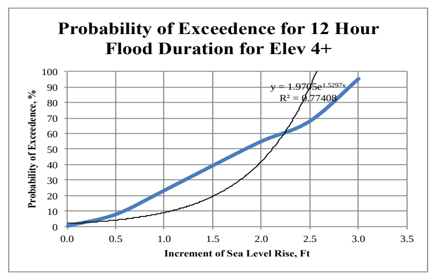
1. Rates based on Intermediate High SLR Scenario.
2. Rate for 2015 from Table 2. Rates for 2035 and 2065 from y = 8.2155*EXP(0.8354*x) from 4% Event Figure.

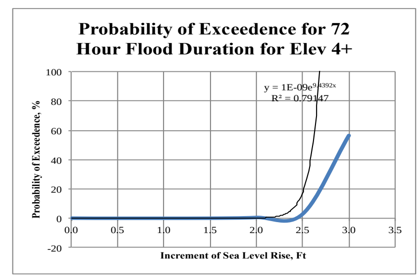


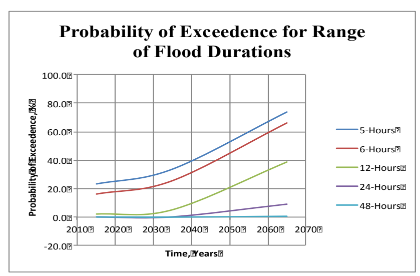


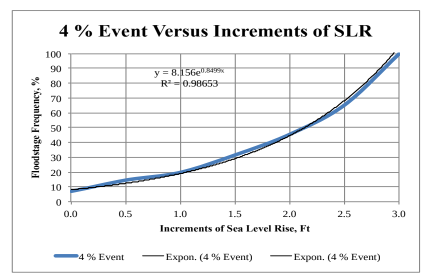






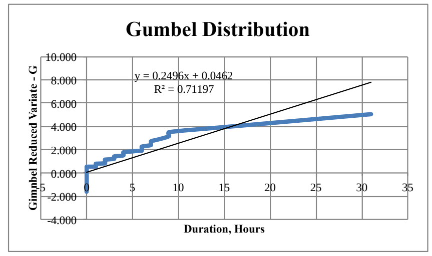




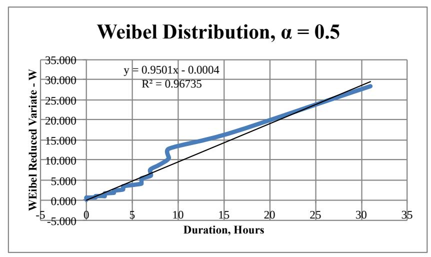


Sheet 2 - Current Year+SLR = 0.0 Ft.

				Q, Gumbel		Q, Weibel	
				C1 =	0.44	C1 =	0.5818
Event Adjusted to 2014 + SLR = +0.0 ft				C2 =	0.12	C2 =	0.5253
	Event	Duration				α =	0.5
Date Time	**Elevation**	**Hours**	**i**	Q	G	Q	W
11/12/09 18:00	6.138	31	1	0.007	5.032	0.005	28.434
9/16/33 18:00	5.719	16	2	0.018	4.002	0.016	16.901
3/7/62 10:00	6.387	9	3	0.030	3.501	0.028	12.798
9/18/03 16:00	6.441	9	4	0.041	3.165	0.040	10.442
9/27/56 2:00	5.174	8	5	0.053	2.911	0.051	8.849
9/18/36 10:00	6.274	7	6	0.065	2.707	0.063	7.677
2/5/98 4:00	5.197	7	7	0.076	2.535	0.074	6.767
10/29/12 8:00	5.178	7	8	0.088	2.387	0.086	6.034
9/19/28 0:00	4.996	6	9	0.099	2.257	0.097	5.429
4/27/78 0:00	5.337	6	10	0.111	2.140	0.109	4.919
10/7/06 9:00	5.002	6	11	0.123	2.034	0.120	4.481
8/27/11 19:00	5.970	6	12	0.134	1.937	0.132	4.102
10/25/82 4:00	4.775	5	13	0.146	1.847	0.144	3.769
10/5/48 11:00	4.756	4	14	0.157	1.764	0.155	3.474
10/6/57 8:00	4.861	4	15	0.169	1.686	0.167	3.211
10/21/58 18:00	4.547	4	16	0.181	1.613	0.178	2.975
9/12/60 6:00	4.816	4	17	0.192	1.544	0.190	2.762
9/13/64 16:00	4.657	4	18	0.204	1.478	0.201	2.569
10/14/77 10:00	4.321	3	19	0.216	1.416	0.213	2.394
4/13/88 7:00	4.366	3	20	0.227	1.356	0.224	2.233
9/25/92 8:00	4.267	3	21	0.239	1.299	0.236	2.085
8/30/99 12:00	4.201	3	22	0.250	1.244	0.248	1.949
9/25/08 18:00	4.283	3	23	0.262	1.192	0.259	1.824
1/24/40 8:00	4.397	2	24	0.274	1.141	0.271	1.708
12/5/45 9:00	4.142	2	25	0.285	1.091	0.282	1.601
1/17/46 9:00	4.127	2	26	0.297	1.044	0.294	1.501
10/21/61 19:00	4.302	2	27	0.308	0.998	0.305	1.408
2/11/73 3:00	4.122	2	28	0.320	0.953	0.317	1.321
10/31/91 16:00	4.029	2	29	0.332	0.909	0.328	1.240
10/19/97 12:00	4.126	2	30	0.343	0.866	0.340	1.164
2/6/10 3:00	4.174	2	31	0.355	0.825	0.352	1.093
8/22/30 20:00	4.166	1	32	0.366	0.784	0.363	1.026
10/4/51 11:00	4.052	1	33	0.378	0.745	0.375	0.964
10/23/53 10:00	4.022	1	34	0.390	0.706	0.386	0.905
3/26/71 21:00	4.051	1	35	0.401	0.667	0.398	0.850
8/17/86 20:00	4.118	1	36	0.413	0.630	0.409	0.798
1/1/87 22:00	4.221	1	37	0.425	0.593	0.421	0.749
1/25/00 12:00	4.058	1	38	0.436	0.557	0.432	0.703
9/22/29 11:00	3.781	0	39	0.448	0.521	0.444	0.659
3/22/31 23:00	3.449	0	40	0.459	0.486	0.456	0.618
9/9/32 17:00	3.335	0	41	0.471	0.451	0.467	0.579
3/20/34 12:00	3.003	0	42	0.483	0.417	0.479	0.543
11/17/35 3:00	3.589	0	43	0.494	0.383	0.490	0.508
1/29/37 10:00	3.959	0	44	0.506	0.350	0.502	0.475
5/30/38 22:00	3.745	0	45	0.517	0.317	0.513	0.445
8/28/39 20:00	3.412	0	46	0.529	0.284	0.525	0.415
1/12/41 8:00	2.699	0	47	0.541	0.251	0.536	0.388
9/30/43 10:00	3.870	0	48	0.552	0.219	0.548	0.362
9/14/44 12:00	3.156	0	49	0.564	0.187	0.560	0.337
11/1/47 11:00	3.981	0	50	0.575	0.155	0.571	0.314
5/11/49 20:00	3.780	0	51	0.587	0.123	0.583	0.292
9/6/50 16:00	2.066	0	52	0.599	0.091	0.594	0.271
2/27/52 10:00	3.637	0	53	0.610	0.059	0.606	0.251
1/23/54 0:00	3.607	0	54	0.622	0.028	0.617	0.233
6/10/55 0:00	3.191	0	55	0.634	-0.004	0.629	0.215
4/12/59 23:00	3.131	0	56	0.645	-0.035	0.640	0.198
9/15/63 20:00	3.570	0	57	0.657	-0.067	0.652	0.183
1/16/65 21:00	3.842	0	58	0.668	-0.099	0.664	0.168
1/27/66 0:00	3.427	0	59	0.680	-0.130	0.675	0.154
9/16/67 19:00	3.812	0	60	0.692	-0.162	0.687	0.141
5/27/68 21:00	3.997	0	61	0.703	-0.195	0.698	0.129
3/2/69 7:00	3.982	0	62	0.715	-0.227	0.710	0.117
10/27/70 7:00	3.567	0	63	0.726	-0.259	0.721	0.107
5/26/72 20:00	3.435	0	64	0.738	-0.292	0.733	0.097
6/28/74 4:00	2.946	0	65	0.750	-0.326	0.745	0.087
11/24/75 13:00	3.160	0	66	0.761	-0.359	0.756	0.078
3/10/76 3:00	2.785	0	67	0.773	-0.394	0.768	0.070
9/24/79 11:00	3.160	0	68	0.784	-0.428	0.779	0.062
1/5/80 12:00	3.046	0	69	0.796	-0.464	0.791	0.055
8/20/81 12:00	3.730	0	70	0.808	-0.500	0.802	0.049
1/28/83 9:00	3.811	0	71	0.819	-0.537	0.814	0.042
10/14/84 12:00	3.294	0	72	0.831	-0.575	0.825	0.037
11/2/85 11:00	3.631	0	73	0.843	-0.614	0.837	0.032
2/24/89 11:00	3.370	0	74	0.854	-0.655	0.849	0.027
10/26/90 2:00	3.395	0	75	0.866	-0.697	0.860	0.023
1/10/93 10:00	3.652	0	76	0.877	-0.741	0.872	0.019
11/17/94 9:00	3.955	0	77	0.889	-0.788	0.883	0.015
8/7/95 18:00	3.251	0	78	0.901	-0.837	0.895	0.012
10/8/96 19:00	3.712	0	79	0.912	-0.889	0.906	0.010
9/30/01 20:00	3.387	0	80	0.924	-0.946	0.918	0.007
10/16/02 5:00	3.248	0	81	0.935	-1.008	0.929	0.005
9/19/04 12:00	3.050	0	82	0.947	-1.078	0.941	0.004
4/16/05 2:00	2.760	0	83	0.959	-1.159	0.953	0.002
11/3/07 4:00	3.235	0	84	0.970	-1.257	0.964	0.001
10/10/13 1:00	3.854	0	85	0.982	-1.389	0.976	0.001
11/1/14 16:00	3.422	0	86	0.993	-1.617	0.987	0.000
	N (Events) =	86					



Yrs of Rec	86	**Gumbel Distribution Analysis for Duration by Return Period**					
N (Events) =	86	**DTR (Hrs) = γ - β*ln(ln{λTR/(λTR-1)})**					
TR, %		**99**	**50**	**25**	**10**	**1**	**0.2**
TR, Years		1.01	2	4	10	100	500
λ = N/YofR	1.00						
A = 1/β	0.2496						
B = -γ/β	0.0462						
β = 1/A	4.01						
γ = -β*B	-0.19						
α =	N/A						
D_{TR}		-6	1	5	9	18	25



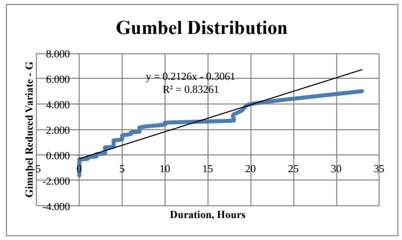
Yrs of Rec	86	**Weibel Distribution Analysis for Duration by Return Period**					
N (Events) =	86	**DTR = γ + β*LN(λ*TR)^(1/α)**					
TR, %		**99**	**50**	**10**	**4**	**1**	**0.2**
TR, Years		1.01	2	10	25	100	500
λ = N/YofR	1.00						
A = 1/β	0.9501						
B = -γ/β	-0.0004						
β = 1/A	1.05						
γ = -β*B	0.00						
α =	0.5						
D_{TR}		0	1	5	7	10	13

Yrs of Rec	86	**Inverse of the Return Periods for the Weibull Analysis for 5, 6, 12, 24, 48 and 72 hours, T_R, %**					
N (Events) =	86						
TR, %		11.8	7.30	0.424	0.001	0.000	0.000
TR, Years		8.48	13.7	236	70600	1.00E+10	1.00E+15
λ = N/YofR	1.00						
A = 1/β	0.9501						
B = -γ/β	-0.0004						
β = 1/A	1.05						
γ = -β*B	0.00						
α =	0.5						
D_{TR}		5	6	12	24	48	73

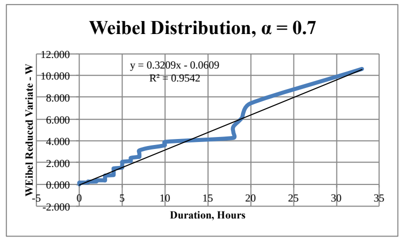
Sheet 3 - Current Year+SLR = 0.5 Ft.

Event Adjusted to 2014 + SLR = +0.5 ft

				Q, Gumbel		**Q, Weibel**	
				C1 =	0.44	C1 =	0.5227
				C2 =	0.12	C2 =	0.4749
						α =	0.7
Date Time	**Event Elevation**	**Duration Hours**	**i**	Q	G	Q	W
11/12/09 18:00	6.638	33	1	0.007	5.032	0.006	10.539
2/5/98 4:00	5.697	20	2	0.018	4.002	0.017	7.427
3/7/62 10:00	6.887	19	3	0.030	3.501	0.029	6.117
9/16/33 18:00	6.219	18	4	0.041	3.165	0.040	5.300
9/27/56 2:00	5.674	18	5	0.053	2.911	0.052	4.715
10/29/12 8:00	5.678	18	6	0.065	2.707	0.063	4.263
10/25/82 4:00	5.275	10	7	0.076	2.535	0.075	3.898
9/18/03 16:00	6.941	10	8	0.088	2.387	0.086	3.593
9/18/36 10:00	6.774	8	9	0.099	2.257	0.098	3.333
10/21/58 18:00	5.047	7	10	0.111	2.140	0.110	3.106
9/13/64 16:00	5.157	7	11	0.123	2.034	0.121	2.907
4/27/78 0:00	5.837	7	12	0.134	1.937	0.133	2.729
8/27/11 19:00	6.470	7	13	0.146	1.847	0.144	2.569
9/19/28 0:00	5.496	6	14	0.157	1.764	0.156	2.425
10/6/57 8:00	5.361	6	15	0.169	1.686	0.167	2.292
10/7/06 9:00	5.502	6	16	0.181	1.613	0.179	2.171
10/5/48 11:00	5.256	5	17	0.192	1.544	0.191	2.059
2/11/73 3:00	4.622	5	18	0.204	1.478	0.202	1.955
4/13/88 7:00	4.866	5	19	0.216	1.416	0.214	1.859
10/31/91 16:00	4.529	5	20	0.227	1.356	0.225	1.769
9/25/92 8:00	4.767	5	21	0.239	1.299	0.237	1.684
8/30/99 12:00	4.701	5	22	0.250	1.244	0.248	1.605
9/25/08 18:00	4.783	5	23	0.262	1.192	0.260	1.531
1/29/37 10:00	4.459	4	24	0.274	1.141	0.271	1.461
12/5/45 9:00	4.642	4	25	0.285	1.091	0.283	1.395
10/4/51 11:00	4.552	4	26	0.297	1.044	0.295	1.332
10/23/53 10:00	4.522	4	27	0.308	0.998	0.306	1.272
9/12/60 6:00	5.316	4	28	0.320	0.953	0.318	1.216
10/21/61 19:00	4.802	4	29	0.332	0.909	0.329	1.162
5/27/68 21:00	4.497	4	30	0.343	0.866	0.341	1.111
3/2/69 7:00	4.482	4	31	0.355	0.825	0.352	1.062
10/14/77 10:00	4.821	4	32	0.366	0.784	0.364	1.015
11/17/94 9:00	4.455	4	33	0.378	0.745	0.376	0.971
10/19/97 12:00	4.626	4	34	0.390	0.706	0.387	0.928
1/25/00 12:00	4.558	4	35	0.401	0.667	0.399	0.887
10/10/13 1:00	4.354	4	36	0.413	0.630	0.410	0.848
9/22/29 11:00	4.281	3	37	0.425	0.593	0.422	0.810
11/29/32 10:00	4.436	3	38	0.436	0.557	0.433	0.774
5/30/38 22:00	4.245	3	39	0.448	0.521	0.445	0.740
1/24/40 8:00	4.897	3	40	0.459	0.486	0.457	0.707
9/30/43 10:00	4.370	3	41	0.471	0.451	0.468	0.675
1/17/46 9:00	4.627	3	42	0.483	0.417	0.480	0.644
11/1/47 11:00	4.481	3	43	0.494	0.383	0.491	0.614
8/12/55 16:00	4.292	3	44	0.506	0.350	0.503	0.586
1/16/65 21:00	4.342	3	45	0.517	0.317	0.514	0.558
9/16/67 19:00	4.312	3	46	0.529	0.284	0.526	0.532
3/26/71 21:00	4.551	3	47	0.541	0.251	0.537	0.506
11/14/81 11:00	4.191	3	48	0.552	0.219	0.549	0.482
1/28/83 9:00	4.311	3	49	0.564	0.187	0.561	0.458
8/17/86 20:00	4.618	3	50	0.575	0.155	0.572	0.435
1/1/87 22:00	4.721	3	51	0.587	0.123	0.584	0.413
2/6/10 3:00	4.674	3	52	0.599	0.091	0.595	0.392
8/22/30 20:00	4.666	2	53	0.610	0.059	0.607	0.371
11/17/35 13:00	4.191	2	54	0.622	0.028	0.618	0.351
5/11/49 20:00	4.280	2	55	0.634	-0.004	0.630	0.332
1/23/54 0:00	4.107	2	56	0.645	-0.035	0.642	0.313
11/2/85 11:00	4.131	2	57	0.657	-0.067	0.653	0.296
1/10/93 10:00	4.152	2	58	0.668	-0.099	0.665	0.278
10/8/96 19:00	4.212	2	59	0.680	-0.130	0.676	0.262
2/27/52 10:00	4.137	1	60	0.692	-0.162	0.688	0.246
9/15/63 20:00	4.070	1	61	0.703	-0.195	0.699	0.230
10/27/70 7:00	4.067	1	62	0.715	-0.227	0.711	0.215
9/21/72 7:00	4.496	1	63	0.726	-0.259	0.722	0.201
12/1/74 10:00	4.177	1	64	0.738	-0.292	0.734	0.187
5/6/05 20:00	4.008	1	65	0.750	-0.326	0.746	0.174
3/22/31 23:00	3.949	0	66	0.761	-0.359	0.757	0.161
3/20/34 12:00	3.503	0	67	0.773	-0.394	0.769	0.148
8/28/39 20:00	3.916	0	68	0.784	-0.428	0.780	0.136
1/12/41 8:00	3.199	0	69	0.796	-0.464	0.792	0.125
9/14/44 12:00	3.656	0	70	0.808	-0.500	0.803	0.114
9/6/50 16:00	2.566	0	71	0.819	-0.537	0.815	0.104
4/12/59 23:00	3.631	0	72	0.831	-0.575	0.827	0.094
1/27/66 0:00	3.927	0	73	0.843	-0.614	0.838	0.084
11/24/75 13:00	3.660	0	74	0.854	-0.655	0.850	0.075
3/10/76 3:00	3.285	0	75	0.866	-0.697	0.861	0.066
9/24/79 11:00	3.660	0	76	0.877	-0.741	0.873	0.058
1/5/80 12:00	3.546	0	77	0.889	-0.788	0.884	0.050
10/14/84 12:00	3.794	0	78	0.901	-0.837	0.896	0.043
2/24/89 11:00	3.870	0	79	0.912	-0.889	0.908	0.036
10/26/90 2:00	3.895	0	80	0.924	-0.946	0.919	0.029
8/7/95 18:00	3.751	0	81	0.935	-1.008	0.931	0.023
9/30/01 20:00	3.887	0	82	0.947	-1.078	0.942	0.018
10/16/02 5:00	3.748	0	83	0.959	-1.159	0.954	0.013
9/19/04 12:00	3.550	0	84	0.970	-1.257	0.965	0.008
11/3/07 4:00	3.735	0	85	0.982	-1.389	0.977	0.005
11/1/14 16:00	3.922	0	86	0.993	-1.617	0.988	0.002
	N (Events) =	86					



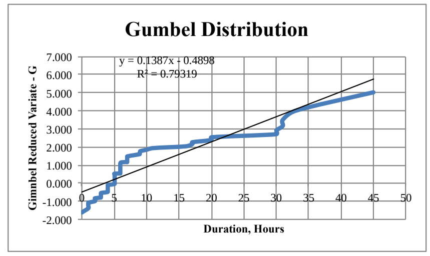
Yrs of Rec	86	**Gumbel Distribution Analysis for Duration by Return Period DTR (Hrs) = γ - β*ln(ln{λTR/(λTR-1)})**					
N (Events) =	86						
TR, %		99	50	25	10	1	0.2
TR, Years		1.01	2	4	10	100	500
λ = N/YofR	1.00						
A = 1/β	0.2126						
B = -γ/β	-0.3061						
β = 1/A	4.70						
γ = -β*B	1.44						
α =	N/A						
D_{TR}		-6	3	7	12	23	31



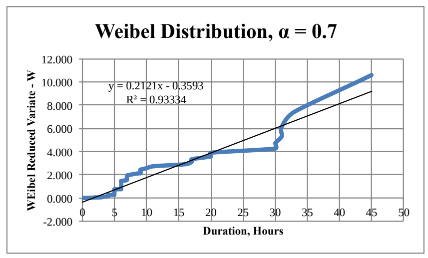
Yrs of Rec	86	**Weibel Distribution Analysis for Duration by Return Period DTR = γ + β*LN(λ*TR)^(1/α)**					
N (Events) =	86						
TR, %		99	50	10	4	1	0.2
TR, Years		1	2	10	25	100	500
λ = N/YofR	1.00						
A = 1/β	0.3209						
B = -γ/β	-0.0609						
β = 1/A	3.12						
γ = -β*B	0.19						
α =	0.7						
D_{TR}		0	3	10	15	21	28

Yrs of Rec	86	**Inverse of the Return Periods for the Weibull Analysis for 5, 6, 12, 24, 48 and 72 hours, T_R, %**					
N (Events) =	86						
TR, %		37.9	30.30	7.87	0.532	0.002	0.000
TR, Years		2.64	3.30	12.7	188.00	41300	1.00E+07
λ = N/YofR	1.00						
A = 1/β	0.3209						
B = -γ/β	-0.0609						
β = 1/A	3.12						
γ = -β*B	0.19						
α =	0.7						
D_{TR}		5	6	12	24	48	72

Sheet 4 - Current Year+SLR = 1.0 Ft.				Q, Gumbel		Q, Weibel	
				C1 =	0.440	C1 =	0.523
Event Adjusted to 2014 + SLR = +1.0 ft				C2 =	0.120	C2 =	0.475
	Event	Duration				α =	0.7
Date Time	Elevation	Hours	i	Q	G	Q	W
11/12/09 18:00	7.138	45	1	0.007	5.032	0.006	10.539
2/5/98 4:00	6.197	33	2	0.018	4.002	0.017	7.427
3/7/62 10:00	7.387	31	3	0.030	3.501	0.029	6.117
10/29/12 8:00	6.178	31	4	0.041	3.165	0.040	5.300
9/27/56 2:00	6.174	30	5	0.053	2.911	0.052	4.715
4/27/78 0:00	6.337	30	6	0.065	2.707	0.063	4.263
9/16/33 18:00	6.719	20	7	0.076	2.535	0.075	3.898
10/21/58 18:00	5.547	20	8	0.088	2.387	0.086	3.593
9/13/64 16:00	5.657	17	9	0.099	2.257	0.098	3.333
10/25/82 4:00	5.775	17	10	0.111	2.140	0.110	3.106
9/1/06 14:00	5.021	16	11	0.123	2.034	0.121	2.907
9/18/03 16:00	7.441	11	12	0.134	1.937	0.133	2.729
9/18/36 10:00	7.274	10	13	0.146	1.847	0.144	2.569
8/12/55 16:00	4.792	9	14	0.157	1.764	0.156	2.425
10/8/96 19:00	4.712	9	15	0.169	1.686	0.167	2.292
8/27/11 19:00	6.970	9	16	0.181	1.613	0.179	2.171
9/19/28 0:00	5.996	8	17	0.192	1.544	0.191	2.059
10/5/48 11:00	5.756	7	18	0.204	1.478	0.202	1.955
10/6/57 8:00	5.861	7	19	0.216	1.416	0.214	1.859
2/11/73 3:00	5.122	7	20	0.227	1.356	0.225	1.769
4/13/88 7:00	5.366	7	21	0.239	1.299	0.237	1.684
10/31/91 16:00	5.029	7	22	0.250	1.244	0.248	1.605
9/25/08 18:00	5.283	7	23	0.262	1.192	0.260	1.531
11/17/35 3:00	4.589	6	24	0.274	1.141	0.271	1.461
1/29/37 10:00	4.959	6	25	0.285	1.091	0.283	1.395
1/24/40 8:00	5.397	6	26	0.297	1.044	0.295	1.332
12/5/45 9:00	5.142	6	27	0.308	0.998	0.306	1.272
8/14/53 10:00	4.622	6	28	0.320	0.953	0.318	1.216
10/21/61 19:00	5.302	6	29	0.332	0.909	0.329	1.162
5/27/68 21:00	4.997	6	30	0.343	0.866	0.341	1.111
3/2/69 7:00	4.982	6	31	0.355	0.825	0.352	1.062
2/11/83 9:00	4.782	6	32	0.366	0.784	0.364	1.015
3/10/87 5:00	4.541	6	33	0.378	0.745	0.376	0.971
10/26/90 2:00	4.395	6	34	0.390	0.706	0.387	0.928
10/19/97 12:00	5.126	6	35	0.401	0.667	0.399	0.887
8/30/99 12:00	5.201	6	36	0.413	0.630	0.410	0.848
1/25/00 12:00	5.058	6	37	0.425	0.593	0.422	0.810
10/10/13 1:00	4.854	6	38	0.436	0.557	0.433	0.774
9/22/29 11:00	4.781	5	39	0.448	0.521	0.445	0.740
11/29/32 10:00	4.936	5	40	0.459	0.486	0.457	0.707
5/30/38 22:00	4.745	5	41	0.471	0.451	0.468	0.675
8/28/39 20:00	4.412	5	42	0.483	0.417	0.480	0.644
9/30/43 10:00	4.870	5	43	0.494	0.383	0.491	0.614
1/17/46 9:00	5.127	5	44	0.506	0.350	0.503	0.586
11/1/47 11:00	4.981	5	45	0.517	0.317	0.514	0.558
10/4/51 11:00	5.052	5	46	0.529	0.284	0.526	0.532
1/23/54 0:00	4.607	5	47	0.541	0.251	0.537	0.506
9/12/60 6:00	5.816	5	48	0.552	0.219	0.549	0.482
1/16/65 21:00	4.842	5	49	0.564	0.187	0.561	0.458
9/16/67 19:00	4.812	5	50	0.575	0.155	0.572	0.435
10/27/70 7:00	4.567	5	51	0.587	0.123	0.584	0.413
3/26/71 21:00	5.051	5	52	0.599	0.091	0.595	0.392
10/14/77 10:00	5.321	5	53	0.610	0.059	0.607	0.371
11/14/81 11:00	4.691	5	54	0.622	0.028	0.618	0.351
8/17/86 20:00	5.118	5	55	0.634	-0.004	0.630	0.332
9/25/92 8:00	5.267	5	56	0.645	-0.035	0.642	0.313
11/17/94 9:00	4.955	5	57	0.657	-0.067	0.653	0.296
8/22/30 20:00	5.166	4	58	0.668	-0.099	0.665	0.278
3/22/31 23:00	4.449	4	59	0.680	-0.130	0.676	0.262
9/30/44 20:00	4.455	4	60	0.692	-0.162	0.688	0.246
5/11/49 20:00	4.780	4	61	0.703	-0.195	0.699	0.230
2/27/52 10:00	4.637	4	62	0.715	-0.227	0.711	0.215
1/27/66 0:00	4.427	4	63	0.726	-0.259	0.722	0.201
9/21/72 7:00	4.996	4	64	0.738	-0.292	0.734	0.187
12/1/74 10:00	4.677	4	65	0.750	-0.326	0.746	0.174
11/2/85 11:00	4.631	4	66	0.761	-0.359	0.757	0.161
1/10/93 10:00	4.652	4	67	0.773	-0.394	0.769	0.148
11/3/07 4:00	4.235	4	68	0.784	-0.428	0.780	0.136
2/6/10 3:00	5.174	4	69	0.796	-0.464	0.792	0.125
11/1/14 16:00	4.422	4	70	0.808	-0.500	0.803	0.114
9/12/50 21:00	4.266	3	71	0.819	-0.537	0.815	0.104
9/15/63 20:00	4.570	3	72	0.831	-0.575	0.827	0.094
10/14/84 12:00	4.294	3	73	0.843	-0.614	0.838	0.084
9/19/89 11:00	4.321	3	74	0.854	-0.655	0.850	0.075
9/30/01 20:00	4.387	3	75	0.866	-0.697	0.861	0.066
10/16/02 5:00	4.248	3	76	0.877	-0.741	0.873	0.058
5/6/05 20:00	4.508	3	77	0.889	-0.788	0.884	0.050
4/12/59 23:00	4.131	2	78	0.901	-0.837	0.896	0.043
9/24/79 11:00	4.160	2	79	0.912	-0.889	0.908	0.036
1/5/80 12:00	4.046	2	80	0.924	-0.946	0.919	0.029
8/7/95 18:00	4.251	2	81	0.935	-1.008	0.931	0.023
3/20/34 12:00	4.003	1	82	0.947	-1.078	0.942	0.018
1/28/41 10:00	4.001	1	83	0.959	-1.159	0.954	0.013
11/24/75 13:00	4.160	1	84	0.970	-1.257	0.965	0.008
9/19/04 12:00	4.050	1	85	0.982	-1.389	0.977	0.005
3/10/76 3:00	3.785	0	86	0.993	-1.617	0.988	0.002
	N (Events) =	86					



Yrs of Rec	86	Gumbel Distribution Analysis for Duration by Return Period					
N (Events) =	86	DTR (Hrs) = γ - β*ln(ln{λTR/(λTR-1)})					
TR, %		99	50	25	10	1	0.2
TR, Years		1.01	2	4	10	100	500
λ = N/YofR	1.00						
A = 1/β	0.1387						
B = -γ/β	-0.4898						
β = 1/A	7.21						
γ = -β*B	3.53						
α =	N/A						
D_{TR}		-7	6	13	20	37	48



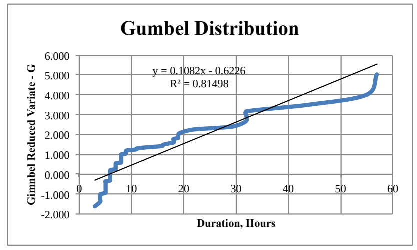
Yrs of Rec	86	Weibel Distribution Analysis for Duration by Return Period					
N (Events) =	86	DTR = γ + β*LN(λ*TR)^(1/α)					
TR, %		99	50	10	4	1	0.2
TR, Years		1	2	10	25	100	500
λ = N/YofR	1.00						
A = 1/β	0.2121						
B = -γ/β	-0.3593						
β = 1/A	4.71						
γ = -β*B	1.69						
α =	0.7						
D_{TR}		2	6	17	23	33	44

Yrs of Rec	86	**Inverse of the Return Periods for the Weibull Analysis for 5, 6, 12, 24, 48 and 72 hours, T_R, %**					
N (Events) =	86						
TR, %		65.8	56.82	23.31	3.922	0.111	0.003
TR, Years		1.52	1.76	4.29	25.5	899	31800
λ = N/YofR	1.00						
A = 1/β	0.2121						
B = -γ/β	-0.3593						
β = 1/A	4.71						
γ = -β*B	1.69						
α =	0.7						
D_{TR}		5	6	12	24	48	72

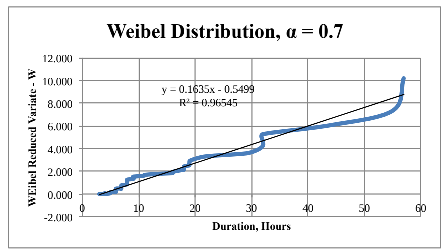
Sheet 5 - Current Year+SLR = 1.5 Ft.

Event Adjusted to 2014 + SLR = +1.5 ft

				Q, Gumbel		**Q, Weibel**	
				C1 =	0.440	C1 =	0.470
				C2 =	0.120	C2 =	0.430
	Event	**Duration**				α =	0.7
Date Time	**Elevation**	**Hours**	**i**	Q	G	Q	W
11/12/09 18:00	7.638	57	1	0.007	5.032	0.006	10.236
2/5/98 4:00	6.697	55	2	0.018	4.002	0.018	7.334
3/7/62 10:00	7.887	44	3	0.030	3.501	0.029	6.064
9/27/56 2:00	6.674	32	4	0.041	3.165	0.041	5.263
4/27/78 0:00	6.837	32	5	0.053	2.911	0.052	4.687
10/29/12 8:00	6.678	32	6	0.065	2.707	0.064	4.241
10/21/58 18:00	6.047	31	7	0.076	2.535	0.076	3.879
10/25/82 4:00	6.275	29	8	0.088	2.387	0.087	3.577
9/16/33 18:00	7.219	22	9	0.099	2.257	0.099	3.319
10/7/06 9:00	6.502	20	10	0.111	2.140	0.110	3.094
11/17/35 13:00	5.191	19	11	0.123	2.034	0.122	2.896
9/13/64 16:00	6.157	19	12	0.134	1.937	0.133	2.719
4/13/88 7:00	5.866	19	13	0.146	1.847	0.145	2.561
9/18/36 10:00	7.774	18	14	0.157	1.764	0.157	2.416
3/2/69 7:00	5.482	18	15	0.169	1.686	0.168	2.285
8/27/11 19:00	7.470	18	16	0.181	1.613	0.180	2.164
10/8/96 19:00	5.212	17	17	0.192	1.544	0.191	2.052
10/26/90 2:00	4.895	16	18	0.204	1.478	0.203	1.949
1/25/00 12:00	5.558	16	19	0.216	1.416	0.214	1.853
9/18/03 16:00	7.941	13	20	0.227	1.356	0.226	1.763
9/19/28 0:00	6.496	11	21	0.239	1.299	0.238	1.679
8/12/55 16:00	5.292	11	22	0.250	1.244	0.249	1.601
1/29/37 10:00	5.459	9	23	0.262	1.192	0.261	1.526
8/14/53 10:00	5.122	9	24	0.274	1.141	0.272	1.456
3/10/87 5:00	5.041	9	25	0.285	1.091	0.284	1.390
10/31/91 16:00	5.529	9	26	0.297	1.044	0.295	1.328
12/5/45 9:00	5.642	8	27	0.308	0.998	0.307	1.268
10/5/48 11:00	6.256	8	28	0.320	0.953	0.319	1.212
10/6/57 8:00	6.361	8	29	0.332	0.909	0.330	1.158
5/27/68 21:00	5.497	8	30	0.343	0.866	0.342	1.107
4/6/71 17:00	4.852	8	31	0.355	0.825	0.353	1.059
2/11/73 3:00	5.622	8	32	0.366	0.784	0.365	1.012
2/11/83 9:00	5.282	8	33	0.378	0.745	0.376	0.968
11/4/85 16:00	4.760	8	34	0.390	0.706	0.388	0.925
8/30/99 12:00	5.701	8	35	0.401	0.667	0.400	0.884
9/25/08 18:00	5.783	8	36	0.413	0.630	0.411	0.845
10/10/13 1:00	5.354	8	37	0.425	0.593	0.423	0.808
9/22/29 11:00	5.281	7	38	0.436	0.557	0.434	0.772
1/24/40 8:00	5.897	7	39	0.448	0.521	0.446	0.737
9/30/43 10:00	5.370	7	40	0.459	0.486	0.457	0.704
11/1/47 11:00	5.481	7	41	0.471	0.451	0.469	0.672
10/4/51 11:00	5.552	7	42	0.483	0.417	0.481	0.642
1/23/54 0:00	5.107	7	43	0.494	0.383	0.492	0.612
10/22/61 8:00	5.500	7	44	0.506	0.350	0.504	0.584
9/25/92 8:00	5.767	7	45	0.517	0.317	0.515	0.556
11/17/94 9:00	5.455	7	46	0.529	0.284	0.527	0.530
10/19/97 12:00	5.626	7	47	0.541	0.251	0.538	0.504
8/22/31 17:00	8.198	6	48	0.552	0.219	0.550	0.480
9/9/32 17:00	4.835	6	49	0.564	0.187	0.561	0.456
8/28/39 20:00	4.912	6	50	0.575	0.155	0.573	0.433
3/19/46 23:00	5.125	6	51	0.587	0.123	0.585	0.411
5/11/49 20:00	5.280	6	52	0.599	0.091	0.596	0.390
9/12/60 6:00	6.316	6	53	0.610	0.059	0.608	0.369
1/16/65 21:00	5.342	6	54	0.622	0.028	0.619	0.350
1/27/66 0:00	4.927	6	55	0.634	-0.004	0.631	0.330
9/16/67 19:00	5.312	6	56	0.645	-0.035	0.642	0.312
10/27/70 7:00	5.067	6	57	0.657	-0.067	0.654	0.294
9/21/72 7:00	5.496	6	58	0.668	-0.099	0.666	0.277
10/14/77 10:00	5.821	6	59	0.680	-0.130	0.677	0.260
8/20/81 12:00	5.230	6	60	0.692	-0.162	0.689	0.244
8/17/86 20:00	5.618	6	61	0.703	-0.195	0.700	0.229
10/25/05 3:00	4.850	6	62	0.715	-0.227	0.712	0.214
11/3/07 4:00	4.735	6	63	0.726	-0.259	0.723	0.200
2/6/10 3:00	5.674	6	64	0.738	-0.292	0.735	0.186
11/1/14 16:00	4.922	6	65	0.750	-0.326	0.747	0.172
8/22/30 20:00	5.666	5	66	0.761	-0.359	0.758	0.160
5/30/38 22:00	5.245	5	67	0.773	-0.394	0.770	0.147
9/30/44 20:00	4.955	5	68	0.784	-0.428	0.781	0.135
9/12/50 21:00	4.766	5	69	0.796	-0.464	0.793	0.124
2/27/52 10:00	5.137	5	70	0.808	-0.500	0.804	0.113
4/12/59 23:00	4.631	5	71	0.819	-0.537	0.816	0.103
9/15/63 20:00	5.070	5	72	0.831	-0.575	0.828	0.093
12/1/74 10:00	5.177	5	73	0.843	-0.614	0.839	0.083
11/24/75 13:00	4.660	5	74	0.854	-0.655	0.851	0.074
9/24/79 11:00	4.660	5	75	0.866	-0.697	0.862	0.065
10/14/84 12:00	4.794	5	76	0.877	-0.741	0.874	0.057
9/19/89 11:00	4.821	5	77	0.889	-0.788	0.885	0.049
1/10/93 10:00	5.152	5	78	0.901	-0.837	0.897	0.042
8/19/95 16:00	4.521	5	79	0.912	-0.889	0.909	0.035
9/30/01 20:00	4.887	5	80	0.924	-0.946	0.920	0.029
3/20/34 12:00	4.503	4	81	0.935	-1.008	0.932	0.023
3/10/76 3:00	4.285	4	82	0.947	-1.078	0.943	0.017
8/22/80 17:00	4.415	4	83	0.959	-1.159	0.955	0.012
10/16/02 5:00	4.748	4	84	0.970	-1.257	0.966	0.008
9/19/04 12:00	4.550	4	85	0.982	-1.389	0.978	0.004
1/28/41 10:00	4.501	3	86	0.993	-1.617	0.990	0.001
	N (Events) =	86					



Yrs of Rec	86	**Gumbel Distribution Analysis for Duration by Return Period DTR (Hrs) = γ - β*ln(ln{λTR/(λTR-1)})**					
N (Events) =	86						
TR, %		99	50	25	10	1	0.2
TR, Years		1.01	2	4	10	100	500
λ = N/YofR	1.00						
A = 1/β	0.1082						
B = -γ/β	-0.6226						
β = 1/A	9.24						
γ = -β*B	5.75						
α =	N/A						
D_{TR}		-8	9	17	27	48	63



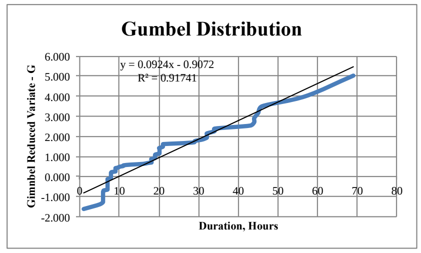
Yrs of Rec	86	**Weibel Distribution Analysis for Duration by Return Period DTR = γ + β*LN(λ*TR)^(1/α)**					
N (Events) =	86						
TR, %		99	50	10	4	1	0.2
TR, Years		1	2	10	25	100	500
λ = N/YofR	1.00						
A = 1/β	0.1635						
B = -γ/β	-0.5499						
β = 1/A	6.12						
γ = -β*B	3.36						
α =	0.7						
D_{TR}		3	9	23	31	44	58

Yrs of Rec	86	**Inverse of the Return Periods for the Weibull Analysis for 5, 6, 12, 24, 48 and 72 hours, T_R, %**					
N (Events) =	86						
TR, %		87.7	78.1	39.4	9.9	0.64	0.04
TR, Years		1.14	1.28	2.54	10.1	157.0	2440.0
λ = N/YofR	1.00						
A = 1/β	0.1635						
B = -γ/β	-0.5499						
β = 1/A	6.12						
γ = -β*B	3.36						
α =	0.7						
D_{TR}		5	6	12	24	48	72

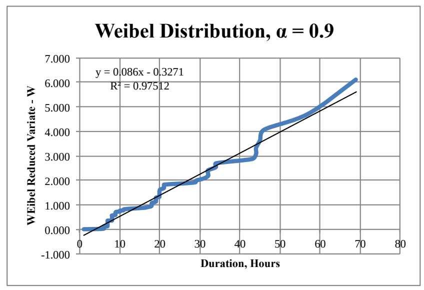
Sheet 6 - Current+SLR = 2.0 Ft.

Event Adjusted to 2014 + SLR = +2.0 ft

				Q, Gumbel		**Q, Weibel**	
				C1 =	0.440	C1 =	0.470
				C2 =	0.120	C2 =	0.430
	Event	**Duration**				α =	0.9
Date Time	**Elevation**	**Hours**	**i**	Q	G	Q	W
11/12/09 18:00	8.138	69	1	0.007	5.032	0.006	6.104
2/5/98 4:00	7.197	57	2	0.018	4.002	0.018	4.710
8/30/99 12:00	6.201	46	3	0.030	3.501	0.029	4.062
10/21/58 18:00	6.547	45	4	0.041	3.165	0.041	3.639
9/27/56 2:00	7.174	44	5	0.053	2.911	0.052	3.325
3/7/62 10:00	8.387	44	6	0.065	2.707	0.064	3.076
4/27/78 0:00	7.337	43	7	0.076	2.535	0.076	2.870
9/16/33 18:00	7.719	34	8	0.088	2.387	0.087	2.695
10/29/12 8:00	7.178	34	9	0.099	2.257	0.099	2.542
10/25/82 4:00	6.775	32	10	0.111	2.140	0.110	2.407
4/13/88 7:00	6.366	32	11	0.123	2.034	0.122	2.287
10/7/06 9:00	7.002	32	12	0.134	1.937	0.133	2.177
4/10/03 15:00	5.515	31	13	0.146	1.847	0.145	2.078
12/5/45 9:00	6.142	29	14	0.157	1.764	0.157	1.986
5/27/68 21:00	5.997	29	15	0.169	1.686	0.168	1.901
9/19/28 0:00	6.996	21	16	0.181	1.613	0.180	1.823
9/13/64 16:00	6.657	21	17	0.192	1.544	0.191	1.749
9/25/08 18:00	6.283	21	18	0.204	1.478	0.203	1.680
9/18/36 10:00	8.274	20	19	0.216	1.416	0.214	1.616
10/6/57 8:00	6.861	20	20	0.227	1.356	0.226	1.554
3/2/69 7:00	5.982	20	21	0.239	1.299	0.238	1.497
3/10/87 5:00	5.541	20	22	0.250	1.244	0.249	1.442
2/6/10 3:00	6.174	20	23	0.262	1.192	0.261	1.389
10/10/13 1:00	5.854	20	24	0.274	1.141	0.272	1.340
11/17/35 13:00	5.691	19	25	0.285	1.091	0.284	1.292
11/6/53 9:00	5.622	19	26	0.297	1.044	0.295	1.247
10/5/92 16:00	4.827	19	27	0.308	0.998	0.307	1.203
11/17/94 9:00	5.955	19	28	0.320	0.953	0.319	1.161
8/27/11 19:00	7.970	19	29	0.332	0.909	0.330	1.121
1/29/37 10:00	5.959	18	30	0.343	0.866	0.342	1.082
2/11/83 9:00	5.782	18	31	0.355	0.825	0.353	1.045
10/26/90 2:00	5.395	18	32	0.366	0.784	0.365	1.009
10/8/96 19:00	5.712	18	33	0.378	0.745	0.376	0.975
4/16/05 2:00	4.760	18	34	0.390	0.706	0.388	0.941
1/25/00 12:00	6.058	17	35	0.401	0.667	0.400	0.909
4/6/71 17:00	5.352	16	36	0.413	0.630	0.411	0.877
8/12/55 16:00	5.792	13	37	0.425	0.593	0.423	0.847
1/24/40 8:00	6.397	11	38	0.436	0.557	0.434	0.818
10/31/91 16:00	6.029	11	39	0.448	0.521	0.446	0.789
1/23/54 0:00	5.607	10	40	0.459	0.486	0.457	0.761
11/4/85 16:00	5.260	10	41	0.471	0.451	0.469	0.734
9/22/29 11:00	5.781	9	42	0.483	0.417	0.481	0.708
9/30/43 10:00	5.870	9	43	0.494	0.383	0.492	0.683
10/5/48 11:00	6.756	9	44	0.506	0.350	0.504	0.658
10/4/51 11:00	6.052	9	45	0.517	0.317	0.515	0.634
10/22/61 8:00	6.000	9	46	0.529	0.284	0.527	0.610
1/27/66 0:00	5.427	9	47	0.541	0.251	0.538	0.587
8/22/31 17:00	8.698	8	48	0.552	0.219	0.550	0.565
8/28/39 20:00	5.412	8	49	0.564	0.187	0.561	0.543
9/14/44 12:00	5.156	8	50	0.575	0.155	0.573	0.522
10/16/49 16:00	5.081	8	51	0.587	0.123	0.585	0.501
9/16/67 19:00	5.812	8	52	0.599	0.091	0.596	0.481
10/27/70 19:00	5.465	8	53	0.610	0.059	0.608	0.461
12/1/74 10:00	5.677	8	54	0.622	0.028	0.619	0.441
8/20/81 12:00	5.730	8	55	0.634	-0.004	0.631	0.423
8/19/95 16:00	5.021	8	56	0.645	-0.035	0.642	0.404
10/19/97 12:00	6.126	8	57	0.657	-0.067	0.654	0.386
11/3/07 4:00	5.235	8	58	0.668	-0.099	0.666	0.368
8/22/30 20:00	6.166	7	59	0.680	-0.130	0.677	0.351
9/9/32 17:00	5.335	7	60	0.692	-0.162	0.689	0.334
5/30/38 22:00	5.745	7	61	0.703	-0.195	0.700	0.318
3/19/46 23:00	5.625	7	62	0.715	-0.227	0.712	0.301
11/1/47 11:00	5.981	7	63	0.726	-0.259	0.723	0.286
4/12/59 23:00	5.131	7	64	0.738	-0.292	0.735	0.270
9/12/60 6:00	6.816	7	65	0.750	-0.326	0.747	0.255
9/15/63 20:00	5.570	7	66	0.761	-0.359	0.758	0.240
1/16/65 21:00	5.842	7	67	0.773	-0.394	0.770	0.225
9/21/72 7:00	5.996	7	68	0.784	-0.428	0.781	0.211
10/14/77 10:00	6.321	7	69	0.796	-0.464	0.793	0.197
10/14/84 12:00	5.294	7	70	0.808	-0.500	0.804	0.184
8/17/86 20:00	6.118	7	71	0.819	-0.537	0.816	0.170
1/10/93 10:00	5.652	7	72	0.831	-0.575	0.828	0.157
9/30/01 20:00	5.387	7	73	0.843	-0.614	0.839	0.144
11/1/14 16:00	5.422	7	74	0.854	-0.655	0.851	0.132
3/20/34 12:00	5.003	6	75	0.866	-0.697	0.862	0.120
9/12/50 21:00	5.266	6	76	0.877	-0.741	0.874	0.108
2/27/52 10:00	5.637	6	77	0.889	-0.788	0.885	0.096
11/24/75 13:00	5.160	6	78	0.901	-0.837	0.897	0.085
3/10/76 3:00	4.785	6	79	0.912	-0.889	0.909	0.074
9/24/79 11:00	5.160	6	80	0.924	-0.946	0.920	0.063
8/22/80 17:00	4.915	6	81	0.935	-1.008	0.932	0.053
9/19/89 11:00	5.321	6	82	0.947	-1.078	0.943	0.043
10/16/02 5:00	5.248	6	83	0.959	-1.159	0.955	0.033
9/19/04 12:00	5.050	6	84	0.970	-1.257	0.966	0.023
1/28/41 10:00	5.001	5	85	0.982	-1.389	0.978	0.015
2/11/73 3:00	6.122	1	86	0.993	-1.617	0.990	0.006
	N (Events) =	86					



Yrs of Rec	86	**Gumbel Distribution Analysis for Duration by Return Period**					
N (Events) =	86	**DTR (Hrs) = γ - β*ln(ln{λTR/(λTR-1)})**					
TR, %		99	50	25	10	1	0.2
TR, Years		1.01	2	4	10	100	500
λ = N/YofR	1.00						
A = 1/β	0.0924						
B = -γ/β	-0.9072						
β = 1/A	10.82						
γ = -β*B	9.82						
α =	N/A						
D_{TR}		-7	14	23	34	60	77



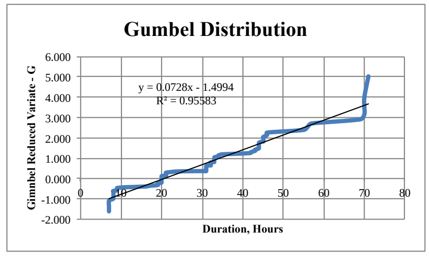
Yrs of Rec	86	**Weibel Distribution Analysis for Duration by Return Period**					
N (Events) =	86	**DTR = γ + β*LN(λ*TR)^(1/α)**					
TR, %		99	50	10	4	1	0.2
TR, Years		1	2	10	25	100	500
λ = N/YofR	1.00						
A = 1/β	0.086						
B = -γ/β	-0.3271						
β = 1/A	11.63						
γ = -β*B	3.80						
α =	0.9						
D_{TR}		4	13	34	45	63	84

Yrs of Rec	86	**Inverse of the Return Periods for the Weibull Analysis for 5, 6, 12, 24, 48 and 72 hours, T_R, %**					
N (Events) =	86						
TR, %		94.3	87.0	54.9	21.7	3.4	0.5
TR, Years		1.06	1.15	1.82	4.60	29.5	189.00
λ = N/YofR	1.00						
A = 1/β	0.086						
B = -γ/β	-0.3271						
β = 1/A	11.63						
γ = -β*B	3.80						
α =	0.9						
D_{TR}		5	6	12	24	48	72

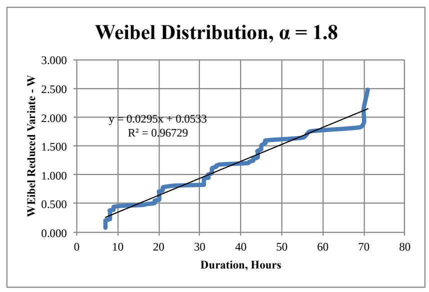
Sheet 7 - Current Year+SLR = 2.5 Ft.

Event Adjusted to 2014 + SLR = +2.5 ft

				Q, Gumbel		**Q, Weibel**	
				C1 =	0.440	C1 =	0.470
				C2 =	0.120	C2 =	0.430
	Event	**Duration**				α =	1.8
Date Time	**Elevation**	**Hours**	**i**	Q	G	Q	W
11/12/09 18:00	8.638	71	1	0.007	5.032	0.006	2.471
10/21/58 18:00	7.047	70	2	0.018	4.002	0.018	2.170
2/5/98 4:00	7.697	70	3	0.030	3.501	0.029	2.016
8/30/99 12:00	6.701	70	4	0.041	3.165	0.041	1.908
11/2/85 11:00	6.131	69	5	0.053	2.911	0.052	1.823
3/7/62 10:00	8.887	57	6	0.065	2.707	0.064	1.754
9/25/08 18:00	6.783	56	7	0.076	2.535	0.076	1.694
12/5/45 9:00	6.642	55	8	0.088	2.387	0.087	1.642
9/27/56 2:00	7.674	46	9	0.099	2.257	0.099	1.594
10/29/12 8:00	7.678	46	10	0.111	2.140	0.110	1.552
9/16/33 18:00	8.219	45	11	0.123	2.034	0.122	1.512
4/27/78 0:00	7.837	45	12	0.134	1.937	0.133	1.476
11/22/06 10:00	7.663	45	13	0.146	1.847	0.145	1.441
11/20/39 16:00	5.610	44	14	0.157	1.764	0.157	1.409
10/27/70 7:00	6.067	44	15	0.169	1.686	0.168	1.379
10/25/82 4:00	7.275	44	16	0.181	1.613	0.180	1.350
10/14/84 12:00	5.794	44	17	0.192	1.544	0.191	1.323
10/31/91 16:00	6.529	44	18	0.204	1.478	0.203	1.296
9/13/64 16:00	7.157	43	19	0.216	1.416	0.214	1.271
9/30/01 20:00	5.887	43	20	0.227	1.356	0.226	1.247
9/5/00 14:00	5.758	42	21	0.239	1.299	0.238	1.223
4/16/05 2:00	5.260	42	22	0.250	1.244	0.249	1.201
3/10/87 5:00	6.041	35	23	0.262	1.192	0.261	1.179
11/2/47 11:00	6.481	34	24	0.274	1.141	0.272	1.157
4/13/88 7:00	6.866	34	25	0.285	1.091	0.284	1.137
10/26/43 7:00	5.871	33	26	0.297	1.044	0.295	1.117
10/21/61 19:00	6.802	33	27	0.308	0.998	0.307	1.097
5/26/72 20:00	5.935	33	28	0.320	0.953	0.319	1.078
12/19/77 5:00	5.811	33	29	0.332	0.909	0.330	1.059
4/10/03 15:00	6.015	33	30	0.343	0.866	0.342	1.040
10/10/13 1:00	6.354	33	31	0.355	0.825	0.353	1.022
10/6/57 8:00	7.361	32	32	0.366	0.784	0.365	1.005
10/19/71 9:00	6.052	32	33	0.378	0.745	0.376	0.987
8/19/95 16:00	5.521	32	34	0.390	0.706	0.388	0.970
2/6/10 3:00	6.674	32	35	0.401	0.667	0.400	0.953
9/19/28 0:00	7.496	31	36	0.413	0.630	0.411	0.937
10/4/51 11:00	6.552	31	37	0.425	0.593	0.423	0.920
5/27/68 21:00	6.497	31	38	0.436	0.557	0.434	0.904
2/11/73 3:00	6.622	31	39	0.448	0.521	0.446	0.888
10/26/90 2:00	5.895	31	40	0.459	0.486	0.457	0.872
10/5/92 16:00	5.327	31	41	0.471	0.451	0.469	0.857
11/17/94 9:00	6.455	31	42	0.483	0.417	0.481	0.841
11/3/07 4:00	5.735	31	43	0.494	0.383	0.492	0.826
8/12/55 16:00	6.292	24	44	0.506	0.350	0.504	0.811
3/2/69 7:00	6.482	22	45	0.517	0.317	0.515	0.796
11/17/35 13:00	6.191	21	46	0.529	0.284	0.527	0.781
3/19/46 23:00	6.125	21	47	0.541	0.251	0.538	0.766
9/29/83 15:00	5.780	21	48	0.552	0.219	0.550	0.752
10/16/02 5:00	5.748	21	49	0.564	0.187	0.561	0.737
8/27/11 19:00	8.470	21	50	0.575	0.155	0.573	0.722
8/22/31 17:00	8.798	20	51	0.587	0.123	0.585	0.708
9/18/36 10:00	8.774	20	52	0.599	0.091	0.596	0.693
1/29/37 10:00	6.459	20	53	0.610	0.059	0.608	0.679
10/5/48 11:00	7.256	20	54	0.622	0.028	0.619	0.664
1/23/54 0:00	6.107	20	55	0.634	-0.004	0.631	0.650
2/1/60 0:00	5.915	20	56	0.645	-0.035	0.642	0.636
1/16/65 21:00	6.342	20	57	0.657	-0.067	0.654	0.621
1/27/66 0:00	5.927	20	58	0.668	-0.099	0.666	0.607
9/16/67 19:00	6.312	20	59	0.680	-0.130	0.677	0.592
10/8/96 19:00	6.212	20	60	0.692	-0.162	0.689	0.578
10/19/97 12:00	6.626	20	61	0.703	-0.195	0.700	0.564
11/6/53 9:00	6.122	19	62	0.715	-0.227	0.712	0.549
11/24/75 13:00	5.660	19	63	0.726	-0.259	0.723	0.534
2/24/89 11:00	5.870	19	64	0.738	-0.292	0.735	0.520
9/19/04 12:00	5.550	19	65	0.750	-0.326	0.747	0.505
9/14/44 12:00	5.656	17	66	0.761	-0.359	0.758	0.490
1/24/40 8:00	6.897	16	67	0.773	-0.394	0.770	0.475
9/22/29 11:00	6.281	11	68	0.784	-0.428	0.781	0.460
11/27/32 8:00	6.334	9	69	0.796	-0.464	0.793	0.444
10/16/49 16:00	5.581	9	70	0.808	-0.500	0.804	0.429
4/12/59 23:00	5.631	9	71	0.819	-0.537	0.816	0.413
3/10/76 3:00	5.285	9	72	0.831	-0.575	0.828	0.397
8/22/30 20:00	6.666	8	73	0.843	-0.614	0.839	0.380
3/20/34 12:00	5.503	8	74	0.854	-0.655	0.851	0.363
5/30/38 22:00	6.245	8	75	0.866	-0.697	0.862	0.346
11/21/52 11:00	5.937	8	76	0.877	-0.741	0.874	0.328
9/15/63 20:00	6.070	8	77	0.889	-0.788	0.885	0.310
12/1/74 10:00	6.177	8	78	0.901	-0.837	0.897	0.291
8/20/81 12:00	6.230	8	79	0.912	-0.889	0.909	0.272
1/10/93 10:00	6.152	8	80	0.924	-0.946	0.920	0.251
11/1/14 16:00	5.922	8	81	0.935	-1.008	0.932	0.230
1/12/41 8:00	5.199	7	82	0.947	-1.078	0.943	0.206
9/12/50 21:00	5.766	7	83	0.959	-1.159	0.955	0.181
9/24/79 11:00	5.660	7	84	0.970	-1.257	0.966	0.153
8/22/80 17:00	5.415	7	85	0.982	-1.389	0.978	0.121
8/17/86 20:00	6.618	7	86	0.993	-1.617	0.990	0.079
	N (Events) =	86					



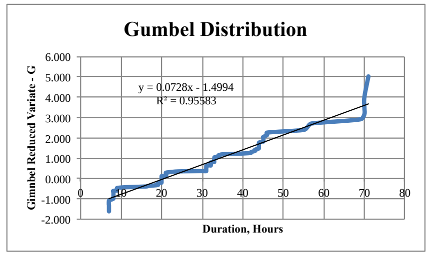
Yrs of Rec	86	**Gumbel Distribution Analysis for Duration by Return Period**					
N (Events) =	86	**DTR (Hrs) = γ - β*ln(ln{λTR/(λTR-1)})**					
TR, %		99	50	25	10	1	0.2
TR, Years		1.01	2	4	10	100	500
λ = N/YofR	1.00						
A = 1/β	0.0728						
B = -γ/β	-1.4994						
β = 1/A	13.74						
γ = -β*B	20.60						
α =	N/A						
D_{TR}		0	26	38	52	84	106



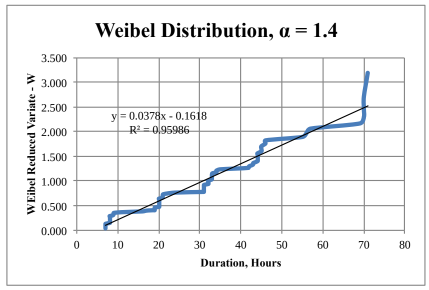
Yrs of Rec	86	**Weibel Distribution Analysis for Duration by Return Period**					
N (Events) =	86	**DTR = γ + β*LN(λ*TR)^(1/α)**					
TR, %		99	50	10	4	1	0.2
TR, Years		1	2	10	25	100	500
λ = N/YofR	1.00						
A = 1/β	0.0295						
B = -γ/β	0.0533						
β = 1/A	33.90						
γ = -β*B	-1.81						
α =	1.8						
D_{TR}		-2	11	42	59	85	115

Yrs of Rec	86	**Inverse of the Return Periods for the Weibull Analysis for 5, 6, 12, 24, 48 and 72 hours, T_R, %**					
N (Events) =	86						
TR, %		71.4	67.6	49.3	26.0	7.2	2.0
TR, Years		1.40	1.48	2.03	3.84	13.80	49.10
λ = N/YofR	1.00						
A = 1/β	0.0295						
B = -γ/β	0.0533						
β = 1/A	33.90						
γ = -β*B	-1.81						
α =	1.8						
D_{TR}		5	6	12	24	48	72

Sheet 8 - Current Year+SLR = 2.5 Ft. ADJUSTED				Q, Gumbel		Q, Weibel	
				C1 =	0.440	C1 =	0.470
Event Adjusted to 2014 + SLR = +2.5 ft				C2 =	0.120	C2 =	0.430
	Event	Duration				α =	1.4
Date Time	Elevation	Hours	i	Q	G	Q	W
11/12/09 18:00	8.638	71	1	0.007	5.032	0.006	3.199
10/21/58 18:00	7.047	70	2	0.018	4.002	0.018	2.708
2/5/98 4:00	7.697	70	3	0.030	3.501	0.029	2.462
8/30/99 12:00	6.701	70	4	0.041	3.165	0.041	2.294
11/2/85 11:00	6.131	69	5	0.053	2.911	0.052	2.165
3/7/62 10:00	8.887	57	6	0.065	2.707	0.064	2.059
9/25/08 18:00	6.783	56	7	0.076	2.535	0.076	1.970
12/5/45 9:00	6.642	55	8	0.088	2.387	0.087	1.891
9/27/56 2:00	7.674	46	9	0.099	2.257	0.099	1.822
10/29/12 8:00	7.678	46	10	0.111	2.140	0.110	1.759
9/16/33 18:00	8.219	45	11	0.123	2.034	0.122	1.702
4/27/78 0:00	7.837	45	12	0.134	1.937	0.133	1.649
11/22/06 10:00	7.663	45	13	0.146	1.847	0.145	1.600
11/20/39 16:00	5.610	44	14	0.157	1.764	0.157	1.554
10/27/70 7:00	6.067	44	15	0.169	1.686	0.168	1.512
10/25/82 4:00	7.275	44	16	0.181	1.613	0.180	1.471
10/14/84 12:00	5.794	44	17	0.192	1.544	0.191	1.433
10/31/91 16:00	6.529	44	18	0.204	1.478	0.203	1.396
9/13/64 16:00	7.157	43	19	0.216	1.416	0.214	1.361
9/30/01 20:00	5.887	43	20	0.227	1.356	0.226	1.328
9/5/00 14:00	5.758	42	21	0.239	1.299	0.238	1.296
4/16/05 2:00	5.260	42	22	0.250	1.244	0.249	1.265
3/10/87 5:00	6.041	35	23	0.262	1.192	0.261	1.235
11/2/47 11:00	6.481	34	24	0.274	1.141	0.272	1.207
4/13/88 7:00	6.866	34	25	0.285	1.091	0.284	1.179
10/26/43 7:00	5.871	33	26	0.297	1.044	0.295	1.152
10/21/61 19:00	6.802	33	27	0.308	0.998	0.307	1.126
5/26/72 20:00	5.935	33	28	0.320	0.953	0.319	1.101
12/19/77 5:00	5.811	33	29	0.332	0.909	0.330	1.076
4/10/03 15:00	6.015	33	30	0.343	0.866	0.342	1.052
10/10/13 1:00	6.354	33	31	0.355	0.825	0.353	1.029
10/6/57 8:00	7.361	32	32	0.366	0.784	0.365	1.006
10/19/71 9:00	6.052	32	33	0.378	0.745	0.376	0.984
8/19/95 16:00	5.521	32	34	0.390	0.706	0.388	0.962
2/6/10 3:00	6.674	32	35	0.401	0.667	0.400	0.940
9/19/28 0:00	7.496	31	36	0.413	0.630	0.411	0.919
10/4/51 11:00	6.552	31	37	0.425	0.593	0.423	0.899
5/27/68 21:00	6.497	31	38	0.436	0.557	0.434	0.879
2/11/73 3:00	6.622	31	39	0.448	0.521	0.446	0.859
10/26/90 2:00	5.895	31	40	0.459	0.486	0.457	0.839
10/5/92 16:00	5.327	31	41	0.471	0.451	0.469	0.820
11/17/94 9:00	6.455	31	42	0.483	0.417	0.481	0.801
11/3/07 4:00	5.735	31	43	0.494	0.383	0.492	0.782
8/12/55 16:00	6.292	24	44	0.506	0.350	0.504	0.764
3/2/69 7:00	6.482	22	45	0.517	0.317	0.515	0.746
11/17/35 13:00	6.191	21	46	0.529	0.284	0.527	0.728
3/19/46 23:00	6.125	21	47	0.541	0.251	0.538	0.710
9/29/83 15:00	5.780	21	48	0.552	0.219	0.550	0.693
10/16/02 5:00	5.748	21	49	0.564	0.187	0.561	0.675
8/27/11 19:00	8.470	21	50	0.575	0.155	0.573	0.658
8/22/31 17:00	8.798	20	51	0.587	0.123	0.585	0.641
9/18/36 10:00	8.774	20	52	0.599	0.091	0.596	0.624
1/29/37 10:00	6.459	20	53	0.610	0.059	0.608	0.608
10/5/48 11:00	7.256	20	54	0.622	0.028	0.619	0.591
1/23/54 0:00	6.107	20	55	0.634	-0.004	0.631	0.575
2/1/60 0:00	5.915	20	56	0.645	-0.035	0.642	0.558
1/16/65 21:00	6.342	20	57	0.657	-0.067	0.654	0.542
1/27/66 0:00	5.927	20	58	0.668	-0.099	0.666	0.526
9/16/67 19:00	6.312	20	59	0.680	-0.130	0.677	0.510
10/8/96 19:00	6.212	20	60	0.692	-0.162	0.689	0.494
10/19/97 12:00	6.626	20	61	0.703	-0.195	0.700	0.478
11/6/53 9:00	6.122	19	62	0.715	-0.227	0.712	0.463
11/24/75 13:00	5.660	19	63	0.726	-0.259	0.723	0.447
2/24/89 11:00	5.870	19	64	0.738	-0.292	0.735	0.431
9/19/04 12:00	5.550	19	65	0.750	-0.326	0.747	0.415
9/14/44 12:00	5.656	17	66	0.761	-0.359	0.758	0.400
1/24/40 8:00	6.897	16	67	0.773	-0.394	0.770	0.384
9/22/29 11:00	6.281	11	68	0.784	-0.428	0.781	0.368
11/27/32 8:00	6.334	9	69	0.796	-0.464	0.793	0.352
10/16/49 16:00	5.581	9	70	0.808	-0.500	0.804	0.336
4/12/59 23:00	5.631	9	71	0.819	-0.537	0.816	0.320
3/10/76 3:00	5.285	9	72	0.831	-0.575	0.828	0.304
8/22/30 20:00	6.666	8	73	0.843	-0.614	0.839	0.288
3/20/34 12:00	5.503	8	74	0.854	-0.655	0.851	0.272
5/30/38 22:00	6.245	8	75	0.866	-0.697	0.862	0.256
11/21/52 11:00	5.937	8	76	0.877	-0.741	0.874	0.239
9/15/63 20:00	6.070	8	77	0.889	-0.788	0.885	0.222
12/1/74 10:00	6.177	8	78	0.901	-0.837	0.897	0.205
8/20/81 12:00	6.230	8	79	0.912	-0.889	0.909	0.187
1/10/93 10:00	6.152	8	80	0.924	-0.946	0.920	0.169
11/1/14 16:00	5.922	8	81	0.935	-1.008	0.932	0.151
1/12/41 8:00	5.199	7	82	0.947	-1.078	0.943	0.131
9/12/50 21:00	5.766	7	83	0.959	-1.159	0.955	0.111
9/24/79 11:00	5.660	7	84	0.970	-1.257	0.966	0.090
8/22/80 17:00	5.415	7	85	0.982	-1.389	0.978	0.066
8/17/86 20:00	6.618	7	86	0.993	-1.617	0.990	0.039
	N (Events) =	86					



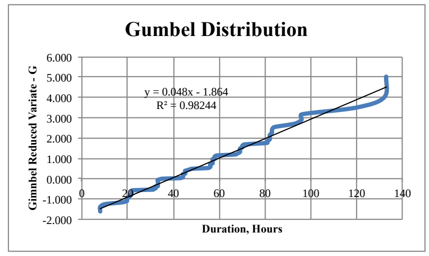
Yrs of Rec	86	Gumbel Distribution Analysis for Duration by Return Period					
N (Events) =	86	DTR (Hrs) = γ - β*ln(ln{λTR/(λTR-1)})					
TR, %		99	50	25	10	1	0.2
TR, Years		1.01	2	4	10	100	500
λ = N/YofR	1.00						
A = 1/β	0.0728						
B = -γ/β	-1.4994						
β = 1/A	13.74						
γ = -β*B	20.60						
α =	N/A						
D_{TR}		0	26	38	52	84	106



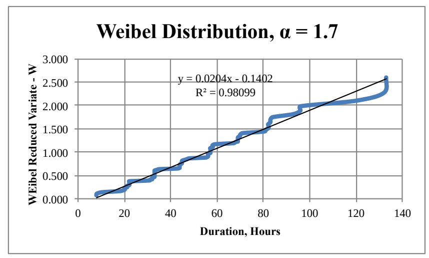
Yrs of Rec	86	Weibel Distribution Analysis for Duration by Return Period					
N (Events) =	86	DTR = γ + β*LN(λ*TR)^(1/α)					
TR, %		99	50	10	4	1	0.2
TR, Years		1	2	10	25	100	500
λ = N/YofR	1.00						
A = 1/β	0.0378						
B = -γ/β	-0.1618						
β = 1/A	26.46						
γ = -β*B	4.28						
α =	1.4						
D_{TR}		4	17	48	65	91	122

Yrs of Rec	86	**Inverse of the Return Periods for the Weibull Analysis for 5, 6, 12, 24, 48 and 72 hours, T_R, %**					
N (Events) =	86						
TR, %		98.0	93.5	68.0	36.1	10.2	2.8
TR, Years		1.02	1.07	1.47	2.77	9.85	35.1
λ = N/YofR	1.00						
A = 1/β	0.0378						
B = -γ/β	-0.1618						
β = 1/A	26.46						
γ = -β*B	4.28						
α =	1.4						
D_{TR}		5	6	12	24	48	72

Sheet 9 - Current Year+SLR = 3.0 Ft.				Q, Gumbel		Q, Weibel	
				C1 =	0.440	C1 =	0.470
Event Adjusted to 2014 + SLR = +3.0 ft				C2 =	0.120	C2 =	0.430
	Event	Duration				α =	1.7
Date Time	Elevation	Hours	i	Q	G	Q	W
2/5/98 4:00	8.197	133	1	0.007	5.032	0.006	2.606
11/2/85 11:00	6.631	132	2	0.018	4.002	0.018	2.272
10/28/56 17:00	6.577	120	3	0.030	3.501	0.029	2.100
10/17/49 17:00	6.380	96	4	0.041	3.165	0.041	1.981
10/23/04 18:00	6.057	96	5	0.053	2.911	0.052	1.889
10/29/77 11:00	6.150	93	6	0.065	2.707	0.064	1.813
8/30/99 12:00	7.201	84	7	0.076	2.535	0.076	1.748
10/21/61 19:00	7.302	83	8	0.088	2.387	0.087	1.690
11/12/09 18:00	9.138	83	9	0.099	2.257	0.099	1.639
11/1/47 11:00	6.981	82	10	0.111	2.140	0.110	1.592
10/21/58 18:00	7.547	82	11	0.123	2.034	0.122	1.549
10/31/91 16:00	7.029	82	12	0.134	1.937	0.133	1.510
10/29/38 13:00	5.646	81	13	0.146	1.847	0.145	1.473
4/10/03 15:00	6.515	81	14	0.157	1.764	0.157	1.438
9/25/08 18:00	7.283	71	15	0.169	1.686	0.168	1.405
10/19/71 9:00	6.552	70	16	0.181	1.613	0.180	1.374
12/12/92 10:00	6.836	70	17	0.192	1.544	0.191	1.345
11/20/39 16:00	6.110	69	18	0.204	1.478	0.203	1.316
12/5/45 9:00	7.142	69	19	0.216	1.416	0.214	1.289
11/27/62 9:00	7.186	69	20	0.227	1.356	0.226	1.263
10/27/70 7:00	6.567	69	21	0.239	1.299	0.238	1.238
10/14/84 12:00	6.294	68	22	0.250	1.244	0.249	1.214
11/22/06 10:00	8.163	67	23	0.262	1.192	0.261	1.190
8/19/95 16:00	6.021	59	24	0.274	1.141	0.272	1.167
9/22/29 11:00	6.781	58	25	0.285	1.091	0.284	1.145
4/27/78 0:00	8.337	58	26	0.297	1.044	0.295	1.124
11/12/10 13:00	6.078	58	27	0.308	0.998	0.307	1.103
8/22/31 17:00	9.198	57	28	0.320	0.953	0.319	1.082
9/16/33 18:00	8.719	57	29	0.332	0.909	0.330	1.062
11/17/35 13:00	6.691	57	30	0.343	0.866	0.342	1.043
9/22/64 9:00	6.657	57	31	0.355	0.825	0.353	1.024
9/24/79 11:00	6.160	57	32	0.366	0.784	0.365	1.005
4/13/88 7:00	7.366	57	33	0.378	0.745	0.376	0.987
3/19/46 23:00	6.625	56	34	0.390	0.706	0.388	0.968
5/26/72 20:00	6.435	56	35	0.401	0.667	0.400	0.951
10/25/82 4:00	7.775	56	36	0.413	0.630	0.411	0.933
11/17/94 9:00	6.955	56	37	0.425	0.593	0.423	0.916
4/16/05 2:00	5.760	56	38	0.436	0.557	0.434	0.899
9/5/00 14:00	6.258	55	39	0.448	0.521	0.446	0.882
10/29/12 8:00	8.178	48	40	0.459	0.486	0.457	0.866
3/10/87 5:00	6.541	47	41	0.471	0.451	0.469	0.849
10/10/13 1:00	6.854	46	42	0.483	0.417	0.481	0.833
10/26/43 7:00	6.371	45	43	0.494	0.383	0.492	0.817
10/6/57 8:00	7.861	45	44	0.506	0.350	0.504	0.801
9/15/63 20:00	6.570	45	45	0.517	0.317	0.515	0.785
9/29/83 15:00	6.280	45	46	0.529	0.284	0.527	0.770
9/30/01 20:00	6.387	45	47	0.541	0.251	0.538	0.754
2/6/37 5:00	5.561	44	48	0.552	0.219	0.550	0.739
3/14/51 0:00	5.831	44	49	0.564	0.187	0.561	0.724
6/16/65 23:00	6.041	44	50	0.575	0.155	0.573	0.709
3/2/69 7:00	6.982	44	51	0.587	0.123	0.585	0.694
10/26/90 2:00	6.395	44	52	0.599	0.091	0.596	0.678
11/3/07 4:00	6.235	44	53	0.610	0.059	0.608	0.664
1/23/54 0:00	6.607	43	54	0.622	0.028	0.619	0.649
2/1/60 0:00	6.415	35	55	0.634	-0.004	0.631	0.634
9/16/67 19:00	6.812	34	56	0.645	-0.035	0.642	0.619
9/19/28 0:00	7.996	33	57	0.657	-0.067	0.654	0.604
6/10/55 0:00	6.191	33	58	0.668	-0.099	0.666	0.589
5/27/68 21:00	6.997	33	59	0.680	-0.130	0.677	0.575
2/11/73 3:00	7.122	33	60	0.692	-0.162	0.689	0.560
11/24/75 13:00	6.160	33	61	0.703	-0.195	0.700	0.545
10/10/86 15:00	5.736	33	62	0.715	-0.227	0.712	0.530
12/16/93 11:00	6.379	33	63	0.726	-0.259	0.723	0.515
6/3/97 20:00	6.523	33	64	0.738	-0.292	0.735	0.500
11/5/11 5:00	6.244	33	65	0.750	-0.326	0.747	0.485
12/9/14 11:00	6.179	33	66	0.761	-0.359	0.758	0.470
10/5/48 11:00	7.756	32	67	0.773	-0.394	0.770	0.454
9/6/50 16:00	5.066	32	68	0.784	-0.428	0.781	0.439
10/16/02 5:00	6.248	32	69	0.796	-0.464	0.793	0.423
1/27/66 0:00	6.427	31	70	0.808	-0.500	0.804	0.408
3/10/76 3:00	5.785	31	71	0.819	-0.537	0.816	0.392
9/9/32 17:00	6.385	22	72	0.831	-0.575	0.828	0.376
9/18/36 10:00	8.274	22	73	0.843	-0.614	0.839	0.359
10/1/40 9:00	6.895	22	74	0.854	-0.655	0.851	0.342
10/23/53 10:00	7.022	22	75	0.866	-0.697	0.862	0.325
8/20/81 12:00	6.730	22	76	0.877	-0.741	0.874	0.308
10/8/96 19:00	6.712	22	77	0.889	-0.788	0.885	0.290
12/4/52 11:00	6.135	21	78	0.901	-0.837	0.897	0.271
6/28/74 4:00	5.946	21	79	0.912	-0.889	0.909	0.252
10/5/34 7:00	5.606	20	80	0.924	-0.946	0.920	0.232
4/12/59 23:00	6.131	20	81	0.935	-1.008	0.932	0.210
2/24/89 11:00	6.370	20	82	0.947	-1.078	0.943	0.188
9/14/44 12:00	6.156	18	83	0.959	-1.159	0.955	0.164
8/22/30 20:00	7.166	10	84	0.970	-1.257	0.966	0.137
1/12/41 8:00	5.699	8	85	0.982	-1.389	0.978	0.107
8/22/80 17:00	5.914	8	86	0.993	-1.617	0.990	0.068
	N (Events) =	86					



Yrs of Rec	86	Gumbel Distribution Analysis for Duration by Return Period					
N (Events) =	86	DTR (Hrs) = γ - β*ln(ln{λTR/(λTR-1)})					
TR, %		99	50	25	10	1	0.2
TR, Years		1.01	2	4	10	100	500
λ = N/YofR	1.00						
A = 1/β	0.048						
B = -γ/β	-1.864						
β = 1/A	20.83						
γ = -β*B	38.83						
α =	N/A						
D_{TR}		7	46	65	86	135	168



Yrs of Rec	86	Weibel Distribution Analysis for Duration by Return Period					
N (Events) =	86	DTR = γ + β*LN(λ*TR)^(1/α)					
TR, %		99	50	10	4	1	0.2
TR, Years		1	2	10	25	100	500
λ = N/YofR	1.00						
A = 1/β	0.0204						
B = -γ/β	-0.1402						
β = 1/A	49.02						
γ = -β*B	6.87						
α =	1.7						
D_{TR}		7	27	73	100	140	186

Yrs of Rec	86	Inverse of the Return Periods for the Weibull Analysis for 5, 6, 12, 24, 48 and 72 hours, T_R, %					
N (Events) =	86						
TR, %		102	101	95	86	70	56
TR, Years		0.980	0.989	1.05	1.16	1.430	1.77
λ = N/YofR	1.00						
A = 1/β	0.0204						
B = -γ/β	-0.1402						
β = 1/A	49.02						
γ = -β*B	6.87						
α =	0.4						
D_{TR}		5	6	12	24	48	72

Event Adjusted to 2014 + SLR = +0.0 ft			Event Adjusted to 2014 + SLR = +0.5 ft			Event Adjusted to 2014 + SLR = +1.0 ft			Event Adjusted to 2014 + SLR = +1.5 ft			Event Adjusted to 2014 + SLR = +2.0 ft			Event Adjusted to 2014 + SLR = +2.5 ft			Event Adjusted to 2014 + SLR = +3.0 ft		
Date Time	Event Elevation	Duration Hours	Date Time	Event Elevation	Duration Hours	Date Time	Event Elevation	Duration Hours	Date Time	Event Elevation	Duration Hours	Date Time	Event Elevation	Duration Hours	Date Time	Event Elevation	Duration Hours	Date Time	Event Elevation	Duration Hours
9/19/28 0:00	4.996	6	9/19/28 0:00	5.496	6	9/19/28 0:00	5.996	8	9/19/28 0:00	6.496	11	9/19/28 0:00	6.996	21	9/19/28 0:00	7.496	31	9/19/28 0:00	7.996	33
9/22/29 11:00	3.781	0	9/22/29 11:00	4.281	3	9/22/29 11:00	4.781	5	9/22/29 11:00	5.281	7	9/22/29 11:00	5.781	9	9/22/29 11:00	6.281	11	9/22/29 11:00	6.781	58
8/22/30 20:00	4.166	1	8/22/30 20:00	4.666	2	8/22/30 20:00	5.166	4	8/22/30 20:00	5.666	5	8/22/30 20:00	6.166	7	8/22/30 20:00	6.666	8	8/22/30 20:00	7.166	10
3/22/31 23:00	3.449	0	3/22/31 23:00	3.949	0	3/22/31 23:00	4.449	4	8/22/31 17:00	8.198	6	8/22/31 17:00	8.698	8	8/22/31 17:00	8.798	20	8/22/31 17:00	9.198	57
9/9/32 17:00	3.335	0	11/29/32 10:00	4.436	3	11/29/32 10:00	4.936	5	9/9/32 17:00	4.835	6	9/9/32 17:00	5.335	7	11/27/32 8:00	6.334	9	9/9/32 17:00	6.385	22
9/16/33 18:00	5.719	16	9/16/33 18:00	6.219	18	9/16/33 18:00	6.719	20	9/16/33 18:00	7.219	22	9/16/33 18:00	7.719	34	9/16/33 18:00	8.219	45	9/16/33 18:00	8.719	57
3/20/34 12:00	3.003	0	3/20/34 12:00	3.503	0	3/20/34 12:00	4.003	1	3/20/34 12:00	4.503	4	3/20/34 12:00	5.003	6	3/20/34 12:00	5.503	8	10/5/34 7:00	5.606	20
11/17/35 3:00	3.589	0	11/17/35 13:00	4.191	2	11/17/35 3:00	4.589	6	11/17/35 13:00	5.191	19	11/17/35 13:00	5.691	19	11/17/35 13:00	6.191	21	11/17/35 13:00	6.691	57
9/18/36 10:00	6.274	7	9/18/36 10:00	6.774	8	9/18/36 10:00	7.274	10	9/18/36 10:00	7.774	18	9/18/36 10:00	8.274	20	9/18/36 10:00	8.774	20	9/18/36 10:00	8.274	22
1/29/37 10:00	3.959	0	1/29/37 10:00	4.459	4	1/29/37 10:00	4.959	6	1/29/37 10:00	5.459	9	1/29/37 10:00	5.959	18	1/29/37 10:00	6.459	20	2/6/37 5:00	5.561	44
5/30/38 22:00	3.745	0	5/30/38 22:00	4.245	3	5/30/38 22:00	4.745	5	5/30/38 22:00	5.245	5	5/30/38 22:00	5.745	7	5/30/38 22:00	6.245	8	10/29/38 13:00	5.646	81
8/28/39 20:00	3.412	0	8/28/39 20:00	3.916	0	8/28/39 20:00	4.412	5	8/28/39 20:00	4.912	6	8/28/39 20:00	5.412	8	11/20/39 16:00	5.610	44	11/20/39 16:00	6.110	69
1/24/40 8:00	4.397	2	1/24/40 8:00	4.897	3	1/24/40 8:00	5.397	6	1/24/40 8:00	5.897	7	1/24/40 8:00	6.397	11	1/24/40 8:00	6.897	16	10/1/40 9:00	6.895	22
1/12/41 8:00	2.699	0	1/12/41 8:00	3.199	0	1/28/41 10:00	4.001	1	1/28/41 10:00	4.501	3	1/28/41 10:00	5.001	5	1/12/41 8:00	5.199	7	1/12/41 8:00	5.699	8
9/30/43 10:00	3.870	0	9/30/43 10:00	4.370	3	9/30/43 10:00	4.870	5	9/30/43 10:00	5.370	7	9/30/43 10:00	5.870	9	10/26/43 7:00	5.871	33	10/26/43 7:00	6.371	45
9/14/44 12:00	3.156	0	9/14/44 12:00	3.656	0	9/30/44 20:00	4.455	4	9/30/44 20:00	4.955	5	9/14/44 12:00	5.156	8	9/14/44 12:00	5.656	17	9/14/44 12:00	6.156	18
12/5/45 9:00	4.142	2	12/5/45 9:00	4.642	4	12/5/45 9:00	5.142	6	12/5/45 9:00	5.642	8	12/5/45 9:00	6.142	29	12/5/45 9:00	6.642	55	12/5/45 9:00	7.142	69
1/17/46 9:00	4.127	2	1/17/46 9:00	4.627	3	1/17/46 9:00	5.127	5	3/19/46 23:00	5.125	6	3/19/46 23:00	5.625	7	3/19/46 23:00	6.125	21	3/19/46 23:00	6.625	56
11/1/47 11:00	3.981	0	11/1/47 11:00	4.481	3	11/1/47 11:00	4.981	5	11/1/47 11:00	5.481	7	11/1/47 11:00	5.981	7	11/2/47 11:00	6.481	34	11/1/47 11:00	6.981	82
10/5/48 11:00	4.756	4	10/5/48 11:00	5.256	5	10/5/48 11:00	5.756	7	10/5/48 11:00	6.256	8	10/5/48 11:00	6.756	9	10/5/48 11:00	7.256	20	10/5/48 11:00	7.756	32
5/11/49 20:00	3.780	0	5/11/49 20:00	4.280	2	5/11/49 20:00	4.780	4	5/11/49 20:00	5.280	6	10/16/49 16:00	5.081	8	10/16/49 16:00	5.581	9	10/17/49 17:00	6.380	96
9/6/50 16:00	2.066	0	9/6/50 16:00	2.566	0	9/12/50 21:00	4.266	3	9/12/50 21:00	4.766	5	9/12/50 21:00	5.266	6	9/12/50 21:00	5.766	7	9/6/50 16:00	5.066	32
10/4/51 11:00	4.052	1	10/4/51 11:00	4.552	4	10/4/51 11:00	5.052	5	10/4/51 11:00	5.552	7	10/4/51 11:00	6.052	9	10/4/51 11:00	6.552	31	3/14/51 0:00	5.831	44
2/27/52 10:00	3.637	0	2/27/52 10:00	4.137	1	2/27/52 10:00	4.637	4	2/27/52 10:00	5.137	5	2/27/52 10:00	5.637	6	11/21/52 11:00	5.937	8	12/4/52 11:00	6.135	21
10/23/53 10:00	4.022	1	10/23/53 10:00	4.522	4	8/14/53 10:00	4.622	6	8/14/53 10:00	5.122	9	11/6/53 9:00	5.622	19	11/6/53 9:00	6.122	19	10/23/53 10:00	7.022	22
1/23/54 0:00	3.607	0	1/23/54 0:00	4.107	2	1/23/54 0:00	4.607	5	1/23/54 0:00	5.107	7	1/23/54 0:00	5.607	10	1/23/54 0:00	6.107	20	1/23/54 0:00	6.607	43
6/10/55 0:00	3.191	0	8/12/55 16:00	4.292	3	8/12/55 16:00	4.792	9	8/12/55 16:00	5.292	11	8/12/55 16:00	5.792	13	8/12/55 16:00	6.292	24	6/10/55 0:00	6.191	33
9/27/56 2:00	5.174	8	9/27/56 2:00	5.674	18	9/27/56 2:00	6.174	30	9/27/56 2:00	6.674	32	9/27/56 2:00	7.174	44	9/27/56 2:00	7.674	46	10/28/56 17:00	6.577	120
10/6/57 8:00	4.861	4	10/6/57 8:00	5.361	6	10/6/57 8:00	5.861	7	10/6/57 8:00	6.361	8	10/6/57 8:00	6.861	20	10/6/57 8:00	7.361	32	10/6/57 8:00	7.861	45
10/21/58 18:00	4.547	4	10/21/58 18:00	5.047	7	10/21/58 18:00	5.547	20	10/21/58 18:00	6.047	31	10/21/58 18:00	6.547	45	10/21/58 18:00	7.047	70	10/21/58 18:00	7.547	82
4/12/59 23:00	3.131	0	4/12/59 23:00	3.631	0	4/12/59 23:00	4.131	2	4/12/59 23:00	4.631	5	4/12/59 23:00	5.131	7	4/12/59 23:00	5.631	9	4/12/59 23:00	6.131	20
9/12/60 6:00	4.816	4	9/12/60 6:00	5.316	4	9/12/60 6:00	5.816	5	9/12/60 6:00	6.316	6	9/12/60 6:00	6.816	7	2/1/60 0:00	5.915	20	2/1/60 0:00	6.415	35
10/21/61 19:00	4.302	2	10/21/61 19:00	4.802	4	10/21/61 19:00	5.302	6	10/22/61 8:00	5.500	7	10/22/61 8:00	6.000	9	10/21/61 19:00	6.802	33	10/21/61 19:00	7.302	83
3/7/62 10:00	6.387	9	3/7/62 10:00	6.887	19	3/7/62 10:00	7.387	31	3/7/62 10:00	7.887	44	3/7/62 10:00	8.387	44	3/7/62 10:00	8.887	57	11/27/62 9:00	7.186	69
9/15/63 20:00	3.570	0	9/15/63 20:00	4.070	1	9/15/63 20:00	4.570	3	9/15/63 20:00	5.070	5	9/15/63 20:00	5.570	7	9/15/63 20:00	6.070	8	9/15/63 20:00	6.570	45
9/13/64 16:00	4.657	4	9/13/64 16:00	5.157	7	9/13/64 16:00	5.657	17	9/13/64 16:00	6.157	19	9/13/64 16:00	6.657	21	9/13/64 16:00	7.157	43	9/22/64 9:00	6.657	57
1/16/65 21:00	3.842	0	1/16/65 21:00	4.342	3	1/16/65 21:00	4.842	5	1/16/65 21:00	5.342	6	1/16/65 21:00	5.842	7	1/16/65 21:00	6.342	20	6/16/65 23:00	6.041	44
1/27/66 0:00	3.427	0	1/27/66 0:00	3.927	0	1/27/66 0:00	4.427	4	1/27/66 0:00	4.927	6	1/27/66 0:00	5.427	9	1/27/66 0:00	5.927	20	1/27/66 0:00	6.427	31
9/16/67 19:00	3.812	0	9/16/67 19:00	4.312	3	9/16/67 19:00	4.812	5	9/16/67 19:00	5.312	6	9/16/67 19:00	5.812	8	9/16/67 19:00	6.312	20	9/16/67 19:00	6.812	34
5/27/68 21:00	3.997	0	5/27/68 21:00	4.497	4	5/27/68 21:00	4.997	6	5/27/68 21:00	5.497	8	5/27/68 21:00	5.997	29	5/27/68 21:00	6.497	31	5/27/68 21:00	6.997	33
3/2/69 7:00	3.982	0	3/2/69 7:00	4.482	4	3/2/69 7:00	4.982	6	3/2/69 7:00	5.482	18	3/2/69 7:00	5.982	20	3/2/69 7:00	6.482	22	3/2/69 7:00	6.982	44
10/27/70 7:00	3.567	0	10/27/70 7:00	4.067	1	10/27/70 7:00	4.567	5	10/27/70 7:00	5.067	6	10/27/70 19:00	5.465	8	10/27/70 7:00	6.067	44	10/27/70 7:00	6.567	69
3/26/71 21:00	4.051	1	3/26/71 21:00	4.551	3	3/26/71 21:00	5.051	5	4/6/71 17:00	4.852	8	4/6/71 17:00	5.352	16	10/19/71 9:00	6.052	32	10/19/71 9:00	6.552	70
5/26/72 20:00	3.435	0	9/21/72 7:00	4.496	1	9/21/72 7:00	4.996	4	9/21/72 7:00	5.496	6	9/21/72 7:00	5.996	7	5/26/72 20:00	5.935	33	5/26/72 20:00	6.435	56
2/11/73 3:00	4.122	2	2/11/73 3:00	4.622	5	2/11/73 3:00	5.122	7	2/11/73 3:00	5.622	8	2/11/73 3:00	6.122	1	2/11/73 3:00	6.622	31	2/11/73 3:00	7.122	33
6/28/74 4:00	2.946	0	12/1/74 10:00	4.177	1	12/1/74 10:00	4.677	4	12/1/74 10:00	5.177	5	12/1/74 10:00	5.677	8	12/1/74 10:00	6.177	8	6/28/74 4:00	5.946	21
11/24/75 13:00	3.160	0	11/24/75 13:00	3.660	0	11/24/75 13:00	4.160	1	11/24/75 13:00	4.660	5	11/24/75 13:00	5.160	6	11/24/75 13:00	5.660	19	11/24/75 13:00	6.160	33
3/10/76 3:00	2.785	0	3/10/76 3:00	3.285	0	3/10/76 3:00	3.785	0	3/10/76 3:00	4.285	4	3/10/76 3:00	4.785	6	3/10/76 3:00	5.285	9	3/10/76 3:00	5.785	31
10/14/77 10:00	4.321	3	10/14/77 10:00	4.821	4	10/14/77 10:00	5.321	5	10/14/77 10:00	5.821	6	10/14/77 10:00	6.321	7	12/19/77 5:00	5.811	33	10/29/77 11:00	6.150	93
4/27/78 0:00	5.337	6	4/27/78 0:00	5.837	7	4/27/78 0:00	6.337	30	4/27/78 0:00	6.837	32	4/27/78 0:00	7.337	43	4/27/78 0:00	7.837	45	4/27/78 0:00	8.337	58
9/24/79 11:00	3.160	0	9/24/79 11:00	3.660	0	9/24/79 11:00	4.160	2	9/24/79 11:00	4.660	5	9/24/79 11:00	5.160	6	9/24/79 11:00	5.660	7	9/24/79 11:00	6.160	57
1/5/80 12:00	3.046	0	1/5/80 12:00	3.546	0	1/5/80 12:00	4.046	2	8/22/80 17:00	4.415	4	8/22/80 17:00	4.915	6	8/22/80 17:00	5.415	7	8/22/80 17:00	5.914	8
8/20/81 12:00	3.730	0	11/14/81 11:00	4.191	3	11/14/81 11:00	4.691	5	8/20/81 12:00	5.230	6	8/20/81 12:00	5.730	8	8/20/81 12:00	6.230	8	8/20/81 12:00	6.730	22
10/25/82 4:00	4.775	5	10/25/82 4:00	5.275	10	10/25/82 4:00	5.775	17	10/25/82 4:00	6.275	29	10/25/82 4:00	6.775	32	10/25/82 4:00	7.275	44	10/25/82 4:00	7.775	56
1/28/83 9:00	3.811	0	1/28/83 9:00	4.311	3	2/11/83 9:00	4.782	6	2/11/83 9:00	5.282	8	2/11/83 9:00	5.782	18	9/29/83 15:00	5.780	21	9/29/83 15:00	6.280	45
10/14/84 12:00	3.294	0	10/14/84 12:00	3.794	0	10/14/84 12:00	4.294	3	10/14/84 12:00	4.794	5	10/14/84 12:00	5.294	7	10/14/84 12:00	5.794	44	10/14/84 12:00	6.294	68
11/2/85 11:00	3.631	0	11/2/85 11:00	4.131	2	11/2/85 11:00	4.631	4	11/4/85 16:00	4.760	8	11/4/85 16:00	5.260	10	11/2/85 11:00	6.131	69	11/2/85 11:00	6.631	132
8/17/86 20:00	4.118	1	8/17/86 20:00	4.618	3	8/17/86 20:00	5.118	5	8/17/86 20:00	5.618	6	8/17/86 20:00	6.118	7	8/17/86 20:00	6.618	7	10/10/86 15:00	5.736	33
1/1/87 22:00	4.221	1	1/1/87 22:00	4.721	3	3/10/87 5:00	4.541	6	3/10/87 5:00	5.041	9	3/10/87 5:00	5.541	20	3/10/87 5:00	6.041	35	3/10/87 5:00	6.541	47
4/13/88 7:00	4.366	3	4/13/88 7:00	4.866	5	4/13/88 7:00	5.366	7	4/13/88 7:00	5.866	19	4/13/88 7:00	6.366	32	4/13/88 7:00	6.866	34	4/13/88 7:00	7.366	57
2/24/89 11:00	3.370	0	2/24/89 11:00	3.870	0	9/19/89 11:00	4.321	3	9/19/89 11:00	4.821	5	9/19/89 11:00	5.321	6	2/24/89 11:00	5.870	19	2/24/89 11:00	6.370	20
10/26/90 2:00	3.395	0	10/26/90 2:00	3.895	0	10/26/90 2:00	4.395	6	10/26/90 2:00	4.895	16	10/26/90 2:00	5.395	18	10/26/90 2:00	5.895	31	10/26/90 2:00	6.395	44
10/31/91 16:00	4.029	2	10/31/91 16:00	4.529	5	10/31/91 16:00	5.029	7	10/31/91 16:00	5.529	9	10/31/91 16:00	6.029	11	10/31/91 16:00	6.529	44	10/31/91 16:00	7.029	82
9/25/92 8:00	4.267	3	9/25/92 8:00	4.767	5	9/25/92 8:00	5.267	5	9/25/92 8:00	5.767	7	10/5/92 16:00	4.827	19	10/5/92 16:00	5.327	31	12/12/92 10:00	6.836	70
1/10/93 10:00	3.652	0	1/10/93 10:00	4.152	2	1/10/93 10:00	4.652	4	1/10/93 10:00	5.152	5	1/10/93 10:00	5.652	7	1/10/93 10:00	6.152	8	12/16/93 11:00	6.379	33
11/17/94 9:00	3.955	0	11/17/94 9:00	4.455	4	11/17/94 9:00	4.955	5	11/17/94 9:00	5.455	7	11/17/94 9:00	5.955	19	11/17/94 9:00	6.455	31	11/17/94 9:00	6.955	56
8/7/95 18:00	3.251	0	8/7/95 18:00	3.751	0	8/7/95 18:00	4.251	2	8/19/95 16:00	4.521	5	8/19/95 16:00	5.021	8	8/19/95 16:00	5.521	32	8/19/95 16:00	6.021	59
10/8/96 19:00	3.712	0	10/8/96 19:00	4.212	2	10/8/96 19:00	4.712	9	10/8/96 19:00	5.212	17	10/8/96 19:00	5.712	18	10/8/96 19:00	6.212	20	10/8/96 19:00	6.712	22
10/19/97 12:00	4.126	2	10/19/97 12:00	4.626	4	10/19/97 12:00	5.126	6	10/19/97 12:00	5.626	7	10/19/97 12:00	6.126	8	10/19/97 12:00	6.626	20	6/3/97 20:00	6.523	33
2/5/98 4:00	5.197	7	2/5/98 4:00	5.697	20	2/5/98 4:00	6.197	33	2/5/98 4:00	6.697	55	2/5/98 4:00	7.197	57	2/5/98 4:00	7.697	70	2/5/98 4:00	8.197	133
8/30/99 12:00	4.201	3	8/30/99 12:00	4.701	5	8/30/99 12:00	5.201	6	8/30/99 12:00	5.701	8	8/30/99 12:00	6.201	46	8/30/99 12:00	6.701	70	8/30/99 12:00	7.201	84
1/25/00 12:00	4.058	1	1/25/00 12:00	4.558	4	1/25/00 12:00	5.058	6	1/25/00 12:00	5.558	16	1/25/00 12:00	6.058	17	9/5/00 14:00	5.758	42	9/5/00 14:00	6.258	55
9/30/01 20:00	3.387	0	9/30/01 20:00	3.887	0	9/30/01 20:00	4.387	3	9/30/01 20:00	4.887	5	9/30/01 20:00	5.387	7	9/30/01 20:00	5.887	43	9/30/01 20:00	6.387	45
10/16/02 5:00	3.248	0	10/16/02 5:00	3.748	0	10/16/02 5:00	4.248	3	10/16/02 5:00	4.748	4	10/16/02 5:00	5.248	6	10/16/02 5:00	5.748	21	10/16/02 5:00	6.248	32
9/18/03 16:00	6.441	9	9/18/03 16:00	6.941	10	9/18/03 16:00	7.441	11	9/18/03 16:00	7.941	13	4/10/03 15:00	5.515	31	4/10/03 15:00	6.015	33	4/10/03 15:00	6.515	81
9/19/04 12:00	3.050	0	9/19/04 12:00	3.550	0	9/19/04 12:00	4.050	1	9/19/04 12:00	4.550	4	9/19/04 12:00	5.050	6	9/19/04 12:00	5.550	19	10/23/04 18:00	6.057	96
4/16/05 2:00	2.760	0	5/6/05 20:00	4.008	1	5/6/05 20:00	4.508	3	10/25/05 3:00	4.850	6	4/16/05 2:00	4.760	18	4/16/05 2:00	5.260	42	4/16/05 2:00	5.760	56
10/7/06 9:00	5.002	6	10/7/06 9:00	5.502	6	9/1/06 14:00	5.021	16	10/7/06 9:00	6.502	20	10/7/06 9:00	7.002	32	11/22/06 10:00	7.663	45	11/22/06 10:00	8.163	67
11/3/07 4:00	3.235	0	11/3/07 4:00	3.735	0	11/3/07 4:00	4.235	4	11/3/07 4:00	4.735	6	11/3/07 4:00	5.235	8	11/3/07 4:00	5.735	31	11/3/07 4:00	6.235	44
9/25/08 18:00	4.283	3	9/25/08 18:00	4.783	5	9/25/08 18:00	5.283	7	9/25/08 18:00	5.783	8	9/25/08 18:00	6.283	21	9/25/08 18:00	6.783	56	9/25/08 18:00	7.283	71
11/12/09 18:00	6.138	31	11/12/09 18:00	6.638	33	11/12/09 18:00	7.138	45	11/12/09 18:00	7.638	57	11/12/09 18:00	8.138	69	11/12/09 18:00	8.638	71	11/12/09 18:00	9.138	83
2/6/10 3:00	4.174	2	2/6/10 3:00	4.674	3	2/6/10 3:00	5.174	4	2/6/10 3:00	5.674	6	2/6/10 3:00	6.174	20	2/6/10 3:00	6.674	32	11/12/10 13:00	6.078	58
8/27/11 19:00	5.970	6	8/27/11 19:00	6.470	7	8/27/11 19:00	6.970	9	8/27/11 19:00	7.470	18	8/27/11 19:00	7.970	19	8/27/11 19:00	8.470	21	11/5/11 5:00	6.244	33
10/29/12 8:00	5.178	7	10/29/12 8:00	5.678	18	10/29/12 8:00	6.178	31	10/29/12 8:00	6.678	32	10/29/12 8:00	7.178	34	10/29/12 8:00	7.678	46	10/29/12 8:00	8.178	48
10/10/13 1:00	3.854	0	10/10/13 1:00	4.354	4	10/10/13 1:00	4.854	6	10/10/13 1:00	5.354	8	10/10/13 1:00	5.854	20	10/10/13 1:00	6.354	33	10/10/13 1:00	6.854	46
11/1/14 16:00	3.422	0	11/1/14 16:00	3.922	0	11/1/14 16:00	4.422	4	11/1/14 16:00	4.922	6	11/1/14 16:00	5.422	7	11/1/14 16:00	5.922	8	12/9/14 11:00	6.179	33

APPENDIX D: Decision Event Tree Analysis

Part 1: Event Tree Tally Sheets

Pump Station New PS 113 Case 1 U = Under O = Over E = Even T = Trial

	Pump Off						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start	0.50	0.10	0.02	0.01	0.01		0.50	0.10	0.03	0.04	0.04		0.50	0.10	0.02	0.01	0.01																
Ali	U	U	U	E		0.01	U	U	O	E		0.01	U	U	U	E		0.01	1.00				0.00	2.00				0.11	3.00				0.22
Mel																																	
Mike	U	U	U	E		0.01	U	U	O	E		0.01	U	U	U	E		0.01	1.00					2.00					3.00				
Rob	U	U	U	E		0.01	U	U	E	O		0.01	U	U	U	E		0.01	1.00					2.00					3.00				

	Pump Off						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start													0.50	0.05	0.02	0.01	0.01																
Ali													U	U	U	E		0.01	1.00				0.00	2.00				0.11	2.00				0.11
Mel																																	
Mike													U	U	U	E		0.01	1.00					2.00					2.00				
Rob													U	U	U	E		0.01	1.00					2.00					2.00				

	Pump On						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert							**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start							0.50	0.01			0.01		0.50	0.01			0.01																
Ali							U	E				0.01	U	E				0.01	1.00				0.00	2.00				0.11	2.00				0.11
Mel																																	
Mike							U	E				0.01	U	E				0.01	1.00					2.00					2.00				
Rob							U	E				0.01	U	E				0.01	1.00					2.00					2.00				

	Pump On						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start													0.50	0.01			0.01																
Ali													U	E				0.01	1.00				0.00	2.00				0.11	2.00				0.11
Mel																																	
Mike													U	E				0.01	1.00					2.00					2.00				
Rob													U	E				0.01	1.00					2.00					2.00				

Pump Station New PS 113 Case 2 U = Under O = Over E = Even T = Trial

	Pump Off						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start	0.50	0.05	0.06		0.06		0.50	0.10			0.10		0.50	0.05	0.02	0.03	0.03																
Ali	U	O	E			0.01	U	U				0.01	U	U	E	E		0.01	2.00				0.11	2.00				0.11	3.00				0.22
Mel																																	
Mike	U	U	U			0.01	U	E				0.01	U	E	O	E		0.01	2.00					2.00					3.00				
Rob	U	O	E			0.01	U	E				0.01	U	U	O	E		0.01	2.00					2.00					3.00				

	Pump Off						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.05	0.02	0.01	0.01																
Ali													U	U	U	E		0.01	2.00				0.11	2.00				0.11	2.00				0.11
Mel																																	
Mike													U	U	E	O		0.01	2.00					2.00					2.00				
Rob													U	U	U	E		0.01	2.00					2.00					2.00				

	Pump On						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert							T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start							0.50	0.05	0.02	0.03	0.03		0.50	0.03	0.02		0.02																
Ali							U	E	O	E		0.01	U	U	E			0.01	2.00				0.11	2.00				0.11	2.00				0.11
Mel																																	
Mike							U	U	O	E		0.01	U	U	E			0.01	2.00					2.00					2.00				
Rob							U	U	O	E		0.01	U	E	O			0.01	2.00					2.00					2.00				

	Pump On						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.01			0.01																
Ali													U	E				0.01	2.00				0.11	2.00				0.11	2.00				0.11
Mel																																	
Mike													U	E				0.01	2.00					2.00					2.00				
Rob													U	E				0.01	2.00					2.00					2.00				

Pump Station New PS 113 Case 3 U = Under O = Over E = Even T = Trial

	Pump Off						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start	0.50	0.10	0.20		0.20		0.50	0.65			0.65		0.50	0.65			0.65																
Ali	U	O	E			0.05	O	E				0.05	O	E				0.05	3.00				0.22	3.00				0.22	3.00				0.22
Mel																																	
Mike	U	O	E			0.05	O	E				0.05	O	E				0.05	3.00					3.00					3.00				
Rob	U	O	E			0.05	O	E				0.05	O	E				0.05	3.00					3.00					3.00				

	Pump Off						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.35			0.35																
Ali													U	E				0.05	3.00				0.22	3.00				0.22	2.00				0.11
Mel																																	
Mike													U	E				0.05	3.00					3.00					2.00				
Rob													U	E				0.05	3.00					3.00					2.00				

	Pump On						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert							T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start							0.50	0.35			0.35		0.50	0.35	0.20		0.20																
Ali							U	E				0.05	U	U	E			0.05	3.00				0.22	3.00				0.22	2.00				0.11
Mel																																	
Mike							U	E				0.05	U	U	E			0.05	3.00					3.00					2.00				
Rob							U	E				0.05	U	U	U			0.05	3.00					3.00					2.00				

	Pump On						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.20	0.10		0.10																
Ali													U	U	E			0.05	3.00				0.22	3.00				0.22	2.00				0.11
Mel																																	
Mike													U	U	E			0.05	3.00					3.00					2.00				
Rob													U	U	E			0.05	3.00					3.00					2.00				

Pump Station New PS 113 Case 4 U = Under O = Over E = Even T = Trial

	Pump Off						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start	0.50	0.35			0.35		0.50	0.65	0.80		0.80		0.50	0.80			0.80																
Ali	U	E				0.05	O	O	E			0.05	O	E				0.05	3.00				0.22	3.00				0.22	3.00				0.22
Mel																																	
Mike	U	E				0.05	O	O	E			0.05	O	E				0.05	3.00					3.00					3.00				
Rob	U	E				0.05	O	O	E			0.05	O	E				0.05	3.00					3.00					3.00				

	Pump Off						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start													0.50	0.20			0.40																
Ali													U	E				0.05	3.00				0.22	3.00				0.22	2.00				0.11
Mel																																	
Mike													U	E				0.05	3.00					3.00					2.00				
Rob													U	E				0.05	3.00					3.00					2.00				

	Pump On						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert							**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start							0.50	0.40	0.45		0.45		0.50	0.35	0.30		0.30																
Ali							U	E	E			0.05	U	U	E			0.05	3.00				0.22	3.00				0.22	2.00				0.11
Mel																																	
Mike							E	O	E			0.05	U	U	E			0.05	3.00					3.00					2.00				
Rob							U	E	E			0.05	U	U	E			0.05	3.00					3.00					2.00				

	Pump On						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start													0.50	0.20			0.20																
Ali													U	U				0.10	3.00				0.22	3.00				0.22	2.00				0.11
Mel																																	
Mike													U	O				0.10	3.00					3.00					2.00				
Rob													U	E				0.10	3.00					3.00					2.00				

Pump Station New PS 113 Case 5 U = Under O = Over E = Even T = Trial

	Pump Off						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start	0.50	0.65			0.65		0.50	0.90			0.90		0.50	0.90			0.90																
Ali	O	E				0.05	O	E				0.05	O	E				0.05	3.00				0.22	3.00				0.22	3.00				0.22
Mel																																	
Mike	O	E				0.05	O	E				0.05	O	E				0.05	3.00					3.00					3.00				
Rob	O	E				0.05	O	E				0.05	O	E				0.05	3.00					3.00					3.00				

	Pump Off						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.45			0.45																
Ali													U	E				0.05	3.00				0.22	3.00				0.22	2.00				0.11
Mel																																	
Mike													U	E				0.05	3.00					3.00					2.00				
Rob													U	E				0.05	3.00					3.00					2.00				

	Pump On						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert							T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start							0.50	0.65			0.65		0.50	0.65	0.60		0.60																
Ali							O	E				0.05	O	E	E			0.05	3.00				0.22	3.00				0.22	2.00				0.11
Mel																																	
Mike							O	E				0.05	O	U	E			0.05	3.00					3.00					2.00				
Rob							O	E				0.05	O	E	E			0.05	3.00					3.00					2.00				

	Pump On						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.35			0.35																
Ali													U	E				0.05	3.00				0.22	3.00				0.22	2.00				0.11
Mel																																	
Mike													U	E				0.05	3.00					3.00					2.00				
Rob													U	E				0.05	3.00					3.00					2.00				

Pump Station New PS 113 Case 6 U = Under O = Over E = Even T = Trial

	Pump Off						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start	0.50	0.70	0.80		0.80		0.50	0.90	0.95		0.95		0.50	0.95			0.95																
Ali	O	O	E			0.05	O	O	E			0.05	O	E				0.05	4.00				0.55	4.00				0.55	3.00				0.22
Mel																																	
Mike	O	O	E			0.05	O	O	E			0.05	O	E				0.05	4.00					4.00					3.00				
Rob	O	O	E			0.05	O	O	E			0.05	O	E				0.05	4.00					4.00					3.00				

	Pump Off						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start													0.50	0.75			0.75																
Ali													O	E				0.05	4.00				0.55	4.00				0.55	2.00				0.11
Mel																																	
Mike													O	E				0.05	4.00					4.00					2.00				
Rob													O	E				0.05	4.00					4.00					2.00				

	Pump On						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert							**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start							0.50	0.65	0.80	0.85	0.85		0.50	0.65	0.80		0.80																
Ali							O	O	O	E		0.05	O	O	E			0.05	4.00				0.55	4.00				0.55	2.00				0.11
Mel																																	
Mike							O	O	O	E		0.05	O	O	E			0.05	4.00					4.00					2.00				
Rob							O	O	O	E		0.05	O	O	E			0.05	4.00					4.00					2.00				

	Pump On						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start													0.50	0.60			0.60																
Ali													U	E				0.05	4.00				0.55	4.00				0.55	2.00				0.11
Mel																																	
Mike													O	E				0.05	4.00					4.00					2.00				
Rob													O	E				0.05	4.00					4.00					2.00				

Pump Station New PS 113 Case 7 U = Under O = Over E = Even T = Trial

	Pump Off						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start	0.50	0.99			0.99		0.50	0.99			0.99		0.50	0.99			0.99																
Ali	O	E				0.01	O	E				0.01	O	E				0.01	4.00				0.55	5.00				1.00	4.00				0.55
Mel																																	
Mike	O	E				0.01	O	E				0.01	O	E				0.01	4.00					5.00					4.00				
Rob	O	E				0.01	O	E				0.01	O	E				0.01	4.00					5.00					4.00				

	Pump Off						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.99			0.99																
Ali													O	E				0.01	4.00				0.55	5.00				1.00	4.00				0.55
Mel																																	
Mike													O	E				0.01	4.00					5.00					4.00				
Rob													O	E				0.01	4.00					5.00					4.00				

	Pump On						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert							T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start							0.50	0.99			0.99		0.50	0.99			0.99																
Ali							O	E				0.01	O	E				0.01	4.00				0.55	5.00				1.00	4.00				0.55
Mel																																	
Mike							O	E				0.01	O	E				0.01	4.00					5.00					4.00				
Rob							O	E				0.01	O	E				0.01	4.00					5.00					4.00				

	Pump On						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.99			0.99																
Ali													O	E				0.01	4.00				0.55	5.00				1.00	4.00				0.55
Mel																																	
Mike													O	E				0.01	4.00					5.00					4.00				
Rob													O	E				0.01	4.00					5.00					4.00				

Pump Station Existing PS 113 Case 1 U = Under O = Over E = Even T = Trial

	Pump Off						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start	0.50	0.10	0.02	0.01	0.01		0.50	0.10	0.03	0.04	0.04		0.50	0.10	0.02	0.01	0.01																
Ali	U	U	U	E		0.01	U	U	O	E		0.01	U	U	U	E		0.01	1.00				0.00	2.00				0.11	3.00				0.22
Mel																																	
Mike	U	U	U	E		0.01	U	U	O	E		0.01	U	U	U	E		0.01	1.00					2.00					3.00				
Rob	U	U	U	E		0.01	U	U	E	O		0.01	U	U	U	E		0.01	1.00					2.00					3.00				

	Pump Off						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start													0.50	0.05	0.02	0.01	0.01																
Ali													U	U	U	E		0.01	1.00				0.00	2.00				0.11	2.00				0.11
Mel																																	
Mike													U	U	U	E		0.01	1.00					2.00					2.00				
Rob													U	U	U	E		0.01	1.00					2.00					2.00				

	Pump On						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert							**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start							0.50	0.01			0.01		0.50	0.01			0.01																
Ali							U	E				0.01	U	E				0.01	1.00				0.00	2.00				0.11	2.00				0.11
Mel																																	
Mike							U	E				0.01	U	E				0.01	1.00					2.00					2.00				
Rob							U	E				0.01	U	E				0.01	1.00					2.00					2.00				

	Pump On						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start													0.50	0.01			0.01																
Ali													U	E				0.01	1.00				0.00	2.00				0.11	2.00				0.11
Mel																																	
Mike													U	E				0.01	1.00					2.00					2.00				
Rob													U	E				0.01	1.00					2.00					2.00				

Pump Station Existing PS 113 Case 2 U = Under O = Over E = Even T = Trial

	Pump Off						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start	0.50	0.05	0.06		0.06		0.50	0.10			0.10		0.50	0.05	0.02	0.03	0.03																
Ali	U	O	E			0.01	U	U				0.01	U	U	E	E		0.01	2.00				0.11	2.00				0.11	3.00				0.22
Mel																																	
Mike	U	U	U			0.01	U	E				0.01	U	E	O	E		0.01	2.00					2.00					3.00				
Rob	U	O	E			0.01	U	E				0.01	U	U	O	E		0.01	2.00					2.00					3.00				

	Pump Off						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.05	0.02	0.01	0.01																
Ali													U	U	U	E		0.01	2.00				0.11	2.00				0.11	2.00				0.11
Mel																																	
Mike													U	U	E	O		0.01	2.00					2.00					2.00				
Rob													U	U	U	E		0.01	2.00					2.00					2.00				

	Pump On						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert							T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start							0.50	0.05	0.02	0.03	0.03		0.50	0.03	0.02		0.02																
Ali							U	E	O	E		0.01	U	U	E			0.01	2.00				0.11	2.00				0.11	2.00				0.11
Mel																																	
Mike							U	U	O	E		0.01	U	U	E			0.01	2.00					2.00					2.00				
Rob							U	U	O	E		0.01	U	E	O			0.01	2.00					2.00					2.00				

	Pump On						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.01			0.01																
Ali													U	E				0.01	2.00				0.11	2.00				0.11	2.00				0.11
Mel																																	
Mike													U	E				0.01	2.00					2.00					2.00				
Rob													U	E				0.01	2.00					2.00					2.00				

Pump Station Existing PS 113 Case 3 U = Under O = Over E = Even T = Trial

	Pump Off						**Insufficient Capacity**						**Spill**						**Social**					**Environmental**					**Cost**				
Expert	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start	0.50	0.65			0.65		0.50	0.65			0.65		0.50	0.65			0.65																
Ali	O	E				0.05	O	E				0.05	O	E				0.05	3.00				0.22	3.00				0.22	3.00				0.22
Mel																																	
Mike	O	E				0.05	O	E				0.05	O	E				0.05	3.00					3.00					3.00				
Rob	O	E				0.05	O	E				0.05	O	E				0.05	3.00					3.00					3.00				

	Pump Off						**Sufficient Capacity**						**Spill**						**Social**					**Environmental**					**Cost**				
Expert													**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start													0.50	0.35			0.35																
Ali													U	E				0.05	3.00				0.22	3.00				0.22	3.00				0.22
Mel																																	
Mike													U	E				0.05	3.00					3.00					3.00				
Rob													U	E				0.05	3.00					3.00					3.00				

	Pump On						**Insufficient Capacity**						**Spill**						**Social**					**Environmental**					**Cost**				
Expert							**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start							0.50	0.35			0.35		0.50	0.35	0.20		0.20																
Ali							U	E				0.05	U	U	E			0.05	3.00				0.22	3.00				0.22	2.00				0.11
Mel																																	
Mike							U	E				0.05	U	U	E			0.05	3.00					3.00					2.00				
Rob							U	E				0.05	U	U	U			0.05	3.00					3.00					2.00				

	Pump On						**Sufficient Capacity**						**Spill**						**Social**					**Environmental**					**Cost**				
Expert													**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**CI**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**	**T-1**	**T-2**	**T-3**	**T-4**	**Finish**
Start													0.50	0.20	0.10		0.10																
Ali													U	U	E			0.05	3.00				0.22	3.00				0.22	2.00				0.11
Mel																																	
Mike													U	U	E			0.05	3.00					3.00					2.00				
Rob													U	U	E			0.05	3.00					3.00					2.00				

Pump Station Existing PS 113 Case 4 U = Under O = Over E = Even T = Trial

Case 1 U = Under O = Over E = Even

	Pump Off						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start	0.50	0.99			0.99		0.50	0.90			0.90		0.50	0.90			0.90																
Ali	O	E				0.05	O	E				0.05	O	E				0.05	3.00				0.22	3.00				0.22	4.00				0.55
Mel																																	
Mike	O	E				0.05	O	E				0.05	O	E				0.05	3.00					3.00					4.00				
Rob	O	E				0.05	O	E				0.05	O	E				0.05	3.00					3.00					4.00				

	Pump Off						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.75			0.75																
Ali													O	E				0.05	3.00				0.22	3.00				0.22	4.00				0.55
Mel																																	
Mike													O	E				0.05	3.00					3.00					4.00				
Rob													O	E				0.05	3.00					3.00					4.00				

	Pump On						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert							T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start							0.50	0.40	0.45		0.45		0.50	0.35	0.30		0.30																
Ali							U	E	E			0.05	U	U	E			0.05	3.00				0.22	3.00				0.22	3.00				0.22
Mel																																	
Mike							E	O	E			0.05	U	U	E			0.05	3.00					3.00					3.00				
Rob							U	E	E			0.05	U	U	E			0.05	3.00					3.00					3.00				

	Pump On						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.20			0.20																
Ali													U	U				0.10	3.00				0.22	3.00				0.22	3.00				0.22
Mel																																	
Mike													U	O				0.10	3.00					3.00					3.00				
Rob													U	E				0.10	3.00					3.00					3.00				

Pump Station Existing PS 113 Case 5 U = Under O = Over E = Even T = Trial

	Pump Off						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start	0.50	0.99			0.99		0.50	0.99			0.99		0.50	0.99			0.99																
Ali	O	E				0.01	O	E				0.01	O	E				0.01	3.00				0.22	3.00				0.22	4.00				0.55
Mel																																	
Mike	O	E				0.01	O	E				0.01	O	E				0.01	3.00					3.00					4.00				
Rob	O	E				0.01	O	E				0.01	O	E				0.01	3.00					3.00					4.00				

	Pump Off						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.99			0.99																
Ali													O	E				0.01	3.00				0.22	3.00				0.22	4.00				0.55
Mel																																	
Mike													O	E				0.01	3.00					3.00					4.00				
Rob													O	E				0.01	3.00					3.00					4.00				

	Pump On						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert							T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start							0.50	0.70			0.70		0.50	0.65			0.65																
Ali							O	E				0.05	O	E				0.05	3.00				0.22	3.00				0.22	3.00				0.22
Mel																																	
Mike							O	E				0.05	O	E				0.05	3.00					3.00					3.00				
Rob							O	E				0.05	O	E				0.05	3.00					3.00					3.00				

	Pump On						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.35	0.40		0.40																
Ali													U	E	E			0.05	3.00				0.22	3.00				0.22	3.00				0.22
Mel																																	
Mike													U	O	E			0.05	3.00					3.00					3.00				
Rob													U	O	E			0.05	3.00					3.00					3.00				

Pump Station Existing PS 113 Case 6 U = Under O = Over E = Even T = Trial

	Pump Off						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start	0.50	0.99			0.99		0.50	0.99			0.99		0.50	0.99			0.99																
Ali	O	E				0.01	O	E				0.01	O	E				0.01	4.00				0.55	4.00				0.55	4.00				0.55
Mel																																	
Mike	O	E				0.01	O	E				0.01	O	E				0.01	4.00					4.00					4.00				
Rob	O	E				0.01	O	E				0.01	O	E				0.01	4.00					4.00					4.00				

	Pump Off						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.99			0.99																
Ali													O	E				0.01	4.00				0.55	4.00				0.55	4.00				0.55
Mel																																	
Mike													O	E				0.01	4.00					4.00					4.00				
Rob													O	E				0.01	4.00					4.00					4.00				

	Pump On						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert							T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start							0.50	0.65	0.80	0.85	0.85		0.50	0.65	0.80		0.80																
Ali							O	O	O	E		0.05	O	O	E			0.05	4.00				0.55	4.00				0.55	3.00				0.22
Mel																																	
Mike							O	O	O	E		0.05	O	O	E			0.05	4.00					4.00					3.00				
Rob							O	O	O	E		0.05	O	O	E			0.05	4.00					4.00					3.00				

	Pump On						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.60			0.60																
Ali													U	E				0.05	4.00				0.55	4.00				0.55	3.00				0.22
Mel																																	
Mike													O	E				0.05	4.00					4.00					3.00				
Rob													O	E				0.05	4.00					4.00					3.00				

Pump Station Existing PS 113 Case 7 U = Under O = Over E = Even T = Trial

	Pump Off						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start	0.50	0.99			0.99		0.50	0.99			0.99		0.50	0.99			0.99																
Ali	O	E				0.01	O	E				0.01	O	E				0.01	4.00				0.55	5.00				1.00	4.00				0.55
Mel																																	
Mike	O	E				0.01	O	E				0.01	O	E				0.01	4.00					5.00					4.00				
Rob	O	E				0.01	O	E				0.01	O	E				0.01	4.00					5.00					4.00				

	Pump Off						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.99			0.99																
Ali													O	E				0.01	4.00				0.55	5.00				1.00	4.00				0.55
Mel													O	E																			
Mike																		0.01	4.00					5.00					4.00				
Rob													O	E				0.01	4.00					5.00					4.00				

	Pump On						Insufficient Capacity						Spill						Social					Environmental					Cost				
Expert							T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start							0.50	0.99			0.99		0.50	0.99			0.99																
Ali							O	E				0.01	O	E				0.01	4.00				0.55	5.00				1.00	4.00				0.55
Mel																																	
Mike							O	E				0.01	O	E				0.01	4.00					5.00					4.00				
Rob							O	E				0.01	O	E				0.01	4.00					5.00					4.00				

	Pump On						Sufficient Capacity						Spill						Social					Environmental					Cost				
Expert													T-1	T-2	T-3	T-4	Finish	CI	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish	T-1	T-2	T-3	T-4	Finish
Start													0.50	0.99			0.99																
Ali													O	E				0.01	4.00				0.55	5.00				1.00	4.00				0.55
Mel																																	
Mike													O	E				0.01	4.00					5.00					4.00				
Rob													O	E				0.01	4.00					5.00					4.00				

APPENDIX D: Decision Event Tree Analysis (Continued)

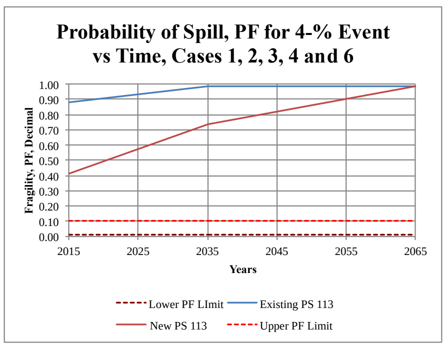
Part 2: Event Tree Computations

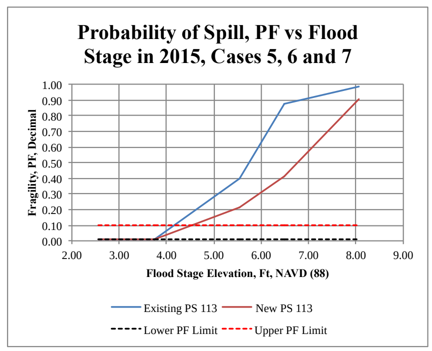
					Existing PS 113					New Pump Station				
Case	Scenario	Flood Stage Ft, NAVD (88)	Storm Event Decimal, P_E	# of MH Inundated %	Elev. 4+ Flood Stage Prob of 5-Hr Dur., %	Probability of Spill at Flood Stage, P_F Decimal[1]	Probability of Spill Occuring Over-One Year, P_L=$P_E(P_F)$	Additive Value Function, V(A)	Risk Score Decimal	72-Hr Prob Decimal	Probability of Spill at Flood Stage, P_F Decimal[1]	Probability of Spill Occuring Over-One Year, P_L=$P_E(P_F)$	Additive Value Function, V(A)	Risk Score Decimal
1	2015	2.56	0.99	8	23	0.01	0.01	0.42	0.001	23.000	0.01	0.01	0.42	0.001
2	2015	3.74	0.50	21	23	0.01	0.01	0.50	0.001	23.000	0.01	0.01	0.50	0.001
3	2015	5.53	0.10	50	23	0.40	0.04	0.76	0.009	23.000	0.22	0.02	0.70	0.004
4	2015	6.49	0.04	62	23	0.88	0.04	1.24	0.014	23.000	0.41	0.02	0.70	0.003
5	2035 Int High	7.10	0.04	71	34	0.99	0.04	1.24	0.016	34.000	0.74	0.03	0.70	0.006
6	2015 BFE	8.06	0.01	96	23	0.99	0.01	1.24	0.005	23.000	0.91	0.01	1.31	0.003
7	2065 Int High	8.35	0.04	100	74	0.99	0.04	1.84	0.027	74.000	0.99	0.04	2.72	0.027

1. Probability of Failure represents the chance for a spill of wastewater.

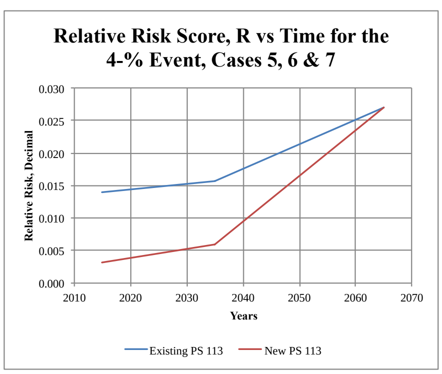
Probability Graphs											
		Existing PS 113				New PS 113					
Year	Elev	P_F	P_L	V(A)	Risk	P_F	P_L	V(A)	Risk	Lower P_L Limit[1]	Upper P_L Limit2
2015	6.49	0.88	0.04	1.24	0.014	0.41	0.02	0.70	0.003	0.01	0.10
2035	7.10	0.99	0.04	1.24	0.016	0.74	0.03	0.70	0.006	0.01	0.10
2065	8.35	0.99	0.04	1.84	0.027	0.99	0.04	2.72	0.027	0.01	0.10

1. Lower Performance Objective for operational pump station for a 4% design event equal to less than 2% in 50 years. See Limits Calcs sheet.
2. Upper Performance Objective for operational pump station for a 4% design event equal to less than 10% in 50 years. See Limits Calcs sheet.





Risk Graphs											
		Existing PS 113				New PS 113					
Scenario	Elev	P_F	P_L	V(A)	Risk	P_F	P_L	V(A)	Risk	Lower Limit	Upper Limit
2015-99%	2.56	0.01	0.01	0.42	0.001	0.01	0.01	0.42	0.001	0.01	0.10
2015-50%	3.74	0.01	0.01	0.50	0.001	0.01	0.01	0.50	0.001	0.01	0.10
2015-10%	5.53	0.40	0.04	0.76	0.009	0.22	0.02	0.70	0.004	0.01	0.10
2015-4%	6.49	0.88	0.04	1.24	0.014	0.41	0.02	0.70	0.003	0.01	0.10
2015 BFE	8.06	0.99	0.01	1.24	0.005	0.91	0.01	1.31	0.003	0.01	0.10



SLR Scenario	2015
ELEVATION:	2.56 Feet, NAVD (88)
Event P	0.990
% MH Inundated	8

Hazard, P_E		Event Tree Analysis - Fragility, P_F									Consequence Analysis, V(A)				Risk Score, R
											Social Impact Weights, w_1	Environment Impact Weights, w_2	Cost Impact Weights, w_3	Additive Value Function	
											0.17	0.29	0.54		
Event	P =	Alernative	Event	P =	Event	P =	Event	P =	Probability of Spill for Flood Stage, P_F	Probability of Spill Occuring Over One-Year, $P_L=P_E*P_F$	Social Impacts Function $V_1(x_1)$	Environment Impacts Function $V_2(x_2)$	Cost Impacts Function $V_3(x_3)$	$V(A)=\Sigma w_i*V_i(x_i)$	$R=P_E*P_F*V(A)$
Flood Stage Event	0.99	Existing Pump Station	Power Off	0.01	Insufficient Capacity	0.04	Spill	0.01	4.00E-06	3.96E-06	0.00	0.11	0.22	0.15	5.97E-07
							No Spill	0.99	3.96E-04	3.92E-04					
					Sufficient Capacity	0.96	Spill	0.01	9.60E-05	9.50E-05	0.00	0.11	0.11	0.09	8.68E-06
							No Spill	0.99	9.50E-03	9.41E-03					
			Power On	0.99	Insufficient Capacity	0.01	Spill	0.01	9.90E-05	9.80E-05	0.00	0.11	0.11	0.09	8.95E-06
							No Spill	0.99	9.80E-03	9.70E-03					
					Sufficient Capacity	0.99	Spill	0.01	9.80E-03	9.70E-03	0.00	0.11	0.11	0.09	8.86E-04
							No Spill	0.99	9.70E-01	9.61E-01					
							Total Expected Value		1.000	0.990			Totals	0.42	0.001
							Spill		0.010	0.010					
							No-Spill		0.990	0.980					
		New Pump Station	Power Off	0.01	Insufficient Capacity	0.04	Spill	0.01	4.00E-06	3.96E-06	0.00	0.11	0.22	0.15	5.97E-07
							No Spill	0.99	3.96E-04	3.92E-04					
					Sufficient Capacity	0.96	Spill	0.01	9.60E-05	9.50E-05	0.00	0.11	0.11	0.09	8.68E-06
							No Spill	0.99	9.50E-03	9.41E-03					
			Power On	0.99	Insufficient Capacity	0.01	Spill	0.01	9.90E-05	9.80E-05	0.00	0.11	0.11	0.09	8.95E-06
							No Spill	0.99	9.80E-03	9.70E-03					
					Sufficient Capacity	0.99	Spill	0.01	9.80E-03	9.70E-03	0.00	0.11	0.11	0.09	8.86E-04
							No Spill	0.99	9.70E-01	9.61E-01					
							Total Expected Value		1.000	0.990			Totals	0.42	0.001
							Spill		0.010	0.010					
							No-Spill		0.990	0.980					

CASE #:	2
SLR Scenario	2015
ELEVATION:	3.74 Feet, NAVD (88)
Event P	0.500
% MH Inundated	21

Hazard, P_E		Event Tree Analysis - Fragility, P_F										Consequence Analysis, V(A)				Risk Score, R
												Social Impact Weights, w_1	Environment Impact Weights, w_2	Cost Impact Weights, w_3	Additive Value Function	
												0.17	0.29	0.54		
Event	P =	Alternative	Event	P =	Event	P =	Event	P =	Probability of Failure, P_F	Probability of Spill Occuring Over One-Year, $P_L=P_E*P_F$		Social Impacts Function $V_1(x_1)$	Environment Impacts Function $V_2(x_2)$	Cost Impacts Function $V_3(x_3)$	$V(A)=\Sigma w_i*V_i(x_i)$	$R=P_E*P_F*V(A)$
							Spill	0.03	1.80E-04	9.00E-05		0.11	0.11	0.22	0.17	1.52E-05
					Insufficient Capacity	0.10										
							No Spill	0.97	5.82E-03	2.91E-03						
			Power Off	0.06												
							Spill	0.01	5.40E-04	2.70E-04		0.11	0.11	0.11	0.11	2.97E-05
					Sufficient Capacity	0.90										
							No Spill	0.99	5.35E-02	2.67E-02						
		Existing Pump Station														
							Spill	0.02	5.64E-04	2.82E-04		0.11	0.11	0.11	0.11	3.10E-05
					Insufficient Capacity	0.03										
							No Spill	0.98	2.76E-02	1.38E-02						
			Power On	0.94												
							Spill	0.01	9.12E-03	4.56E-03		0.11	0.11	0.11	0.11	5.01E-04
					Sufficient Capacity	0.97										
							No Spill	0.99	9.03E-01	4.51E-01						
						Total Expected Value			1.000	0.500				Totals	0.50	0.001
							Spill		0.010	0.005						
							No-Spill		0.990	0.495						
Flood Stage Event	0.50															
							Spill	0.03	1.80E-04	9.00E-05		0.11	0.11	0.22	0.17	1.52E-05
					Insufficient Capacity	0.10										
							No Spill	0.97	5.82E-03	2.91E-03						
			Power Off	0.06												
							Spill	0.01	5.40E-04	2.70E-04		0.11	0.11	0.11	0.11	2.97E-05
					Sufficient Capacity	0.90										
							No Spill	0.99	5.35E-02	2.67E-02						
		New Pump Station														
							Spill	0.02	5.64E-04	2.82E-04		0.11	0.11	0.11	0.11	3.10E-05
					Insufficient Capacity	0.03										
							No Spill	0.98	2.76E-02	1.38E-02						
			Power On	0.94												
							Spill	0.01	9.12E-03	4.56E-03		0.11	0.11	0.11	0.11	5.01E-04
					Sufficient Capacity	0.97										
							No Spill	0.99	9.03E-01	4.51E-01						
						Total Expected Value			1.000	0.500				Totals	0.50	0.001
							Spill		0.010	0.005						
							No-Spill		0.990	0.495						

CASE #:	3	
SLR Scenario		2015
ELEVATION:	5.53	Feet, NAVD (88)
Event P	0.100	
% MH Inundated	50	

Hazard, P_E		Event Tree Analysis - Fragility, P_F										Consequence Analysis, V(A)				Risk Score, R
												Social Impact Weights, w_1	Environment Impact Weights, w_2	Cost Impact Weights, w_3	Additive Value Function	
												0.17	0.29	0.54		
Event	P =	Alternative	Event	P =	Event	P =	Event	P =	Probability of Failure, P_F	Probability of Spill Occuring Over One-Year, $P_L=P_E*P_F$	Social Impacts Function $V_1(x_1)$	Environment Impacts Function $V_2(x_2)$	Cost Impacts Function $V_3(x_3)$	$V(A)=\Sigma w_i*V_i(x_i)$		$R=P_E*P_F*V(A)$
Flood Stage Event	0.10	Existing Pump Station	Power Off	0.65	Insufficient Capacity	0.65	Spill	0.65	2.75E-01	2.75E-02	0.22	0.22	0.22	0.22		6.04E-03
							No Spill	0.35	1.48E-01	1.48E-02						
					Sufficient Capacity	0.35	Spill	0.35	7.96E-02	7.96E-03	0.22	0.22	0.22	0.22		1.75E-03
							No Spill	0.65	1.48E-01	1.48E-02						
			Power On	0.35	Insufficient Capacity	0.35	Spill	0.20	2.45E-02	2.45E-03	0.22	0.22	0.11	0.16		3.93E-04
							No Spill	0.80	9.80E-02	9.80E-03						
					Sufficient Capacity	0.65	Spill	0.10	2.28E-02	2.28E-03	0.22	0.22	0.11	0.16		3.65E-04
							No Spill	0.90	2.05E-01	2.05E-02						
					Total Expected Value				1.000	0.100			Totals	0.76		0.009
							Spill		0.402	0.040						
							No-Spill		0.599	0.060						
		New Pump Station	Power Off	0.20	Insufficient Capacity	0.65	Spill	0.65	8.45E-02	8.45E-03	0.22	0.22	0.22	0.22		1.86E-03
							No Spill	0.35	4.55E-02	4.55E-03						
					Sufficient Capacity	0.35	Spill	0.35	2.45E-02	2.45E-03	0.22	0.22	0.11	0.16		3.93E-04
							No Spill	0.65	4.55E-02	4.55E-03						
			Power On	0.80	Insufficient Capacity	0.35	Spill	0.20	5.60E-02	5.60E-03	0.22	0.22	0.11	0.16		8.99E-04
							No Spill	0.80	2.24E-01	2.24E-02						
					Sufficient Capacity	0.65	Spill	0.10	5.20E-02	5.20E-03	0.22	0.22	0.11	0.16		8.35E-04
							No Spill	0.90	4.68E-01	4.68E-02						
					Total Expected Value				1.000	0.100			Totals	0.70		0.004
							Spill		0.217	0.022						
							No-Spill		0.783	0.078						

CASE #:	4
SLR Scenario	2015
ELEVATION:	6.49 Feet, NAVD (88)
Event P	0.040
% MH Inundated	62

Hazard, P_E		Event Tree Analysis - Fragility, P_F										Consequence Analysis, V(A)				Risk Score, R
												Social Impact Weights, w_1	Environment Impact Weights, w_2	Cost Impact Weights, w_3	Additive Value Function	
												0.17	0.29	0.54		
Event	P =	Alternative	Event	P =	Event	P =	Event	P =	Probability of Failure, P_F	Probability of Spill Occuring Over One-Year, $P_L=P_E*P_F$	Social Impacts Function $V_1(x_1)$	Environment Impacts Function $V_2(x_2)$	Cost Impacts Function $V_3(x_3)$	$V(A)=\Sigma w_i*V_i(x_i)$		$R=P_E*P_F*V(A)$
Flood Stage Event	0.04	Existing Pump Station	Power Off	0.99	Insufficient Capacity	0.90	Spill	0.90	8.02E-01	3.21E-02	0.22	0.22	0.55	0.40		1.28E-02
							No Spill	0.10	8.91E-02	3.56E-03						
					Sufficient Capacity	0.10	Spill	0.75	7.43E-02	2.97E-03	0.22	0.22	0.55	0.40		1.18E-03
							No Spill	0.25	2.48E-02	9.90E-04						
			Power On	0.01	Insufficient Capacity	0.45	Spill	0.30	1.35E-03	5.40E-05	0.22	0.22	0.22	0.22		1.19E-05
							No Spill	0.70	3.15E-03	1.26E-04						
					Sufficient Capacity	0.55	Spill	0.20	1.10E-03	4.40E-05	0.22	0.22	0.22	0.22		9.68E-06
							No Spill	0.80	4.40E-03	1.76E-04						
							Total Expected Value		1.000	0.040			Totals	1.24		0.014
							Spill		0.879	0.035						
							No-Spill		0.121	0.005						
		New Pump Station	Power Off	0.35	Insufficient Capacity	0.80	Spill	0.80	2.24E-01	8.96E-03	0.22	0.22	0.22	0.22		1.97E-03
							No Spill	0.20	5.60E-02	2.24E-03						
					Sufficient Capacity	0.20	Spill	0.40	2.80E-02	1.12E-03	0.22	0.22	0.11	0.16		1.80E-04
							No Spill	0.60	4.20E-02	1.68E-03						
			Power On	0.65	Insufficient Capacity	0.45	Spill	0.30	8.78E-02	3.51E-03	0.22	0.22	0.11	0.16		5.64E-04
							No Spill	0.70	2.05E-01	8.19E-03						
					Sufficient Capacity	0.55	Spill	0.20	7.15E-02	2.86E-03	0.22	0.22	0.11	0.16		4.59E-04
							No Spill	0.80	2.86E-01	1.14E-02						
							Total Expected Value		1.000	0.040			Totals	0.70		0.003
							Spill		0.411	0.016						
							No-Spill		0.589	0.024						

CASE #:	5
SLR Scenario	2035 Inter High
ELEVATION:	7.10 Feet, NAVD (88)
Event P	0.040
% MH Inundated	71

Hazard, P_E		Event Tree Analysis - Fragility, P_F										Consequence Analysis, V(A)				Risk Score, R
												Social Impact Weights, w_1	Environment Impact Weights, w_2	Cost Impact Weights, w_3	Additive Value Function	
												0.17	0.29	0.54		
Event	P =	Alternative	Event	P =	Event	P =	Event	P =	Probability of Failure, P_F	Probability of Spill Occuring Over One-Year, $P_L=P_E*P_F$	Social Impacts Function $V_1(x_1)$	Environment Impacts Function $V_2(x_2)$	Cost Impacts Function $V_3(x_3)$	$V(A)=\Sigma w_i*V_i(x_i)$		$R=P_E*P_F*V(A)$
Flood Stage Event	0.04	Existing Pump Station	Power Off	0.99	Insufficient Capacity	0.99	Spill	0.99	9.70E-01	3.88E-02	0.22	0.22	0.55	0.40		0.0155
							No Spill	0.01	9.80E-03	3.92E-04						
					Sufficient Capacity	0.01	Spill	0.99	9.80E-03	3.92E-04	0.22	0.22	0.55	0.40		0.0002
							No Spill	0.01	9.90E-05	3.96E-06						
			Power On	0.01	Insufficient Capacity	0.70	Spill	0.65	4.55E-03	1.82E-04	0.22	0.22	0.22	0.22		0.0000
							No Spill	0.35	2.45E-03	9.80E-05						
					Sufficient Capacity	0.30	Spill	0.40	1.20E-03	4.80E-05	0.22	0.22	0.22	0.22		0.0000
							No Spill	0.60	1.80E-03	7.20E-05						
							Total Expected Value		1.000	0.040			Totals	1.24		0.02
							Spill		0.986	0.039						
							No-Spill		0.014	0.001						
		New Pump Station	Power Off	0.65	Insufficient Capacity	0.90	Spill	0.90	5.27E-01	2.11E-02	0.22	0.22	0.22	0.22		4.63E-03
							No Spill	0.10	5.85E-02	2.34E-03						
					Sufficient Capacity	0.10	Spill	0.45	2.93E-02	1.17E-03	0.22	0.22	0.11	0.16		1.88E-04
							No Spill	0.55	3.58E-02	1.43E-03						
			Power On	0.35	Insufficient Capacity	0.65	Spill	0.60	1.37E-01	5.46E-03	0.22	0.22	0.11	0.16		8.77E-04
							No Spill	0.40	9.10E-02	3.64E-03						
					Sufficient Capacity	0.35	Spill	0.35	4.29E-02	1.72E-03	0.22	0.22	0.11	0.16		2.75E-04
							No Spill	0.65	7.96E-02	3.19E-03						
							Total Expected Value		1.000	0.040			Totals	0.70		0.006
							Spill		0.735	0.029						
							No-Spill		0.265	0.011						

CASE #:	6
SLR Scenario	2015 BFE
ELEVATION:	8.06 Feet, NAVD (88)
Event P	0.010
% MH Inundated	96

Hazard, P_E		Event Tree Analysis - Fragility, P_F										Consequence Analysis, V(A)				Risk Score, R
												Social Impact Weights, w_1	Environment Impact Weights, w_2	Cost Impact Weights, w_3	Additive Value Function	
												0.17	0.29	0.54		
Event	P =	Alternative	Event	P =	Event	P =	Event	P =	Probability of Failure, P_F	Probability of Spill Occuring Over One-Year, $P_L=P_E*P_F$	Social Impacts Function $V_1(x_1)$	Environment Impacts Function $V_2(x_2)$	Cost Impacts Function $V_3(x_3)$	$V(A)=\Sigma w_i*V_i(x_i)$		$R=P_E*P_F*V(A)$
Flood Stage Event	0.01	Existing Pump Station	Power Off	0.99	Insufficient Capacity	0.99	Spill	0.99	9.70E-01	9.70E-03	0.55	0.55	0.55	0.55		5.34E-03
							No Spill	0.01	9.80E-03	9.80E-05						
					Sufficient Capacity	0.01	Spill	0.99	9.80E-03	9.80E-05	0.55	0.55	0.55	0.55		5.39E-05
							No Spill	0.01	9.90E-05	9.90E-07						
			Power On	0.01	Insufficient Capacity	0.85	Spill	0.80	6.80E-03	6.80E-05	0.55	0.55	0.22	0.37		2.53E-05
							No Spill	0.20	1.70E-03	1.70E-05						
					Sufficient Capacity	0.15	Spill	0.60	9.00E-04	9.00E-06	0.55	0.55	0.22	0.37		3.35E-06
							No Spill	0.40	6.00E-04	6.00E-06						
						Total Expected Value			1.000	0.010			Totals	1.84		0.005
							Spill		0.988	0.010						
							No-Spill		0.012	0.000						
		New Pump Station	Power Off	0.80	Insufficient Capacity	0.95	Spill	0.95	7.22E-01	7.22E-03	0.55	0.55	0.22	0.37		2.68E-03
							No Spill	0.05	3.80E-02	3.80E-04						
					Sufficient Capacity	0.05	Spill	0.75	3.00E-02	3.00E-04	0.55	0.55	0.11	0.31		9.37E-05
							No Spill	0.25	1.00E-02	1.00E-04						
			Power On	0.20	Insufficient Capacity	0.85	Spill	0.80	1.36E-01	1.36E-03	0.55	0.55	0.11	0.31		4.25E-04
							No Spill	0.20	3.40E-02	3.40E-04						
					Sufficient Capacity	0.15	Spill	0.60	1.80E-02	1.80E-04	0.55	0.55	0.11	0.31		5.62E-05
							No Spill	0.40	1.20E-02	1.20E-04						
						Total Expected Value			1.000	0.010			Totals	1.31		0.003
							Spill		0.906	0.009						
							No-Spill		0.094	0.001						

CASE #:	7
SLR Scenario	2065 Inter High
ELEVATION:	8.35 Feet, NAVD (88)
Event, P_E	0.040
% MH Inundated	100

Hazard, P_E		Event Tree Analysis - Fragility, P_F										Consequence Analysis, V(A)				Risk Score, R
												Social Impact Weights, w_1	Environment Impact Weights, w_2	Cost Impact Weights, w_3	Additive Value Function	
												0.17	0.29	0.54		
Event	P =	Alternative	Event	P =	Event	P =	Event	P =	Probability of Failure, P_F	Probability of Spill Occuring Over One-Year, $P_L=P_E*P_F$		Social Impacts Function $V_1(x_1)$	Environment Impacts Function $V_2(x_2)$	Cost Impacts Function $V_3(x_3)$	$V(A)=\Sigma w_i*V_i(x_i)$	$R=P_E*P_F*V(A)$
Flood Stage Event	0.04	Existing Pump Station	Power Off	0.99	Insufficient Capacity	0.99	Spill	0.99	9.70E-01	3.88E-02		0.55	1.00	0.55	0.68	2.64E-02
							No Spill	0.01	9.80E-03	3.92E-04						
					Sufficient Capacity	0.01	Spill	0.99	9.80E-03	3.92E-04		0.55	1.00	0.55	0.68	2.67E-04
							No Spill	0.01	9.90E-05	3.96E-06						
			Power On	0.01	Insufficient Capacity	0.99	Spill	0.99	9.80E-03	3.92E-04		0.55	1.00	0.55	0.68	2.67E-04
							No Spill	0.01	9.90E-05	3.96E-06						
					Sufficient Capacity	0.01	Spill	0.99	9.90E-05	3.96E-06		0.55	1.00	0.55	0.68	2.69E-06
							No Spill	0.01	1.00E-06	4.00E-08						
							Total Expected Value		1.000	0.040				Totals	2.72	0.027
							Spill		0.990	0.040						
							No-Spill		0.010	0.000						
		New Pump Station	Power Off	0.99	Insufficient Capacity	0.99	Spill	0.99	9.70E-01	3.88E-02		0.55	1.00	0.55	0.68	2.64E-02
							No Spill	0.01	9.80E-03	3.92E-04						
					Sufficient Capacity	0.01	Spill	0.99	9.80E-03	3.92E-04		0.55	1.00	0.55	0.68	2.67E-04
							No Spill	0.01	9.90E-05	3.96E-06						
			Power On	0.01	Insufficient Capacity	0.99	Spill	0.99	9.80E-03	3.92E-04		0.55	1.00	0.55	0.68	2.67E-04
							No Spill	0.01	9.90E-05	3.96E-06						
					Sufficient Capacity	0.01	Spill	0.99	9.90E-05	3.96E-06		0.55	1.00	0.55	0.68	2.69E-06
							No Spill	0.01	1.00E-06	4.00E-08						
							Total Expected Value		1.000	0.040				Totals	2.72	0.027
							Spill		0.990	0.040						
							No-Spill		0.010	0.000						

Event Tree Analysis for Existing PS 113							
Scenario	Sea Level Stage E(Δt=t2-t1), Feet[1]	Storm Event w/ Wave Set-Up, Feet, NAVD (88)[2, 3]					
		99%	50%	10%	4%	1%	0.2%
2015	0.00	2.56	3.74	5.53	6.49	8.06	9.89
2025 Inter High	0.28	2.84	4.02	5.81	6.77	8.34	10.17
2035 Inter High	0.61	3.17	4.35	6.14	7.10	8.67	10.50
2045 Inter High	0.98	3.54	4.72	6.51	7.47	9.04	10.87
2055 Inter High	1.40	3.96	5.14	6.93	7.89	9.46	11.29
2065 Inter High	1.86	4.42	5.60	7.39	8.35	9.92	11.75

1. Sea Level

2. Storm Event elevations from SLR Curves with Flood Levels spreadsheet. Also, Table 12 in report.

3. Elevations highlighted in green used for study.

Existing Pump Station 113																								
Hazard, P_E					Event Tree Fragility, P_F																			
		Flood Stage	Storm Event	# of MH In-undated	Elev. 4+ Prob of 5-hr	Power		Power Off		Power On		Power Off				Power On				Prob-ability for	Value Function V(A)	Risk Score R
												Insufficient Capacity		Sufficient Capacity		Insufficient Capacity		Sufficient Capacity				
Case	Scenario	Ft, NAVD (88)	Decimal	%	%	Off	On	Insuff Capacity	Suff Capacity	Insuff Capacity	Suff Capacity	Spill	No Spill	Spill	No Spill	Spill	No Spill	Spill	No Spill	Decimal	Decimal	Decimal
1	2015 BFE	2.56	0.99	8	23	0.01	0.99	0.04	0.96	0.01	0.99	0.01	0.99	0.01	0.99	0.01	0.99	0.01	0.99	0.010	0.42	0.001
2	2015 BFE	3.74	0.50	21	23	0.06	0.94	0.10	0.90	0.03	0.97	0.03	0.97	0.01	0.99	0.02	0.98	0.01	0.99	0.010	0.50	0.001
3	2015 BFE	5.53	0.10	50	23	0.65	0.35	0.65	0.35	0.35	0.65	0.65	0.35	0.35	0.65	0.20	0.80	0.10	0.90	0.402	0.76	0.009
4	2015 BFE	6.49	0.04	62	23	0.99	0.01	0.90	0.10	0.45	0.55	0.90	0.10	0.75	0.25	0.30	0.70	0.20	0.80	0.879	1.24	0.014
5	2035 Inter High	7.10	0.04	71	34	0.99	0.01	0.99	0.01	0.70	0.30	0.99	0.01	0.99	0.01	0.65	0.35	0.40	0.60	0.986	1.24	0.016
6	2015 BFE	8.06	0.01	96	23	0.99	0.01	0.99	0.01	0.85	0.15	0.99	0.01	0.99	0.01	0.80	0.20	0.60	0.40	0.988	1.84	0.005
7	2065 Inter High	8.35	0.04	100	74	0.99	0.01	0.99	0.01	0.99	0.01	0.99	0.01	0.99	0.01	0.99	0.01	0.99	0.01	0.990	2.72	0.027

New Pump Station 113																								
Hazard, P_E					Event Tree Fragility, P_F																			
		Flood Stage	Storm Event	# of MH In-undated	Elev. 4+ Prob of 5-hr	Power		Power Off		Power On		Power Off				Power On				Prob-ability for	Value Function V(A)	Risk Score R
												Insufficient Capacity		Sufficient Capacity		Insufficient Capacity		Sufficient Capacity				
Case	Scenario	Ft, NAVD (88)	Decimal	%	%	Off	On	Insuff Capacity	Suff Capacity	Insuff Capacity	Suff Capacity	Spill	No Spill	Spill	No Spill	Spill	No Spill	Spill	No Spill	Decimal	Decimal	Decimal
1	2015 BFE	2.56	0.99	8	23	0.01	0.99	0.04	0.96	0.01	0.99	0.01	0.99	0.01	0.99	0.01	0.99	0.01	0.99	0.010	0.42	0.001
2	2015 BFE	3.74	0.50	21	23	0.06	0.94	0.10	0.90	0.03	0.97	0.03	0.97	0.01	0.99	0.02	0.98	0.01	0.99	0.010	0.50	0.001
3	2015 BFE	5.53	0.10	50	23	0.20	0.80	0.65	0.35	0.35	0.65	0.65	0.35	0.35	0.65	0.20	0.80	0.10	0.90	0.217	0.70	0.004
4	2015 BFE	6.49	0.04	62	23	0.35	0.65	0.80	0.20	0.45	0.55	0.80	0.20	0.40	0.60	0.30	0.70	0.20	0.80	0.411	0.70	0.003
5	2035 Inter High	7.10	0.04	71	34	0.65	0.35	0.90	0.10	0.65	0.35	0.90	0.10	0.45	0.55	0.60	0.40	0.35	0.65	0.735	0.70	0.006
6	2015 BFE	8.06	0.01	96	23	0.80	0.20	0.95	0.05	0.85	0.15	0.95	0.05	0.75	0.25	0.80	0.20	0.60	0.40	0.906	1.31	0.003
7	2065 Inter High	8.35	0.04	100	74	0.99	0.01	0.99	0.01	0.99	0.01	0.99	0.01	0.99	0.01	0.99	0.01	0.99	0.01	0.990	2.72	0.027

VITA

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Employment and Position
From 2010 to 2015, graduate student, Old Dominion University (ODU), Civil and Environmental Engineering (CEE) program and as of February 2014, a doctoral candidate

- Member, ODU, Center for Sea Level Rise, Infrastructure Working Group
- Adjunct instructor for ODU, Department of CEE

From 1974 to 2010, a civil (geotechnical) engineer for the U. S. Army Corps of Engineers, retiring as Deputy Chief of Engineering and Construction, Civil Works Directorate, Headquarters, 441 G ST. NW, Washington, DC 20314-1000

Education
ME, 1993, Civil and Environmental Engineering, Old Dominion University, Norfolk, VA
BS, 1974, Civil Engineering, The Pennsylvania State University, State College, PA
BA, 1973, General Engineering, St. Francis College, Loretto, PA

Certifications
Certification in Coastal Engineering, Old Dominion University, 2012
American Society of Civil Engineers, Academy for Geo-Professionals, Diplomate

Professional License
Professional Engineer, Virginia

Academic Committee Memberships
Civil & Environmental Engineering Visiting Council, Old Dominion University
Civil Engineering Advisory Council, U. S. Coast Guard Academy

Selected Professional Memberships and Activities
Chi Epsilon, National Engineering Honor Society
American Society of Civil Engineers, Fellow and Life Member

- Member, AGP Board of Trustees

Society of American Military Engineers (SAME)

- Old Dominion University, SAME Student Chapter Faculty Advisor

American Shore and Beach Preservation Association