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Flood Damage and Shutdown Times for Industrial Process Facilities

Matthew Lane Flynn

Louisiana State University and Agricultural and Mechanical College

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FLOOD DAMAGE AND SHUTDOWN TIMES FOR INDUSTRIAL PROCESS FACILITIES

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Construction Management

by
Matthew Lane Flynn
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ABSTRACT

The vulnerability of the Gulf Coast to inundation poses a real threat to both national security and the regional economy due to the concentration of the nation's energy infrastructure throughout the waterways of the southeastern United States' waterways. Mitigation efforts thus far have been qualitative and fail to provide raw, quantitative data to aid in the successful management of flooding liabilities. This paper proposes a novel approach to analyzing infrastructure susceptibility by means of a component-based approach to consequences posed by water-borne incursions. Systems are simplified to collections of components, each with a lowest-member elevation, thereby identifying the benchmark for vulnerability. Further, the maintenance efforts required to return these systems to processing capability are integrated into the component database, identified by available repair and replacement tasks. Simulations for site-specific flood information are analyzed through National Oceanic and Atmospheric Agency data, which provide the expected inundation levels for the five separate categories of tropical events on the Saffir-Simpson Hurricane Wind Scale. These levels are applied to the elevations determined in the component analysis, thereby producing a legitimate estimate, measured in manhours, for reconstruction efforts following a flood event. These manhours are then used to calculate cost within a labor database composed of technical laborers and supervision, yielding a labor cost. Material costs based on historic pricing, equipment costs based on current market rates, and company overhead costs, composed of site project management, are aggregated to realize a total direct cost as a result of inundation at a specified flood depth. From this total direct cost, decisions at the owner level can be made concerning acceptable risk with quantitative data to support mitigation and prevention strategies.

CHAPTER 1: INTRODUCTION

The U.S. Gulf Coast is an industrialized landscape marked by an array of process facilities extending from Alabama to the Texas/Mexico border. This area faces flood threats both from riverine flooding in the spring as well as coastal surges accompanying the Atlantic hurricane season's storms. Bolstering the U.S. oil and gas industry's resilience to coastal hazards has the promise to decrease an estimated \$350 billion in expected hurricane reconstruction expenditures over the next two decades, an amount nearly three percent of the regional GDP (Entergy 2010). It is estimated that approximately ninety-five percent of flood losses can be mitigated by following proper flood protection techniques (Rose, Porter et al. 2007), thereby increasing the impetus for developing appropriate means to understand flood damage within the confines of individual industrial sites. A more resilient infrastructure capable of resisting the impacts of flood hazards would also reduce the risks of materials release following a major event (Pine 2006, Stout, Liu et al. 2007). Risks posed to the surrounding community and environment, due to infrastructure failure, can therefore be reasonably lessened by refining flood damage assessment and developing prevention strategies. Local communities that are economically tied to the operation of plants would similarly benefit from better understanding and mitigation of flood hazards by reducing plant shutdowns and outages, providing more stable employment for workers.

Barriers to the development of industrial infrastructure vulnerability assessment methodologies to flooding have been identified by several scholars. The cornerstone of these barriers is the wide range of systems and components within the broad industrial structure classification (Booyesen, Viljoen et al. 1999). *Building use* is the key difference between the evaluation of industrial facility susceptibility and other occupancies. It is not possible to define industrial facilities within the same taxonomic systems used for residential and commercial

structures. Standard damage may be assessed for the latter in terms of loss per unit area (Blong 2003) due to the lack of material and construction variance across the landscape. However, production processes vary significantly (e.g., textile mills, breweries, oil refineries), which concentrates capital assets in a wide range of locations, precluding the implementation of a standardized loss per unit area approach across all industrial structures. Moreover, the effort required to detail the affected object's behavior and aggregate flood performance metrics into a standard approach for the entire industrial landscape of a region would be too great (Merz, Kreibich et al. 2010).

In spite of these previous findings, the economic value of industrial process facilities, their importance to national security, and the potential economic and environmental consequences of flood damage to those facilities are so great that development of methodologies to estimate the shutdown and economic impacts of flood events is imperative. By taking advantage of computational power and relational databases, it is possible to construct component-based depth-consequence relationships for specific facilities, which can be further extended to the network level. As the predecessor to the conceptualization of industrial flood vulnerability analysis, Kates (1965) proposed the use of synthetic flood functions to clarify the benefits of alternative adjustments to structures and land use change through the use of a five-step process that crudely quantified impacts within the entire industrial flood zone. Of particular interest is his fourth point, the focus of this research, which is to design a matrix in which appropriate stage-unit functions are applied to the specified structure, contents, and production components.

Establishing a benchmark for the development of modern flood vulnerability assessment techniques, Kates noted that his system was lacking, and that the ideal synthesis of information

would grow from individual facilities, with inventories being developed and consequence functions realized. Perhaps it may be “science fiction of the highest order” (Kates 1963, p. 26), but by anticipating failures in the system before they develop, mitigation can be proactive in preventing possible future disruptions.

This proposed process reconciles the barriers identified by previous scholars with the aims of Kates to synthesize a holistic method for the identification and quantification of the vulnerabilities of not only individual plants, but also of an industrialized region as a total system. Foremost, by combining the noted weaknesses detailed throughout the existing literature, the assessment commences at the component level and is extended on a systems basis only to the boundaries of the facility. By analyzing the effects of inundation, starting with the most basic elements of plant functions, a better means to understand and mitigate flood damage is not only realized through this ground-up approach, but a general template is also constructed for application to all elements of the industrial built environment.

1.1 Problem Statement

Flood vulnerability assessments are key to optimal decision-making for flood mitigation strategies, but little academic attention has been devoted to improve assessment of industrial infrastructure vulnerabilities (Merz, Kreibich et al. 2010). Insurance companies and others dedicate large amounts of money for damage modeling, but the focus of these studies is generally an overall risk assessment of the landscape, rather than a specific facility owner-level vulnerability study to locate and remedy issues in planning for flood damage. Current loss evaluations are based on qualitative estimates (Changnon 2003), leaving a gap in the translation from descriptive to numerical calculation of waterborne threats. The quantification of loss potential is essential for understanding and communicating the inherent liabilities of the

constructed environment in response to natural hazards (Downton and Pielke 2005, Scawthorn, Flores et al. 2006).

1.2 Goals of the Study

The goal of this study is to quantify the economic threat of flooding to process facilities. As a step toward achieving this goal, this research details a conceptual vulnerability assessment process (VAP) to estimate the repair requirements, shutdown/outage time (i.e., schedule), and economic cost consequences for process facilities using a component-based approach. This is realized in two objectives:

1. Design a component-based VAP methodology to determine consequences of inundation at the part/unit level that aggregates flood, facility, and repair/replacement (construction) information in a single location for review.
2. Test the developed VAP by applying it to a complete subsystem to demonstrate flood depth-consequences within that process, rendering manpower and equipment requirements and budget to bring that subsystem back into a production capacity.

1.3 Scope of the Study

The information developed from this research can be applied horizontally across industrial facilities. It is a component-based approach, rendering reliable data based on the quality of the inputs, specifically the inventory of parts within the system.

1.4 Limitations of the Study

This research focuses on the direct consequences of inundation to process facilities. It does not identify costs associated with indirect consequences such as environmental cleanup of any shutdown-caused release, local economic hardship due to extended plant shutdown/outage time, or capital losses accrued by the owner from decreased production capacity through the

duration of the maintenance. Further, the flood scenarios are based on the data available, and while many facilities in the area under investigation have levees, berms, and other structures in place to control floodwater incursion, this study has no means of evaluating the quality of those structures, and therefore takes for granted that the protection will perform as expected under all conditions.

1.5 Organization of the Thesis

This thesis is organized by objective topic. Chapter 2 presents the development of a Vulnerability Assessment Process framework for understanding consequences in industrial facilities. Key to this chapter is clearly defining terms and phrases used throughout the body of this research, as well as presenting and explaining the databases used for investigation. Chapter 3 serves as an application of the proposed framework to a specific unit within a process facility. Chapter 4 discusses the conclusions reached by the study, and proposes recommendations for future work.

CHAPTER 2: DEVELOPMENT OF VULNERABILITY ASSESSMENT PROCESS FRAMEWORK FOR INDUSTRIAL FACILITIES

This chapter provides clarification for terms specific to this research. It also highlights the nature of the relationships within industrial facilities to enhance understanding of subsystem components' interdependency. Ultimately, the aforementioned are molded, through the tropical event and facility data, as well as maintenance labor information, into a concisely developed methodology for determining the total direct costs associated with returning processing capability following infrastructure inundation.

2.1 Concept of Vulnerability

Vulnerability generally refers to the degree to which a system is likely to experience harm due to exposure to a hazard (Brooks 2003, Turner, Kaspersen et al. 2003). For flood hazards, it can therefore be understood to mean “susceptibility to damage” posed by floodwaters, with the inundation level acting as the independent variable. In turn, a thorough vulnerability assessment involves examining system elements and design, as well as identifying component failure modes in response to a given set of threats (Baker 2005). This comprehensive facility vulnerability assessment establishes the framework to organize a system of components with associated damage functions and failure modes in response to hazard impacts. The database formed from this consequence matrix serves as the foundation for the synthetic estimation analysis proposed in this paper.

2.2 Flood Vulnerability Assessment and Management

Flood management has undergone a shift in focus from original practices implemented by land developers, which prioritize containing the hazard through flood control structures (e.g., dikes, levee systems). Rather than simply mitigating flood risk, expansion of the built environment within the floodplain requires more consideration of the performance of at-risk

elements exposed to flood hazards (Merz, Kreibich et al. 2010). Contemporary practices recognize system elements and layout, and attempt to evaluate their failure modes within the context of the natural threat to identify the overall flooding vulnerability to the system. These practices tend to identify “critical” components where a loss of function would immediately lead to downstream failures within the process system. However, the failure to recognize the importance of “non-critical” elements on overall system performance may have devastating consequences. For example, an oil spool piece has flange gaskets that, should they fail in a flood event, will allow contaminated water to enter the lubrication system, potentially causing damage to the efficiency and alignment of rotating machinery, thus transforming a seemingly noncritical element into an essential component within the function of the total system. To account for this, the operation, design, and interrelationships of the plant (i.e., plant subsystems and subsystem components) are detailed within the proposed VAP to determine failure modes and system repair requirements. From this point of view, the importance of individual process subsystems is recognized and recommendations can be made to reduce the vulnerability of the subsystem, and in turn the total facility system (Baker 2005).

2.3 Damage Estimation

The contemporary approach to determining costs associated with natural hazards is economic estimation of direct damage (i.e. monetary loss) by applying depth-damage functions (Krzysztofowicz and Davis 1983, Dutta, Herath et al. 2003, Van der Sande, De Jong et al. 2003, Merz, Kreibich et al. 2004, Apel, Thielen et al. 2006, Pistrika and Tsakiris 2007, Friedland 2009). Rather than using the term “depth-damage,” this paper utilizes a more appropriate “depth-consequence” conceptualization to characterize inundation impacts. The depth-consequence function integrates the idea of physical damage with an estimate of facility loss to define the quantifiable effects of flooding within a single facility. To clarify disparity between the terms

within the context of the framework, the following distinction between damage and loss is incorporated (Friedland 2009):

- Damage is a direct consequence, expressed as a physical attribute that can be directly measured in terms of a level of degradation, spoil, removal or destruction
- Loss is an indirect consequence, measured as the monetary obligation required to return a physically damaged condition to its full, undamaged state, expressed in absolute or relative economic terms

Messner and Meyer (2006) emphasized the importance of spatial scale for flooding characteristics, differentiating macro-, meso-, and micro-scale approaches. As this VAP focuses on an individual facility, and more specifically, components and subsystems within that facility, a micro-level approach is taken, “as small-scale analyses tend to use more accurate methods” (Messner and Meyer 2006, p. 13). Further, absolute depth-loss functions, in which increased inundation is directly correlated with increased consequences (Penning-Rowse and Chatterton 1977, Penning-Rowse, Johnson et al. 2003), are disregarded in favor of a relative depth-consequence function so that Kates’ adaptation option function can be incorporated.

2.4 Understanding Component Relationships

It is necessary to fully understand the nature of the analysis within the facility by defining terms used in the context of this paper. Rinaldi, Peerenboom et al. (2001) proposed a hierarchy of terms for a taxonomic identification of plant components, which is modified here with specific examples for oil and gas process facilities. *Parts* are individually identifiable components (e.g. a length of pipe or a bearing within a motor). *Units* are a collection of parts (e.g. insulated piping assemblies and complete motors). A *subsystem* refers to an entity of interdependent units (e.g. the oil house for a gas turbine containing motors, pumps, electrical systems, and piping). The

system is an aggregation of all subsystems fulfilling a common task (e.g. a mechanical starting package, a generator, a gas turbine, and a boiler, with all auxiliary subsystems, produce the steam supply for an oil refinery). *Infrastructure* is understood as the complete network of systems within a particular field (e.g. an oil refinery's process systems are fed by steam created from a cogeneration system, which also supplies surplus electricity to instrumentation and control systems).

2.5 Failure Modes

Descriptions of failure modes allow separation of the characteristics of impact upon the system through the failure of parts, units, and subsystems (Rinaldi, Peerenboom et al. 2001). A *cascading* failure is a disruption affecting each downstream process from the initial failure (e.g. a water-permeated gasket in one unit results in a water intrusion into the lube oil subsystem, leading to damage in the mechanical function of the entire gas turbine system). An *escalating* failure is a disruption in one system that causes a failure in a second, independent system (e.g. an unscheduled outage resulting from water intrusion in the gas turbine system forces a refinery to shutdown coker processes due to decreased steam feedstock). Finally, *isolated* failures are those disruptions that do not affect production processes or other elements of the system. Cognizance of the interactions within the infrastructure is vital to recognizing the scope of potentially small threats to overall resiliency.

2.6 Proposed Component-Level Vulnerability Assessment Process

The proposed component-based approach for assessing industrial flood vulnerability assessment is outlined in Figure 2.1. The process depends upon two phases: 1) collection of facility information and construction of the associated database, and 2) synthetic damage and economic loss modeling.

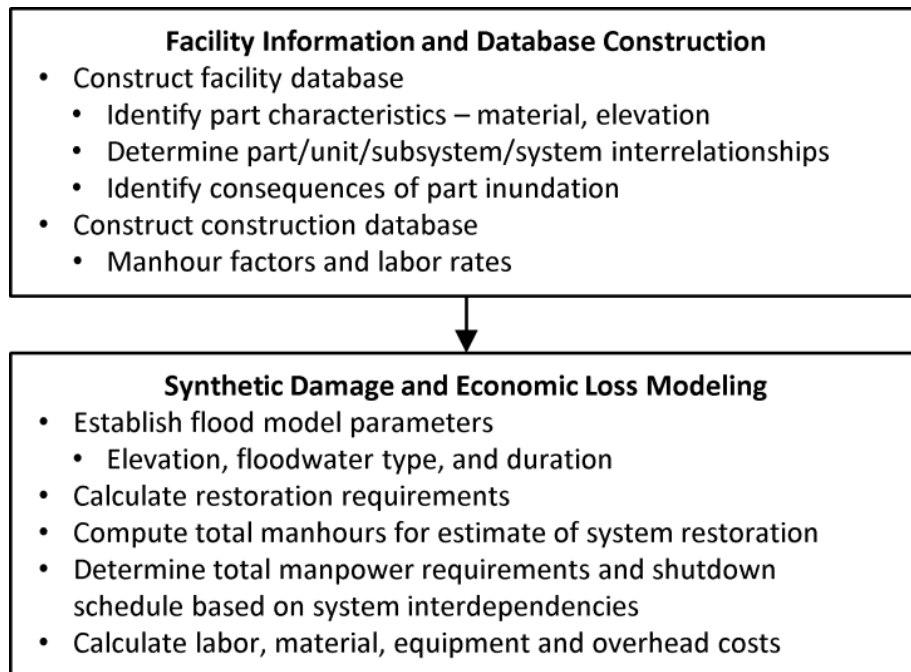


Figure 2.1 Component-based VAP methodology outline

2.6.1 Facility Database

The first phase of the infrastructure VAP requires detailing the specific site through the use of facility documents or electronic copies of plant information. Piping and instrumentation diagrams (P&IDs) and equipment drawings are reviewed to develop a complete component inventory. The site plans of the facility are also useful to determine structural bottom-of-member elevations for synthetic modeling. The associations of individual plant elements are identified to establish part/unit/subsystem/system interrelationships which may result in failures between systems. This step of the methodology requires direct industrial input to gain access to all necessary data, whether in hardcopy or electronic form. A partnership between industrial facility and researcher at this stage in the design is critical; without industrial collaboration, the necessary data cannot be compiled and the procedure is of no avail.

The facility database is populated with a complete component inventory from the facility. Database entries are at the part or component level; the selection of which is dictated by the

function of the piece under investigation. For example, piping, which is a part within the context of this methodology, is analyzed the same as a motor, which is considered a unit. The interdependencies previously noted are examined to understand whether potential failures are isolated or have a cascading effect through the system, and escalating effects can be determined by further implementation of the same process in neighboring systems throughout the infrastructure.

2.6.2 Construction Database

The construction database consists of the necessary manpower and management needed to complete a job. Industrial collaboration, again, is of the utmost importance to develop an accurate labor database measured in manhour units. Past invoices from maintenance are valid references for establishing typical productivity rates and labor costs for part and unit repair. The collection of those costs can then be aggregated into a subsystem repair cost, and further up to render a total system repair cost.

2.6.3 Synthetic Damage and Economic Loss Modeling

Figure 2.2 identifies the process by which the damage and loss model is run to determine shutdown duration and labor, material, equipment, and overhead costs. The primary components of the process are described in further detail in the following sections.

2.6.3.1 Flood Model Parameters

Flood model parameters may be determined by several methods, including consideration of specific historic or future events, or evaluation of an ensemble of probabilistic events, which can be used in a detailed risk model framework. The key components that need to be identified are: the floodwater elevation, including waves (if applicable).

2.6.3.2 Calculation of Restoration Requirements

To calculate restoration requirements, flood parameters are compared with individual entries in the Facility Database. The component level VAP begins with the first system, and proceeds through each part of that system, then proceeding to the next system. The first evaluation is to determine if the flood elevation is greater than the part elevation. If the flood elevation is higher than the part elevation, the part is assumed to be inundated, the direct restoration actions, whether to repair or replace, are determined, and the system is incremented to the next part in the system. If the floodwater elevation is below the part elevation, no direct consequence to the component is considered; however, there may be a consequence to other parts due to the process flow. Each part is evaluated to determine indirect consequences.

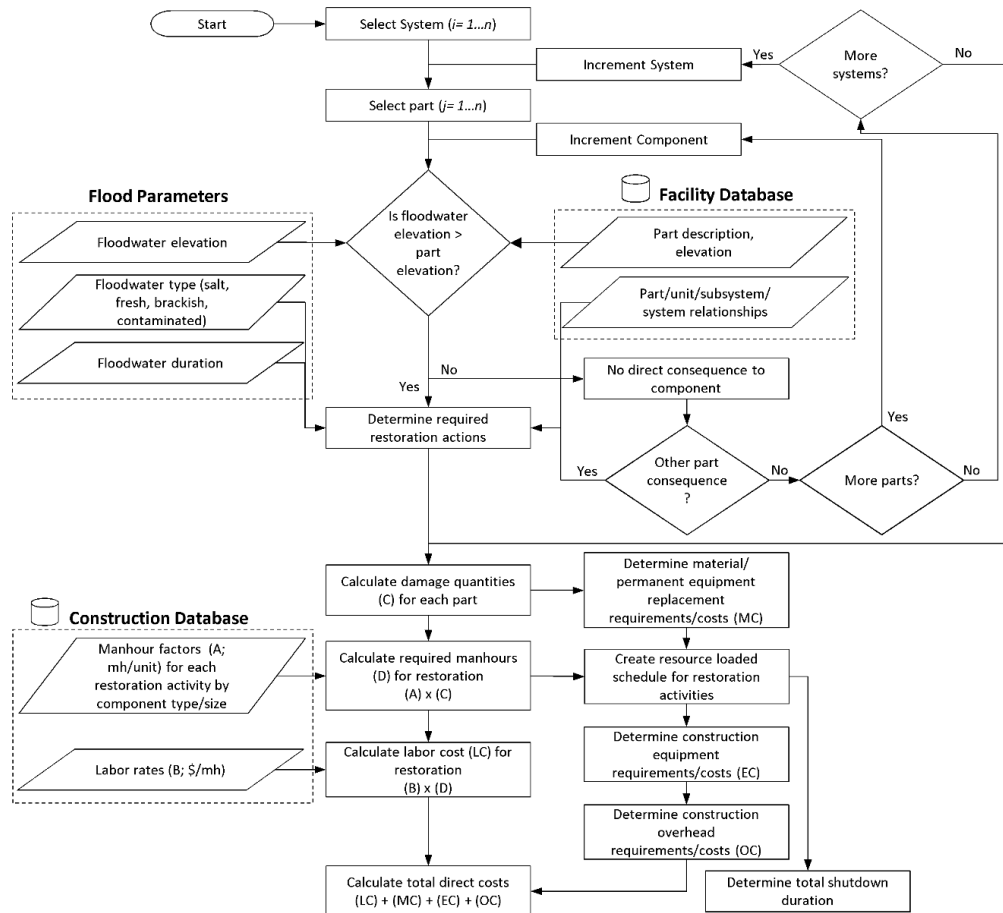


Figure 2.2 Vulnerability assessment process diagram

2.6.3.3 Determination of Total Manhours for System Restoration

To determine the total manhours for system restoration, the manhour factor data within the Construction Database is needed as described in Section 2.6.2. Based on the quantities of damaged material (C) for each part, and the application of historic manhour factors (A), the required manhours (D) for system restoration based on labor type (e.g., pipefitter, boilermaker) are calculated as shown in Equation 2.1. This process is repeated for each part within the Facility Database and summed to determine the total hours required for system restoration for the entire facility.

$$D = A \times C \quad \text{(Equation 2.1)}$$

2.6.3.4 Manpower Requirements and Restoration Schedule

Using the total number of manhours (D) and the specified labor type, a schedule for restoration is manually created. Stacking trades and overtime may be considered within the restoration planning and scheduling process. Labor inefficiency caused by stacking trades should be considered by adjusting the manhour factors (A) and any premium time pay should be considered when calculating labor costs. Based on the construction schedule and other considerations, the total shutdown time can be estimated.

2.6.3.5 Labor, Material, Equipment, and Overhead Costs

Labor cost (LC) is determined from the number of manhours (D) and the labor pay rates (B) for each trade, plus any premium pay from scheduled overtime (Equation 2.2). Material cost (MC) is calculated by determination of the permanent materials (e.g., parts, components) and expendable materials required to complete the repairs, including the damage quantities for each part (C). Once the requirements are determined, material costs are calculated on a unit basis plus costs for expendable materials (Equation 2.3). Based on the previously-created schedule, an estimate of equipment requirements is performed and equipment cost (EC) is calculated by the

number and type of equipment required times the company or outside rental rates for the required duration (Equation 2.4). The overhead cost (OC) is estimated based on the schedule using management requirements as the basis. The overall estimated total direct cost (TDC) of the repair is therefore the sum of LC, MC, EC, and OC (Equation 2.5).

$$LC = B \times D \quad (\text{Equation 2.2})$$

$$MC = C \times \text{Unit Cost} + \text{Expendable Material Cost} \quad (\text{Equation 2.3})$$

$$EC = \text{Number} \times \text{Duration} \times \text{Equipment Rental Rate} \quad (\text{Equation 2.4})$$

$$TDC = LC + MC + EC + OC \quad (\text{Equation 2.5})$$

2.7 Chapter Summary

This chapter presented a new component-based methodology to quantifiably assess the consequences of flooding in process facilities. By narrowing the investigative approach to the behavior of individual components within an inundated interrelated system, depth-damage consequences can be understood more clearly. Further, identifying the affected components and cross-referencing them against construction manhour and cost data allow for standard construction estimating and scheduling practices to be applied to estimate the cost and time required to return the facility to operational capacity.

Table 3.1 Case study subsystem within the facility database

ID	Quantity	Unit	Component	Material	Elevation
1	1	each	47 gpm pump	Stainless steel, hastelloy, cast iron, and gaskets	17 ft
2	1	each	40 hp motor	Stainless steel, hastelloy, cast iron, and gaskets	17 ft
3	2	each	1/2" valve	Cast iron	17 ft
4	2	each	3/4" angle valve	Cast iron	12 ft
5	1	each	Swing check valve	Cast iron	20 ft
6	1	each	Suction pulsation bottle	Aluminum	20 ft
7	1	each	Discharge pulsation bottle	Aluminum	20 ft
8	1	spool	3" pipe	Stainless steel uninsulated	20 ft
9	1	spool	2" pipe	Stainless steel uninsulated	20 ft
10	1	spool	1 1/2" pipe	Stainless steel uninsulated	20 ft
11	1	spool	1" pipe	Stainless steel uninsulated	20 ft
12	1	spool	3/4" pipe	Stainless steel uninsulated	12 ft
13	1	spool	1/2" pipe	Stainless steel uninsulated	17 ft
14	1	each	Pressure switch	N/A	16 ft
15	1	each	Glass viewer	N/A	19.5 ft
16	1	each	Pressure indicator	N/A	16 ft

In Table 3.2, the system interdependencies are shown in binary format (i.e., either 0 or 1), reflecting the influence of one part on another part. The IDs listed in the first column show the parts evaluated with respect to floodwater elevation. The IDs across the top show the parts that would suffer indirect damage from damage to the component listed in the first column.

A cursory understanding of the process flow for this subsystem is needed to adequately recognize the relationships proposed in Table 3.2, and the maintenance requirements it necessitates. The pump, component 1, is the critical element to the system in that the failure of the pump translates into the failure of the subsystem in its entirety. Whereas the motor, component 2, is for the most part isolated, simply existing to drive component 1, component 1 pressurizes the system and facilitates the flow of product throughout the subsystem to the exit points. Foreign material incursion into component 1 is anticipated to occur at the gasketed

flanges and seals of the component, thereby contaminating the product, and affecting all downstream members internally. Due to the relatively small size of components 1 and 2, repair requirements exceed the liability posed by simply replacing them following exposure. Valves and piping in the subsystem, components 3-5 and 8-13, even if only subjected to external exposure, require, at a minimum, disassembly, cleaning, inspection, and reassembly with new gasket material. Instrumentation and control components, components 6-7 and 14-16, require complete replacement following any level of inundation.

Table 3.2 Case study system interrelationships by part within the facility database

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
2	0	1	0	1	0	0	0	0	0	0	0	0	0	1	1	1
3	1	1	1	1	1	1	0	1	1	1	1	0	0	1	1	1
4	0	1	1	1	0	1	0	1	0	0	0	1	0	1	1	1
5	1	1	1	0	1	1	0	1	1	1	1	1	0	0	1	1
6	0	1	1	1	1	1	0	1	0	0	0	1	0	1	1	1
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	0	1	1	0	0	0	0	1	0	0	1	1	0	1	1	1
9	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
13	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
14	1	1	0	0	0	1	0	1	1	1	1	1	0	1	0	1
15	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
16	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1

For example, assume floodwaters exceed the 17 ft lowest-member elevation of component 1. The paper gasket used for lube oil systems is compromised due to water permeation, thereby allowing for foreign material to enter the subsystem. Because of infrastructure design, the same lube oil supplied to the pump is circulated for supply to the motor, exposing the internal bearings and components to foreign material. If the product flow seals within the pump are also compromised, foreign material can be assumed to have entered

the product and been transported through the subsystem. To know whether or not contamination has occurred, disassembly of all downstream components for inspection is necessary. Cleaning is required prior to assembly of any closed system. Further, once a flange is opened, new gasket material is needed to ensure the integrity of the flange. Any downstream component subjected to possible contamination is assumed to require replacement for quality and reliability concerns.

The ID numbers shown in Tables 3.1 and 3.2 constitute the Facility Database. In future research, these interdependencies can also be expressed as a probabilistic ratio, which would allow for more robust risk estimation.

3.3 Construction Database

The construction database details all elements required of an industrial contractor to return the subsystem to processing capacity. It not only quantitatively estimates the direct cost of restoration, but also provides the data to construct a reasonable schedule for the project. Using a manhour as the measuring unit, each part is assigned a total number of manhours necessary for either repair or replacement. Included in repair estimates are activities such as disassembly, correcting consequences due to foreign fluids and debris, cleaning, assembly with replacement of necessary material, and inspection for quality at each phase of activity.

Table 3.3 provides the quantities, labor units, labor type, and manhour factors and material cost for repair and replacement of each part within the subsystem. Repair values shown as “--” indicates that the component cannot be repaired and must instead be replaced. In these cases, the repair calculations use the replacement manhour factors and material costs. Table 3.4 provides the labor rates for trades required to complete repairs or replacement. Tables 3.3 and 3.4 constitute the Construction Database. Table 3.5 provides construction equipment rental rates, which are used in estimating equipment cost.

Table 3.3 Case study repair and replacement requirements for each part

ID	Quantity	Unit	Labor Type	Repair		Replace	
				Manhour Factor	MC	Manhour Factor	MC
1	1	each	--	--	--	16	\$ 5,000
2	1	each	--	--	--	16	\$ 6,500
3	2	each	MW	1	\$ 100	.5	\$ 1,000
4	2	each	MW	1	\$ 100	.5	\$ 1,500
5	1	each	MW	4	\$ 100	2	\$ 2,500
6	1	each	--	--	--	2	\$ 1,000
7	1	each	--	--	--	2	\$ 1,000
8	1	spool	MW	0.12	\$ 100	0.08	\$ 6,000
9	1	spool	MW	0.6	\$ 100	0.4	\$ 1,500
10	1	spool	MW	0.6	\$ 100	0.4	\$ 1,000
11	1	spool	MW	0.6	\$ 100	0.4	\$ 1,000
12	1	spool	MW	0.3	\$ 100	0.2	\$ 1,000
13	1	spool	MW	0.6	\$ 100	0.4	\$ 750
14	1	each	--	--	--	1	\$ 650
15	1	each	--	--	--	1	\$ 2,500
16	1	each	--	--	--	1	\$ 1,000

Note: For components marked '--', components would be replaced rather than repaired.

Table 3.4 Case study labor rate for indicated labor type within Construction Database

Labor Type	Standard hourly rate (\$/hr unless noted)	Overtime hourly rate (\$/hr unless noted)
Millwright (MW) II	\$23.00	\$34.50
Millwright (MW) I	\$28.00	\$42.00
Labor Supervisor	\$32.00	\$48.00
Field Engineer	\$29.00	\$43.50
Safety Specialist	\$27.00	\$40.50
Project Manager	\$34.00	\$51.00
Crane Operator	\$29.50	\$44.25
Per Diem (all employees)	\$150.00/day	

Table 3.5 Case study equipment rental rates

Equipment Type	Rental Rate
Crane Rental (per day)	\$620
Fork Lift Rental (per day)	\$120

3.4 Flood Parameters

Determining flood parameters for simulation provides an extent for the threat of inundation. The location for the system under investigation is St. Bernard, Louisiana. The above mean sea level (AMSL) height is 4', according to a site survey completed in 2010. Flood insurance rate maps (FIRMs) produced by FEMA detail the flooding characteristics of the area. These maps list the base flood elevation (BFE), or 1% chance of flooding, which is the regulatory requirement for the flood proofing of structures. In addition to this minimum elevation, the site's FIRM also denotes the likely sources of inundation. For St. Bernard, the primary sources of inundation are the Mississippi River, the Gulf of Mexico, and Lake Borgne. From the study area FIRM (Figures 3.2 and 3.3), the site is located in a leveed area, which protects it from the 100-year flood event.

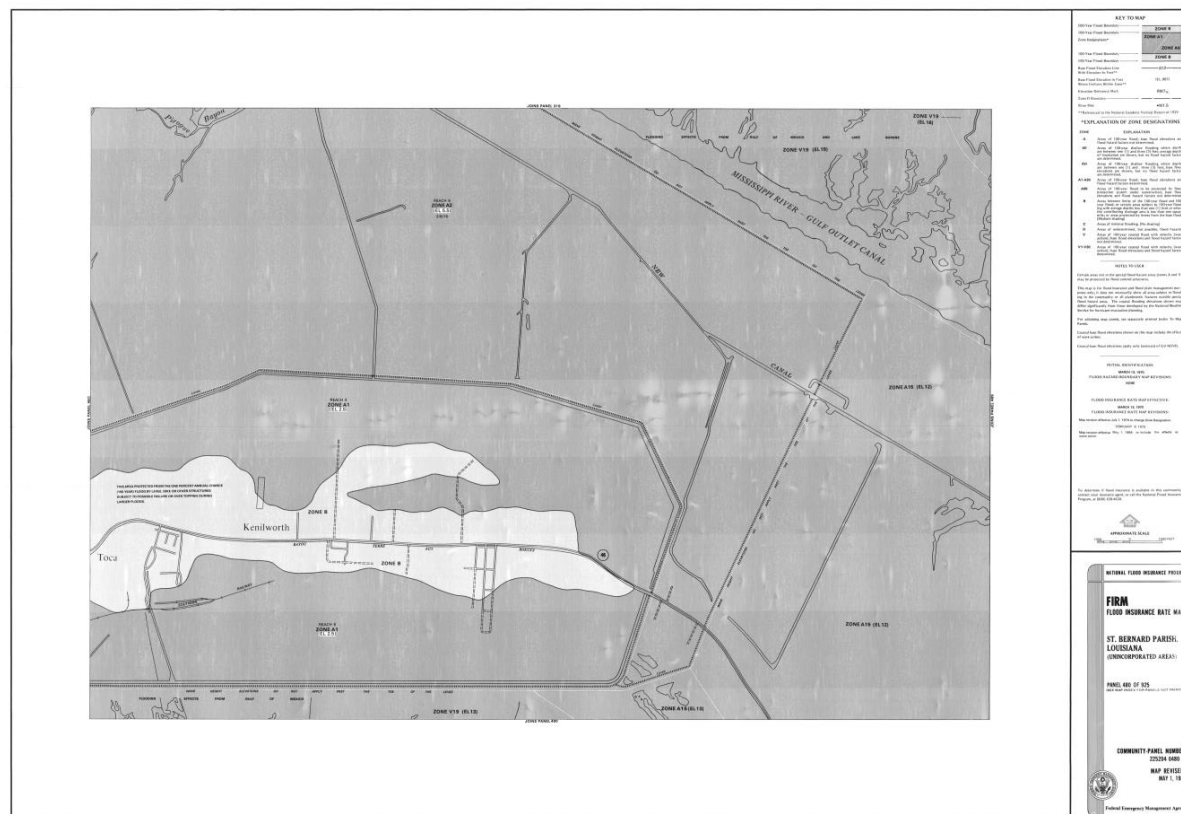


Figure 3.2 Site FIRM panel (FEMA, #2252040480B)

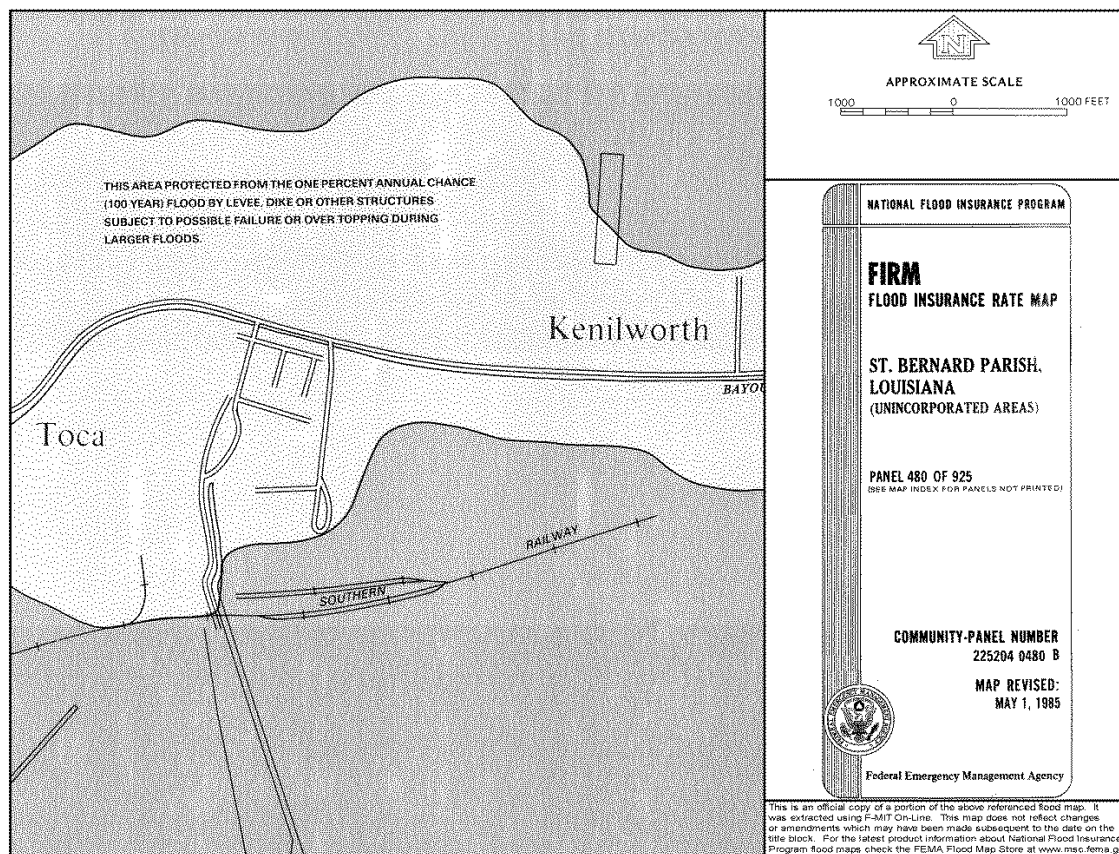


Figure 3.3 Site FIRM panel, zoomed to study area (FEMA, #2252040480B)

Therefore, to determine the flood characteristics to consider in the VAP, hurricane storm surge simulations were used to develop the flood data input. Elevation data for the study area were obtained from the 2006 Statewide National Elevation Dataset (NED) at 1/9-arc second resolution, obtained from the USGS National Map Viewer (<http://viewer.nationalmap.gov/viewer>) and published in 2009. Figure 3.4 provides the digital elevation map (DEM) of the general study area, referenced to the North American Vertical Datum of 1988 (NAVD88). It is noted that levees of elevations up to 19.2 feet surround the study area, shown by the dark brown lines toward the top and bottom of the figure.

The NOAA SLOSH Model (Jelesnianski, Chen et al. 1992) was used to generate the flooding scenarios evaluated in Chapter 3. SLOSH considers general direction and intensity of a

hurricane making landfall within a defined basin. Two model outputs are available from SLOSH: Maximum Envelope of Water (MEOW) and Maximum of Maximums (MOM) analyses, where MOM ensemble outputs represent the maximum storm surge in any location from the combination of MEOW outputs for a given Saffir-Simpson hurricane category. Tidal interaction is not considered in SLOSH, although low or high tide values are superimposed on the generated storm surge surface. SLOSH is a two-dimensional model that neglects non-linear terms of the continuity and momentum equations and can be run on a personal computer (PC). Stated accuracy of the model is $\pm 20\%$ and results generally indicate the maximum amount of surge that could be expected under the modeled conditions. For this analysis, Saffir-Simpson Hurricane Category 1-5 MOM storm surge outputs were evaluated.

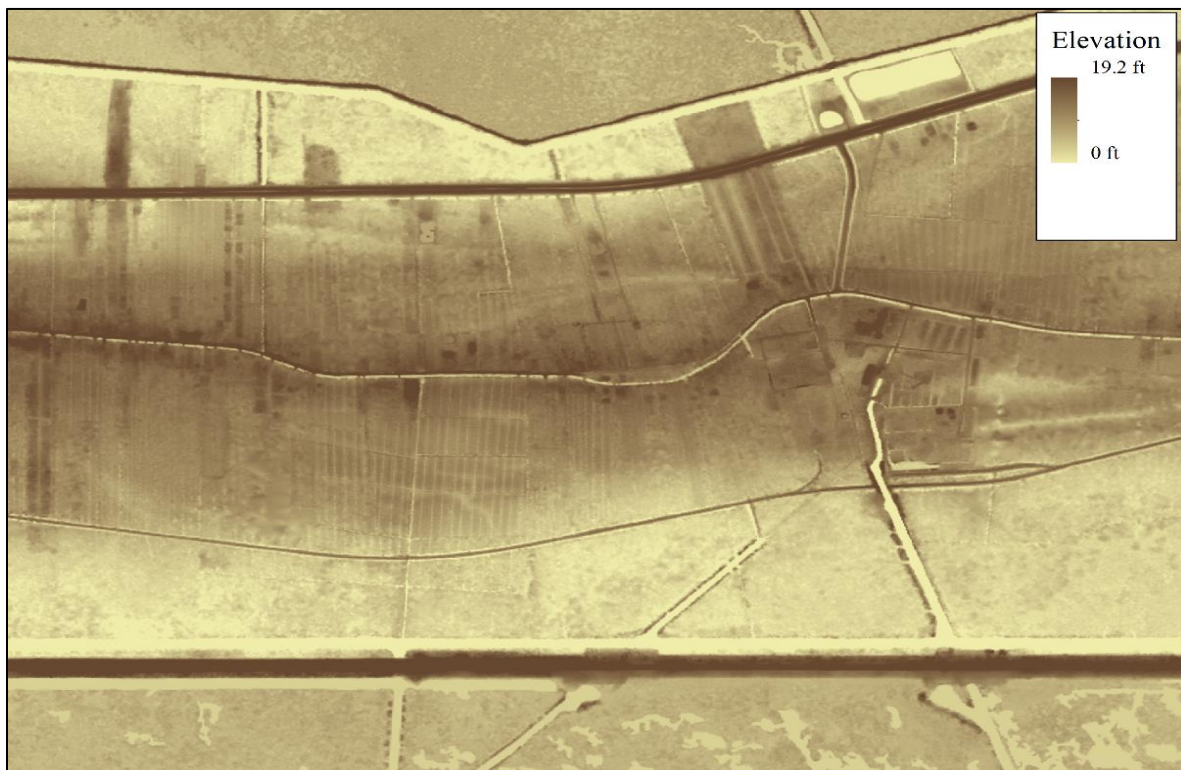


Figure 3.4 Digital elevation model (DEM) of general study area

Figure 3.5 shows the output of the SLOSH Model considering flooded (light blue) and non-flooded (dark brown) areas for Category 1-3 hurricanes. Figure 3.5(a) shows that the tops of

the levees are still dry during a Category 1 hurricane, indicating that while the elevation of the leveed area is less than the flood elevation, the leveed area is actually expected to be dry. Figure 3.5(b) shows the model results for a Category 2 hurricane, which shows the northern levee would be overtopped although most of the southern levee is dry; however, given the nature of storm surge, it is anticipated that the study area would still be flooded from the north. Figure 3.5(c) shows that both the north and south levees are nearly totally inundated, indicating that the study area would be flooded for Category 3 hurricanes and above.

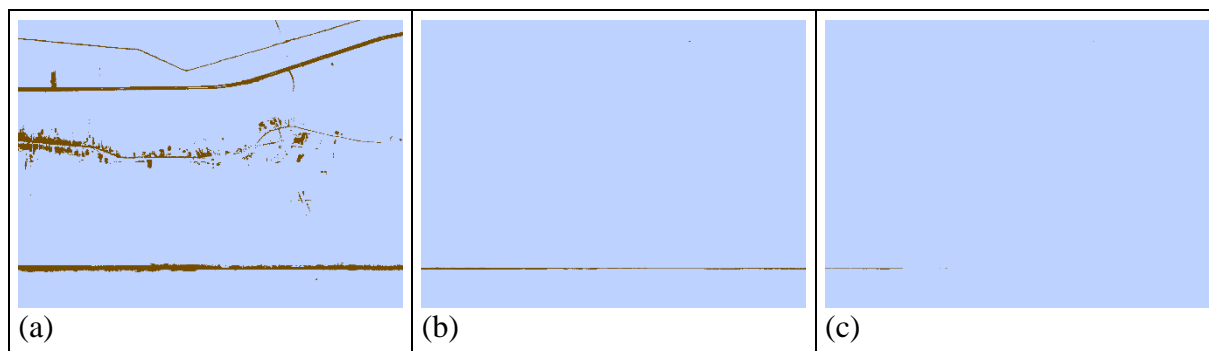


Figure 3.5 Flooded (light blue) vs. non-flooded (brown) footprint for NOAA SLOSH MOM scenarios a) Category 1, b) Category 2, c) Category 3

After determination of the hurricane categories that would result in flooding of the leveed area, the predicted storm surge values for each event were obtained from SLOSH. SLOSH provides storm tide elevation referenced to the NGVD29 vertical datum, so conversion between datums was accomplished using VDatum, a vertical datum transformation tool developed by NOAA (<http://vdatum.noaa.gov>). Table 3.6 provides the MOM storm surge elevations for each Saffir-Simpson Hurricane Category in feet.

Table 3.6 Modeled storm surge elevations

Saffir-Simpson Hurricane Category	MOM Storm Surge Elevation (ft), NAVD88
Category 1	6.1, but levees dry, so no flooding considered
Category 2	12.6
Category 3	16.4
Category 4	19.7
Category 5	22.8

3.5 Flood Repair Cost and Shutdown Time Estimation

3.5.1 Category 1 Event

Because the levees surrounding the site are modeled to be dry during the Category 1 event, no flooding of the facility is considered.

3.5.2 Category 2 Event

A Category 2 event reaches a height of 12.6' within the protected zone following an overtopping of the north levee. These flood data are then referenced against the facility database. Components 4 and 12 have lowest-member elevations below the watermark, translating into inundation. Additionally, as referenced in the binary table, the inundation of these two components has immediate consequences for downstream components, indicated by a "1" in Table 3.7, shaded for clarity.

Table 3.7 Category 2 storm surge affected components matrix

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
4	0	1	1	1	0	1	0	1	0	0	0	1	0	1	1	1
12	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1

Therefore, in the event of a Category 2 storm, two components will be inundated, and the consequences of that water intrusion will necessitate maintenance of not only those two components, but also another seven components due to subsystem relationships and position. These nine components can then be assessed against the construction database, in which the minimum repair requirement and a maximum replacement requirement can be quantified for

understanding. The ultimate cost of returning the system to processing capability, however, will be dictated by the inspection results once the system is opened and cleaned.

Table 3.8 Case study repair/replacement requirements (Category 2)

ID	Quantity	Unit	Labor Type	Repair		Replace	
				Manhour Factor	MC	Manhour Factor	MC
2	1	each	--	--	--	16	\$ 6,500
3	2	each	MW	1	\$ 100	.5	\$ 1,000
4	2	each	MW	1	\$ 100	.5	\$ 1,500
6	1	each	--	--	--	2	\$ 1,000
8	1	spool	MW	0.12	\$ 100	0.08	\$ 6,000
12	1	spool	MW	0.3	\$ 100	0.2	\$ 1,000
13	1	spool	MW	0.6	\$ 100	0.4	\$ 750
14	1	each	--	--	--	1	\$ 650
15	1	each	--	--	--	1	\$ 2,500
16	1	each	--	--	--	1	\$ 1,000

Note: For components marked '--', components would be replaced rather than repaired.

Labor Costs (LC) can now be calculated based on repair and replacement requirements.

Table 3.9 shows the total number of manhours for each component using data from the Construction Database (Table 3.8). The total time needed to repair the identified components is 26.0 hours and the time needed to replace is 23.7 hours.

Table 3.9 Case study manhour calculations (Category 2)

ID	Quantity	Unit	Manhour Factor		Hours	
			Repair	Replace	Repair	Replace
2	1	each	--	16	16	16
3	2	each	1	0.5	2	1
4	2	each	1	0.5	2	1
6	1	each	--	2	2	2
8	1	spool	0.12	0.08	0.12	0.08
12	1	spool	0.3	0.2	0.3	0.2
13	1	spool	0.6	0.4	0.6	0.4
14	1	each	--	1	1	1
15	1	each	--	1	1	1
16	1	each	--	1	1	1
Totals					26.0	23.7

Note: For components marked '--', components would be replaced rather than repaired.

Assuming a two-person team composed of a MW1 and MW2, the hourly crew rate is \$25.50 (Table 3.10). Assuming the crews work an average work week of 60 hours/week during the shutdown, the premium pay factor is 17% (Table 3.11), calculated as the equivalent hours paid divided by the work hours minus one. Labor burdens are assumed as: payroll taxes of 14.5% on all wages, and insurance of 10% benefits of 8% on straight time wages only. Using these assumptions, the labor cost to repair the damaged components is \$1,204 and to replace is the damaged components \$1,097 (Table 3.12).

Table 3.10 Case study composite crew rate

Labor Type	Quantity	Hourly Pay Rate	Extended Pay Rate
Millwright (MW) II	1	\$23.00	\$23.00
Millwright (MW) I	1	\$28.00	\$28.00
Totals	2		\$51.00
Composite Crew Rate			\$25.50

Table 3.11 Case study premium time factor

	Work Hours	Pay Factor	Equivalent Hours Paid
Straight-time hours	40	1	40
Overtime hours	20	1.5	30
Totals	60		70
Premium Time Factor			17%

Table 3.12 Case study labor cost (Category 2)

	Repair	Replace
Manhours	26.0	23.7
Composite Crew Pay Rate	\$25.50	\$25.50
Straight Time Wages	\$663	\$604
Overtime Wages	17%	17%
Total Wages	\$663	\$605
Payroll Taxes	\$96	\$88
Insurance + Benefits	\$119	\$109
Clock Hours	13.0	11.9
Days	1.1	1.0
Individual Per Diem	\$163	\$148
Crew Per Diem	\$325	\$296

Table 3.12 Case study labor cost (Category 2) continued

	Repair	Replace
Total Labor Cost	\$1,204	\$1,097

Material costs (MC) are calculated using the data in the Construction Database for this case study (Table 3.8). As previously noted, certain components are rendered unserviceable following exposure to inundation and would be replaced rather than repaired, indicated by '--'. The anticipated materials costs for repair are \$12,350, while the material costs for replacement are estimated as \$24,400 (Table 3.13).

Table 3.13 Case study material cost (Category 2)

ID	Quantity	Unit	Unit MC		MC	
			Repair	Replace	Repair	Replace
2	1	each	--	\$6,500	\$6,500	\$6,500
3	2	each	\$100	\$1,000	\$200	\$2,000
4	2	each	\$100	\$1,500	\$200	\$3,000
6	1	each	--	\$1,000	\$1,000	\$1,000
8	1	spool	\$100	\$6,000	\$100	\$6,000
12	1	spool	\$100	\$1,000	\$100	\$1,000
13	1	spool	\$100	\$750	\$100	\$750
14	1	each	--	\$650	\$650	\$650
15	1	each	--	\$2,500	\$2,500	\$2,500
16	1	each	--	\$1,000	\$1,000	\$1,000
Totals					\$12,350	\$24,400

Note: For components marked '--', components would be replaced rather than repaired.

A crane and forklift are anticipated to be needed for the duration of either the repair or replacement. Equipment Cost (EC) is calculated using the rental rates shown in Table 3.5 for the durations of the repair and replacement activities. Rental days are calculated based on an 8-hour rental day. The total EC (Table 3.14) for this scenario is \$1,203 (repair) and \$1,096 (replace).

Table 3.14 Case study equipment cost (Category 2)

Description	Daily Rental	Clock Hours		Days*		Equipment Cost	
		Repair	Replace	Repair	Replace	Repair	Replace
Crane Rental	\$620	13.0	11.9	1.6	1.5	\$1,008	\$918
Fork Lift Rental	\$120	13.0	11.9	1.6	1.5	\$195	\$178
Totals						\$1,203	\$1,096

*assumes an 8-hour rental day

Overhead costs (OC) include time for the labor supervisor, site engineer, safety specialist, project manager, and equipment operators. The amount of total work at the project site will dictate the proportion of overhead cost for each activity, but an estimate of 10% of staff supervisors' time is allocated to this particular activity, along with fulltime presence for the labor supervisor and equipment operators. Based on these assumptions, the overhead hourly rate is \$100.00 per field hour (Table 3.15). The total OC (Table 3.16) is \$2,259 (repair) and \$2,059 (replace).

Table 3.15 Case study overhead hourly rate (Category 2)

Labor Type	Quantity	Pay Rate	Extended Pay Rate
Labor Supervisor	1	\$32.00	\$32.00
Field Engineer	0.1	\$29.00	\$2.90
Safety Specialist	0.1	\$27.00	\$2.70
Project Manager	0.1	\$34.00	\$3.40
Equipment Operators	2	\$29.50	\$59.00
Totals	3.3		\$100.00
Overhead Hourly Rate			\$100.00

Table 3.16 Case study overhead cost (Category 2)

	Repair	Replace
Clock Hours	13.0	11.9
Overhead Hourly Rate	\$100.00	\$100.00
Straight Time Wages	\$1,300	\$1,185
Overtime Wages	17%	17%
Total Wages	\$1,300	\$1,185
Payroll Taxes	\$189	\$172
Insurance + Benefits	\$234	\$213
Days	1.1	1.0

Table 3.16 Case study overhead cost (Category 2) continued

	Repair	Replace
Individual Per Diem	\$163	\$148
Crew Per Diem	\$536	\$489
Total Labor Cost	\$2,259	\$2,059

Therefore, in the event of a Category 2 storm inundating this particular pump and motor assembly, the total direct cost (TDC) is calculated as LC+MC+EC+OC, or \$17,015 (repair) and \$28,652 (replace), shown in Table 3.17.

Table 3.17 Case study total direct cost (Category 2)

	Repair	Replace
Labor Cost	\$1,204	\$1,097
Material Cost	\$12,350	\$24,400
Equipment Cost	\$1,203	\$1,096
Overhead Cost	\$2,259	\$2,059
Total Direct Cost	\$17,015	\$28,652

3.5.3 Category 3 and 4 Events

A Category 3 event reaches a height of 16.4' thereby inundating nearly the complete zone. This flood data is then referenced against the facility database. Components 4, 12, 14, and 16 have lowest-member elevations below the watermark, translating into inundation. Additionally, as referenced in the binary table, the inundation of these four components has immediate consequences for downstream components, indicated by a "1" in Table 3.18, shaded for clarity.

Table 3.18 Category 3 storm surge affected components matrix

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
4	0	1	1	1	0	1	0	1	0	0	0	1	0	1	1	1
12	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
14	1	1	0	0	0	1	0	1	1	1	1	1	0	1	0	1
16	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1

The four components flooded by a Category 3 event are expected to subject eleven other components to inundation consequences.

A Category 4 event reaches a height of 19.7' thereby inundating nearly the complete zone. Components 1-4 and 12-16 have lowest-member elevations below the watermark, translating into inundation. Additionally, as referenced in the binary table, the inundation of these nine components has immediate consequences for downstream components, indicated by a "1" in Table 3.19, shaded for clarity. The 15 components affected by Category 3 and 4 storm surge are then referenced against the Construction Database (Table 3.20).

Table 3.19 Category 4 storm surge affected components matrix

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
2	0	1	0	1	0	0	0	0	0	0	0	0	0	1	1	1
3	1	1	1	1	1	1	0	1	1	1	1	0	0	1	1	1
4	0	1	1	1	0	1	0	1	0	0	0	1	0	1	1	1
12	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
13	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
14	1	1	0	0	0	1	0	1	1	1	1	1	0	1	0	1
15	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
16	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1

Table 3.20 Case study repair/replacement requirements (Category 3 and 4)

ID	Quantity	Unit	Labor Type	Repair		Replace	
				Manhour Factor	MC	Manhour Factor	MC
1	1	each	--	--	--	16	\$5,000
2	1	each	--	--	--	16	\$6,500
3	2	each	MW	1	\$100	0.5	\$1,000
4	2	each	MW	1	\$100	0.5	\$1,500
5	1	each	MW	4	\$100	2	\$2,500
6	1	each	--	--	--	2	\$1,000
8	1	spool	MW	0.12	\$100	0.08	\$6,000
9	1	spool	MW	0.6	\$100	0.4	\$1,500
10	1	spool	MW	0.6	\$100	0.4	\$1,000
11	1	spool	MW	0.6	\$100	0.4	\$1,000
12	1	spool	MW	0.3	\$100	0.2	\$1,000
13	1	spool	MW	0.6	\$100	0.4	\$750
14	1	each	--	--	--	1	\$650

Table 3.20 Case study repair/replacement requirements (Category 3 and 4) continued

ID	Quantity	Unit	Labor Type	Repair		Replace	
				Manhour Factor	MC	Manhour Factor	MC
15	1	each	--	--	--	1	\$2,500
16	1	each	--	--	--	1	\$1,000

Table 3.21 shows the total number of manhours for each component using data from the Construction Database (Table 3.8). The total time needed to repair the identified components is 47.8 hours and the time needed to replace is 42.9 hours.

Assuming the same crew composition, work week, and labor burdens as for the Category 2 example, the hourly crew rate is \$25.50 (Table 3.9), and the premium pay factor is 17% (Table 3.10). Using these assumptions, the labor cost to repair the damaged components is \$2,513 and to replace is the damaged components \$2,253 (Table 3.22).

Table 3.21 Case study manhour calculations (Category 3 and 4)

ID	Quantity	Unit	Manhour Factor		Hours	
			Repair	Replace	Repair	Replace
1	1	each	--	16	16	16
2	1	each	--	16	16	16
3	2	each	1	0.5	2	1
4	2	each	1	0.5	2	1
5	1	each	4	2	4	2
6	1	each	--	2	2	2
8	1	spool	0.12	0.08	0.12	0.08
9	1	spool	0.6	0.4	0.6	0.4
10	1	spool	0.6	0.4	0.6	0.4
11	1	spool	0.6	0.4	0.6	0.4
12	1	spool	0.3	0.2	0.3	0.2
13	1	spool	0.6	0.4	0.6	0.4
14	1	each	--	1	1	1
15	1	each	--	1	1	1
16	1	each	--	1	1	1
Totals					47.8	42.9

Note: For components marked '--', components would be replaced rather than repaired.

Table 3.22 Case study labor cost (Category 3 and 4)

	Repair	Replace
Manhours	47.8	42.9
Composite Crew Pay Rate	\$25.50	\$25.50
Straight Time Wages	\$1,219	\$1,093
Overtime Wages	17%	17%
Total Wages	\$1,220	\$1,094
Payroll Taxes	\$177	\$159
Insurance + Benefits	\$219	\$197
Clock Hours	23.9	21.4
Days	2.0	1.8
Individual Per Diem	\$299	\$268
Crew Per Diem	\$897	\$804
Total Labor Cost	\$2,513	\$2,253

Material costs (MC) are calculated using the data in the Construction Database for this case study (Table 3.20). The anticipated materials costs for repair are \$17,750, while the material costs for replacement are estimated as \$35,400 (Table 3.23).

Table 3.23 Case study material cost (Category 3 and 4)

ID	Quantity	Unit	Unit MC		MC	
			Repair	Replace	Repair	Replace
1	\$5,000	each	--	\$5,000	\$5,000	\$5,000
2	\$6,500	each	--	\$6,500	\$6,500	\$6,500
3	\$200	each	\$100	\$1,000	\$200	\$2,000
4	\$200	each	\$100	\$1,500	\$200	\$3,000
5	\$100	each	\$100	\$2,500	\$100	\$2,500
6	\$1,000	each	--	\$1,000	\$1,000	\$1,000
8	\$100	spool	\$100	\$6,000	\$100	\$6,000
9	\$100	spool	\$100	\$1,500	\$100	\$1,500
10	\$100	spool	\$100	\$1,000	\$100	\$1,000
11	\$100	spool	\$100	\$1,000	\$100	\$1,000
12	\$100	spool	\$100	\$1,000	\$100	\$1,000
13	\$100	spool	\$100	\$750	\$100	\$750
14	\$650	each	--	\$650	\$650	\$650
15	\$2,500	each	--	\$2,500	\$2,500	\$2,500
16	\$1,000	each	--	\$1,000	\$1,000	\$1,000
Totals					\$17,750	\$35,400

Note: For components marked '--', components would be replaced rather than repaired.

A crane and forklift are anticipated to be needed for the duration of either the repair or replacement. Equipment Cost (EC) is calculated using the rental rates shown in Table 3.5 for the durations of the repair and replacement activities. Rental days are calculated based on an 8-hour rental day. The total EC (Table 3.24) for this scenario is \$2,212 (repair) and \$1,983 (replace).

Table 3.24 Case study equipment cost (Category 3 and 4)

Description	Daily Rental	Clock Hours		Days*		Equipment Cost	
		Repair	Replace	Repair	Replace	Repair	Replace
Crane Rental	\$620	23.9	21.4	3.0	2.7	\$1,853	\$1,662
Fork Lift Rental	\$120	23.9	21.4	3.0	2.7	\$359	\$322
Totals						\$2,212	\$1,983

*assumes an 8-hour rental day

The same assumption is made as for the Category 2 scenario – that 10% of staff supervisors' time is allocated to this particular activity, along with fulltime presence for the field supervisor and equipment operators. The overhead hourly rate is \$100.00 per field hour (Table 3.15). The total OC (Table 3.25) is \$4,155 (repair) and \$3,725 (replace).

Table 3.25 Case study overhead cost (Category 3 and 4)

	Repair	Replace
Clock Hours	23.9	21.4
Overhead Hourly Rate	\$100.00	\$100.00
Straight Time Wages	\$2,391.0	\$2,144.0
Overtime Wages	17%	17%
Total Wages	\$2,391	\$2,144
Payroll Taxes	\$347	\$311
Insurance + Benefits	\$430	\$386
Days	2.0	1.8
Individual Per Diem	\$299	\$268
Crew Per Diem	\$986	\$884
Total Labor Cost	\$4,155	\$3,725

Therefore, in the event of a Category 3 storm inundating this particular pump and motor assembly, the total direct cost (TDC) is calculated as LC+MC+EC+OC, or \$26,629 (repair) and \$43,362 (replace), shown in Table 3.26.

Table 3.26 Case study total direct cost (Category 3 and 4)

	Repair	Replace
Labor Cost	\$2,513	\$2,253
Material Cost	\$17,750	\$35,400
Equipment Cost	\$2,212	\$1,983
Overhead Cost	\$4,155	\$3,725
Total Direct Cost	\$26,629	\$43,362

3.5.5 Category 5 Event

The flooding from a Category 5 event would completely inundate the subsystem at 22.8' of water. A Category 5 event can be expected to subject all sixteen components to floodwater, necessitating repair or replacement throughout the entire pump and motor assembly, indicated by a "1" in Table 3.27, shaded for clarity.

The 16 components affected by Category 5 storm surge constitute the entire Construction Database, which is repeated here for reference (Table 3.28).

Table 3.27 Category 5 storm surge affected components matrix

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
2	0	1	0	1	0	0	0	0	0	0	0	0	0	1	1	1
3	1	1	1	1	1	1	0	1	1	1	1	0	0	1	1	1
4	0	1	1	1	0	1	0	1	0	0	0	1	0	1	1	1
5	1	1	1	0	1	1	0	1	1	1	1	1	0	0	1	1
6	0	1	1	1	1	1	0	1	0	0	0	1	0	1	1	1
7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	0	1	1	0	0	0	0	1	0	0	1	1	0	1	1	1
9	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
13	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
14	1	1	0	0	0	1	0	1	1	1	1	1	0	1	0	1
15	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
16	0	1	0	1	1	1	0	1	1	0	0	0	1	1	1	1

Table 3.28 Case study repair/replacement requirements (Category 5)

ID	Quantity	Unit	Labor Type	Repair		Replacement	
				Manhour Factor	MC	Manhour Factor	MC
1	1	each	--	--	--	16	\$5,000
2	1	each	--	--	--	16	\$6,500
3	2	each	MW	1	\$100	0.5	\$1,000
4	2	each	MW	1	\$100	0.5	\$1,500
5	1	each	MW	4	\$100	2	\$2,500
6	1	each	--	--	--	2	\$1,000
7	1	each	--	--	--	2	\$1,000
8	1	spool	MW	0.12	\$100	0.08	\$6,000
9	1	spool	MW	0.6	\$100	0.4	\$1,500
10	1	spool	MW	0.6	\$100	0.4	\$1,000
11	1	spool	MW	0.6	\$100	0.4	\$1,000
12	1	spool	MW	0.3	\$100	0.2	\$1,000
13	1	spool	MW	0.6	\$100	0.4	\$750
14	1	each	--	--	--	1	\$650
15	1	each	--	--	--	1	\$2,500
16	1	each	--	--	--	1	\$1,000

Table 3.29 shows the total number of manhours for each component using data from the Construction Database (Table 3.8). The total time needed to repair the identified components is 49.8 hours and the time needed to replace is 44.9 hours.

Table 3.29 Case study manhour calculations (Category 5)

ID	Quantity	Unit	Manhour Factor		Hours	
			Repair	Replace	Repair	Replace
1	1	each	--	16	16	16
2	1	each	--	16	16	16
3	2	each	1	0.5	2	1
4	2	each	1	0.5	2	1
5	1	each	4	2	4	2
6	1	each	--	2	2	2
7	1	each	--	2	2	2
8	1	spool	0.12	0.08	0.12	0.08
9	1	spool	0.6	0.4	0.6	0.4
10	1	spool	0.6	0.4	0.6	0.4
11	1	spool	0.6	0.4	0.6	0.4
12	1	spool	0.3	0.2	0.3	0.2
13	1	spool	0.6	0.4	0.6	0.4
14	1	each	--	1	1	1

Table 3.29 Case study manhour calculations (Category 5) continued

ID	Quantity	Unit	Manhour Factor		Hours	
			Repair	Replace	Repair	Replace
15	1	each	--	1	1	1
16	1	each	--	1	1	1
Totals					49.8	44.9

Note: For components marked '--', components would be replaced rather than repaired.

Assuming the same crew composition, work week, and labor burdens as scenarios, the hourly crew rate is \$25.50 (Table 3.9), and the premium pay factor is 17% (Table 3.10). Using these assumptions, the labor cost to repair the damaged components is \$2,618 and to replace is the damaged components \$2,358 (Table 3.30).

Material costs (MC) are calculated using the data in the Construction Database for this case study (Table 3.30). The anticipated materials costs for repair are \$18,750, while the material costs for replacement are estimated as \$36,400 (Table 3.31).

Table 3.30 Case study labor cost (Category 5)

	Repair	Replace
Manhours	49.8	44.9
Composite Crew Pay Rate	\$25.50	\$25.50
Straight Time Wages	\$1,270	\$1,144
Overtime Wages	17%	17%
Total Wages	\$1,271	\$1,145
Payroll Taxes	\$184	\$166
Insurance + Benefits	\$229	\$206
Clock Hours	24.9	22.4
Days	2.1	1.9
Individual Per Diem	\$311	\$281
Crew Per Diem	\$934	\$842
Total Labor Cost	\$2,618	\$2,358

Table 3.31 Case study material cost (Category 5)

ID	Quantity	Unit	Unit MC		MC	
			Repair	Replace	Repair	Replace
1	1	each	--	\$5,000	\$5,000	\$5,000
2	1	each	--	\$6,500	\$6,500	\$6,500

Table 3.31 Case study material cost (Category 5) continued

ID	Quantity	Unit	Unit MC		MC	
			Repair	Replace	Repair	Replace
3	2	each	\$100	\$1,000	\$200	\$2,000
4	2	each	\$100	\$1,500	\$200	\$3,000
5	1	each	\$100	\$2,500	\$100	\$2,500
6	1	each	--	\$1,000	\$1,000	\$1,000
7	1	each	--	\$1,000	\$1,000	\$1,000
8	1	spool	\$100	\$6,000	\$100	\$6,000
9	1	spool	\$100	\$1,500	\$100	\$1,500
10	1	spool	\$100	\$1,000	\$100	\$1,000
11	1	spool	\$100	\$1,000	\$100	\$1,000
12	1	spool	\$100	\$1,000	\$100	\$1,000
13	1	spool	\$100	\$750	\$100	\$750
14	1	each	--	\$650	\$650	\$650
15	1	each	--	\$2,500	\$2,500	\$2,500
16	1	each	--	\$1,000	\$1,000	\$1,000
Totals					\$18,750	\$36,400

Note: For components marked '--', components would be replaced rather than repaired.

A crane and forklift are anticipated to be needed for the duration of either the repair or replacement. Equipment Cost (EC) is calculated using the rental rates shown in Table 3.5 for the durations of the repair and replacement activities. Rental days are calculated based on an 8-hour rental day. The total EC (Table 3.32) for this scenario is \$2,304 (repair) and \$2,076 (replace).

Table 3.32 Case study equipment cost (Category 5)

Description	Daily Rental	Clock Hours		Days*		Equipment Cost	
		Repair	Replace	Repair	Replace	Repair	Replace
Crane Rental	\$620	24.9	22.4	3.1	2.8	\$1,931	\$1,739
Fork Lift Rental	\$120	24.9	22.4	3.1	2.8	\$374	\$337
Totals						\$2,304	\$2,076

*assumes an 8-hour rental day

The same assumption is made as for the previous scenarios – that 10% of supervisors' time is allocated to this particular activity, along with fulltime presence for the equipment

operators. The overhead hourly rate remains at \$100.00 per field hour (Table 3.15). The total OC (Table 3.33) is \$4,328 (repair) and \$3,899 (replace).

Table 3.33 Case study overhead cost (Category 5)

	Repair	Replace
Clock Hours	24.9	22.4
Overhead Hourly Rate	\$100.00	\$100.00
Straight Time Wages	\$2,491	\$2,244
Overtime Wages	17%	17%
Total Wages	\$2,491	\$2,244
Payroll Taxes	\$361	\$325
Insurance + Benefits	\$448	\$404
Days	2.1	1.9
Individual Per Diem	\$311	\$281
Crew Per Diem	\$1,028	\$926
Total Labor Cost	\$4,328	\$3,899

Therefore, in the event of a Category 3 storm inundating this particular pump and motor assembly, the total direct cost (TDC) is calculated as LC+MC+EC+OC, or \$28,000 (repair) and \$44,733 (replace), shown in Table 3.34.

Table 3.34 Case study total direct cost (Category 5)

	Repair	Replace
Labor Cost	\$2,618	\$2,358
Material Cost	\$18,750	\$36,400
Equipment Cost	\$2,304	\$2,076
Overhead Cost	\$4,328	\$3,899
Total Direct Cost	\$28,000	\$44,733

Table 3.35 aggregates the findings of the individual analyses for tropical events. For Category 2-5 storms, if only repairs are needed, the minimum expected cost to return to processing capability is \$17,015. The maximum cost, in the event that full replacement of the system is required, is \$44,733. The anticipated repair/replacement time for this system ranges from 1.0 days to 2.1 days. The deciding factor of which level of cost and time are required depends on the damage to the system and whether components can be repaired or must be

replaced. Additionally, some consideration of time versus budget may warrant spending more money on material costs to replace parts rather than spend the labor time to repair them, thus reducing shutdown durations.

Table 3.35 Case study summary of total direct cost of inundation for Category 1-5 events

Cost Component	Category 2		Category 3 and 4		Category 5	
	Repair	Replace	Repair	Replace	Repair	Replace
Labor Cost	\$1,204	\$1,097	\$2,513	\$2,253	\$2,618	\$2,358
Material Cost	\$12,350	\$24,400	\$17,750	\$35,400	\$18,750	\$36,400
Equipment Cost	\$1,203	\$1,096	\$2,212	\$1,983	\$2,304	\$2,076
Overhead Cost	\$2,259	\$2,059	\$4,155	\$3,725	\$4,328	\$3,899
Total Direct Cost	\$17,015	\$28,652	\$26,629	\$43,362	\$28,000	\$44,733
Shutdown Time (days)	1.1	1.0	2.0	1.8	2.1	1.9

3.6 Chapter Summary

This chapter presented the application of the new Vulnerability Assessment Process methodology for the assessment of damage from inundation. By isolating the components of a subsystem and defining their individual characteristics, a facility database was created. Those components were also assigned labor manhours for equipment repair and replacement based on historical data to return operational capacity to the subsystem within the developed Construction Database. Flood parameters for the affected area were determined by modeling. Elevation information was gathered from the 2006 Statewide National Elevation Dataset (NED) and inundation scenarios were developed using NOAA's SLOSH program to analyze the maximum expected depth of water for each Saffir-Simpson category. The total direct cost for repair and replacement were separately calculated for each storm surge scenario and the results were aggregated to provide estimates of cost and duration to repair the system for each hurricane category storm surge.

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

4.1 Introduction

The goal of this thesis was to improve the understanding of the interaction of storm surge with the built industrial environment. Two objectives were identified to further this understanding: design a component-based VAP methodology to determine consequences of inundation at the part/unit level that aggregates flood, facility, and repair/replacement (construction) information in a single location for review; and test the developed VAP by applying it to a complete subsystem to demonstrate flood-depth consequences within that process to achieve a reliable schedule and budget to return the subsystem to operating capacity. A summary of the work performed and findings for each of the objectives were presented at the end of each chapter. This chapter summarizes the way in which each of these objectives increases our understanding of the effects of flooding on industrial infrastructure and outlines future work in this topic.

4.2 Development of Vulnerability Assessment Process Framework for Industrial Facilities

The first objective of this research was to create a framework by which flood, facility, and construction information could be aggregated to develop a single estimate of cost and duration to return the facility to operational status following an inundation event. A study into contemporary research on industrial hazard mitigation was conducted in Chapter 2, focusing on identifying gaps in the state of the art and clearly defining the terms to be used throughout the research. Based on review of the literature, vulnerability as it pertains specifically to flooding was recognized, as well as vulnerability management practices. Efforts have primarily focused on assets labeled as critical, while ignoring the interrelationships between those critical and non-critical elements in which failure can cascade from an isolated incident to a subsystem failure.

The term “depth-consequence” was proposed to better gauge the effects of flooding to certain components, wherein the damage may not be confined to that specific point of process, but rather flow from that component, causing multiple consequences within the system. No methodology was found that determined the effects of flooding on single components and analyzed those damages in light of the relationships of individual parts within subsystems, thereby contributing to the overall operational capacity of the system.

A whole-system evaluation was proposed by inventorying all components within that system through construction drawings. Relationships between components are determined by examining the piping and instrumentation diagrams to follow the process flow. Variables in the isolated components are identified, allowing for the manipulation of exposure data to affect materials.

The construction database is a resource of previous productivity and cost data for the manpower needed to return the equipment to production. This includes general labor, specialty services, and management. It also takes into account the unique variables of performing in adverse conditions following a storm by incorporating certain productivity factors based on historical factors or determining a coefficient to represent diminished returns on worker output.

Estimates of flood inundation, as well as the consequences of certain categories of storms are determined from flood modeling software, previous events, or hypothetical levels. Further, consideration of water quality in this methodology allows for the understanding of damage to a system based on salt or contaminant content.

4.3 Application of the Vulnerability Assessment Process

The tank and pump subsystem in Chapter 3 was used to demonstrate the utility of this methodology. The subsystem is broken down into components that are further identified by their

material composition, elevation of lowest member, repair/replacement requirements, as well as the immediately affected downstream component.

The flood database pulls from several sources of information to achieve a thorough understanding of vulnerability. The FIRM panel was used to identify sources of inundation; the DEM was referenced for elevation data; and NOAA's SLOSH model produced the inundation characteristics of flooding scenarios.

A hypothetical construction database was developed that identifies the resources needed to return the subsystem to production. It identifies a standard mechanical field service crew, complete with a project management team and specialty contractors necessary to complete the maintenance.

By combining all three databases into a single focused study, the consequences of inundation were calculated. Effort directed at developing a detailed inventory of plant equipment is the key to utilizing the VAP properly. Simple scenarios run through publicly available flood modeling software and seeking bids for hypothetical repair projects can then easily translate into new flooding mitigation strategies for facilities, safeguarding both owner assets and local dependence on the production processes that funnel money into the economy.

4.4 Final Remarks and Future Work

This research provides a novel framework for better understanding infrastructure vulnerability to flooding. However, as the first version of a process, it needs further review and validation. Were construction data more available for projects immediately following events, a more precise monetary estimate could be ascertained. Also, as experiences develop with future reconstruction efforts, more appropriate productivity coefficients can be applied to certain areas under certain conditions to further refine the scheduling practice. Significant modeling advances are also recommended for future work, including consideration of probabilistic repair/return

relationships and more rigorous definition of repair/replace prerequisites and requirements that include multiple trades.

The coast is constantly changing. While this research provides an initial direction, attention needs to be paid to environmental factors affecting the areas under investigation. Increasing rates of subsidence, heightened sea levels, diminished wetlands, and stronger storms are all going to affect future analyses and would be appropriately added for a more thorough evaluation of mitigation strategies. These could have far-reaching effects into coastal preservation and resilience techniques.

The Gulf Coast is a hub of critical infrastructure. By better understanding the consequences of the natural environment, better practices can be utilized to construct the built environment, as well as bolster the as-built environment. Development along this energy corridor is currently increasing as more focus is placed on natural gas, both increasing the refining capacity and raising the demand on an outdated utility transmission grid. Several mega projects are in the construction phase at this time between Southwestern Louisiana and the Houston ship channel, and maintenance is an ongoing operation at all surrounding points. Hurricanes Katrina and Rita both touched the region as Category 3 storms and wrecked the lifeline infrastructure in their respective paths. As storm strength intensifies, a Category 4 or 5 is inevitable, necessitating, rather than recommending, better mitigation strategies.

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VITA

Matthew L. Flynn was born in Alexandria, Louisiana to Evelyn Jill Flynn. Matthew has two older sisters, Kim and Leigh. Following graduation from Bolton High School in Alexandria, Matthew enlisted in the United States Marine Corps and served as an infantry team leader with 2nd Battalion, 4th Marine Regiment, 1st Marine Division in Camp Pendleton, California. Matthew deployed to Iraq with the 15th Marine Expeditionary Unit (Special Operations Capable), conducting counter-insurgency operations in Ar Ramadi and Ar Rutbah, Iraq. After an honorable discharge from service, Matthew enrolled at Louisiana State University, completing two Bachelor of Arts degrees. Matthew is currently a field service engineer for Mitsubishi Hitachi Power Systems Americas, Incorporated, managing power generation outages in North and South America and the Middle East.