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# A Stochastic Capacitated Facility Location Model For Pre-Positioning Port Commodities During A Disaster

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# A STOCHASTIC CAPACITATED FACILITY LOCATION MODEL FOR PRE-POSITIONING PORT COMMODITIES DURING A DISASTER

by

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## BIOGRAPHICAL SKETCH

Jessye Leigh Bemley was born June 12, 1986, in Washington, DC. She received her Bachelor of Science degree in 2008 from North Carolina A&T State University in Industrial Engineering. On campus she participated in North Carolina A&T State University Gospel Choir, National Society of Black Engineers (NSBE) and Institute of Industrial Engineers (IIE). She has presented papers at numerous national and international engineering, scientific and computing conferences, symposia and meetings. She is a Master of Science candidate for Industrial & Systems Engineering.

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**ABSTRACT**

**Bemley, Jessye Leigh.** A STOCHASTIC CAPACITATED FACILITY LOCATION MODEL FOR PRE-POSITIONING PORT COMMODITIES DURING A DISASTER. **(Major Advisor: Dr. Lauren Davis)**, North Carolina Agricultural and Technical State University.

As the intensity of natural disasters increases, there is a need to develop policies and procedures to assist various humanitarian relief groups, industry or government agencies with moving aid to affected areas. One of the biggest hindrances to this process is damage to transportation networks, in particular, waterways. To keep waterways safe, aids to navigation (ATONs) are placed in various areas to guide mariners and ships to their final destinations. If the ATONs are damaged, then the waterways are left unsafe and it is difficult to move supplies to repair them and recover from a disaster. A stochastic facility location model is presented to understand the advantage of prepositioning repair supplies in order to maximize the repair of ATONs. The first stage decisions focus on location determination of resources that are prepositioned. The second stage decisions consist of the distribution of supplies and teams to affected areas. The results will show the benefits of a prepositioning policy toward the responsiveness of restoring waterway.

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Ports and waterways are a vital part of the inter-modal transportation network and allow for the movement of goods and people around the world. A port consists of terminals, cranes, containers, and storage facilities. In addition, the ports are designed in a manner to allow entrances for trucks and trains to carry commodities to their final destination. Currently, the United States has 360 ports that are either publicly or privately owned and operated. The public ports are operated and owned specifically by port authorities. An example of this is the Port of Houston. The Port of Houston Authority serves as a landlord by allowing different private companies to rent space at the port. Each port has distinct terminals dedicated to a diverse group of cargo. Ports account for 95% of the country's shipped commercial cargo. According to the Association of American Port Authorities (AAPA), ports enable waterborne commerce that injects about $3.1 trillion into local, regional, and national economies and handles about 2 billion tons of import and exports annually. Since ports and waterways are open to damage, major disasters can leave these areas vulnerable to disruptions.

### 1.2 Impact of Disruption

Disruptions caused at ports can cause major economic impact which can be detrimental to certain industries, such as oil industries. Disruption can also occur due to natural or manmade disasters.  For example, the 2002 west coast (Los Angeles/Long Beach) port shutdown due to labor disputes caused the U. S. Economy to lose approximately 6.3 to 19.4 billion dollars (Park, 2008). During Hurricane Katrina, ports on the Gulf Coast were shutdown causing oil prices to increase as a result of oil rigs having to close (Haveman, 2006).

The recovery process due to disruption can be lengthened if materials needed to rebuild are not readily available. For instance Hurricane Katrina was one of the most catastrophic natural disasters to hit the United States. As a result, Port Fourchon was the only petroleum handling facility that was 90% operational a year after the storm. The other two terminals in the area were still damaged which caused an influx of traffic at Port Fourchon (Ellis, 2005). Hurricane Ike caused 14 refineries in Texas to be shutdown which caused a major disruption in the energy supplies nationwide. Some energy officials even expected a possible rise in gasoline prices (Nichols, 2008). In the case of the recent Haiti Earthquake tragedy, the damage of the docks located at the port caused humanitarian aid not to be delivered to the affected victims (BBC, 2010).

Additionally, due to the geographical location of ports, there is a high chance that a terrorist can create a disruption. The Congressional Research Service (CRS) Report for Congress (2005) on terrorist attacks estimates that if a 10 to 20 kiliton weapon of mass destruction was to be detonated at a port it would result in killing 500,000 to 1,000,000 people and disrupt trade by $100 to $200 billion.  These examples, illustrate the impact of disruptions caused by natural and manmade disasters and also demonstrates the need for guidelines that will help with preparation and recovery from disasters.

**1.3 Motivation**

During the recovery process there are many logistical issues such as: coordination among agencies, a lack of resources needed for damaged areas, when to pre-position relief commodities and determining locations to pre-position. Some examples of these issues can be seen in Hurricane Katrina, Hurricane Ike and the earthquake in Haiti. The CEO of the Port of New Orleans commented that one-third of the port infrastructure was damaged due to Hurricane Katrina.  During that time period, no trade or vessels were coming in and out of the port (Ellis, 2005). After Hurricane Ike passed by Texas, various areas around Port Arthur were used as points of distribution to provide supplies to residents (VanderVelde, 2008)

For the case of the recent Haiti Earthquake tragedy, piers and equipment such as cranes were damaged at the port and ships were unable to be loaded (CNN, 2010).The port also had an airport, but there was not enough space or fuel for plane traffic from organizations to drop off humanitarian aid to those in need. In order to fix the damage at the port, the Prime Minister of Haiti asked other countries to bring salvage equipment such as cranes, tugs, barges and dredges (CNN, 2010). Due to the damage of the port, it was difficult for planes carrying aid to land. Many streets leading into the city were impassable, making it difficult for humanitarian organizations to reach people that needed help.

Bharoas et. al (2009) discusses the various obstacles and challenges with information sharing among multiple agencies at the Port of Rotterdam in the Netherlands. Their study showed that relief workers want to receive rather than give out information that would be beneficial to other agencies or groups. These examples demonstrate the importance of the level of coordination, amount of resources and suppliers that are necessary to ensure a responsive recovery from a disaster. This reveals the need for developing a policy that will inform decision makers on when to pre-position resources and how to coordinate their efforts.

As large scale natural and manmade disasters increase in intensity there is a greater need for emergency preparedness and response tools, not just for responding to needs of the affected population, but other entities as well.  From these disasters (e.g. Hurricane Katrina, 9/11) we have seen many people and locations going without basic necessities for long periods of time due to logistical issues among recovery agencies. Current research in humanitarian logistics/relief has focused on issues such as container security, emergency preparedness and response in regards to location of emergency services, evacuation from damaged areas and response after a disaster occurs (Johnstone et.al, 2004; Jia et.al., 2005; Chapman 2007; Kapucu et.al., 2007). However, there is a limited amount of research dealing with security, emergency preparedness and response in relation to ports (Green & Kolesar, 2004; Larson , 2004).

Currently some ports (e.g. Houston, NewYork/New Jersey, Louisiana, Alabama, Florida) have hurricane preparedness plans that are updated as needed. However, there is a lack of preparedness plans at ports specifically designed for other natural disasters. As a result of 9/11, ports have incorporated different security measures to adhere to Homeland Security maritime security initiatives such as the Transportation Worker Identification Card (TWIC), Container Security Initiative (CSI), and the Customs Trade Partnership Against Terrorism (C-TPAT). Most of the preparedness plans only consider basic preparation and recovery activities, in which very little pre-positioning are done.

Pre-positioning is not a novel concept, but has been used by the military on several occasions to expedite the response time for allocating resources for war (Johnstone et. al, 2004). However, many organizations and agencies have opted to use this technique (Duran et. al 2008). Rawls & Turnquist (2006) developed a stochastic model to determine locations for emergency supplies and allocation of those supplies needed. This model does not take into account the commodities or characteristics of a port that would be helpful in pre-positioning. Chapman (2007) proposes a model that determines the best cost strategy for pre-positioning supplies that are in a high risk path for a particular event. Although, Chapman comes up with a pre-positioning policy he does not consider time which is critical in response nor does the research address the unique challenges of pre-positioning resources for port recovery.

### *1.3.1 Pre-positioning Aids to Navigations*

For this research we will focus on pre-positioning commodities in facilities that house equipment that is used to repair Aids to Navigation if a natural disaster were to occur. Aids to Navigation (ATONs) are considered the equivalent to a light used on roadways to control the flow of traffic and help the waterways to remain navigable. There are different types of ATONs such as lighted/ unlighted buoys, beacons, lights and lighthouses. The United States Coast Guard (USCG) is the primary organization in charge of ATONs along with the National Oceanic and Atmospheric Association (NOAA) and United States Army Corps of Engineers (USACOE).

The USCG responsibilities include: developing, administering and operating ATONs to serve maritime commerce, controlling private aids that are under the jurisdiction of the United States/continental shelf and on the high seas, and to mark wrecks to warn mariners of obstructions (United States Coast Guard, 2005). If ATONs are damaged or move from their original position, then ATONs teams are sent out to survey the aids and make repairs. All other federal agencies are responsible for maintenance, repairs and identity of their own aids unless under Coast Guard jurisdiction (United States Coast Guard, 2005).

According to the USCG, after Hurricane Katrina approximately 63% of aids in New Orleans, LA and 87% of aids in Mobile, AL were in the storm affected area on position, but their sound and light signals were working at low frequency (Guard, 2005). To obtain the equipment to fix the ATONs the Coast Guard consults with their personal Engineering and Logistics Center, other companies that sell products that are outfitted on the aid (e.g. horn, bell reflectors, batteries) and the U.S. General Services Administration (GSA). The lack of pre-positioning models dedicated to ports and port commodities (i.e. ATONs) gives motivation for developing new policies in this area.

### 1.4 Research Scope

The purpose of this research is to identify a framework that can help with understanding the impact of a port disruption and the effectiveness of pre-positioning emergency commodities (e.g. GPS, Aids to Navigation Teams, buoy tenders, flashers, reflective tape, steel and plastic buoys) to provide rapid response for port recovery actions. The port preparation and recovery activities are modeled as a stochastic programming problem, where the first stage decisions will be based on known information about the disaster to help with pre-positioning. The second stage decisions will be based on responding to the damage after the disaster has occurred. Data based on supply and demand of commodities will be used to run the model.

The following model assumes that decision makers rely on historical data and experience to help with planning for emergency items needed during hurricane season. If inventory is unavailable, it is ordered and stored until needed after an event has occurred. Some supplies and commodities need to be pre-positioned ahead of the storm such as GPS, Aids to Navigation Teams, buoy tenders, flashers, reflective tape, steel and plastic buoys. The USCG polls the barge industry to receive these supplies and services in time to send them to a safe location. A safe location is considered any distance away that will not result in damage to the commodities. If a safe location is damaged, then the commodities have to come from another port or terminal. The usage of safe locations will be determined, based on the probability that the hurricane will strike.

Since the magnitude of disasters changes over time there is always some level of uncertainty in coordination, quantity/ type of resources and availability of suppliers. The scope of this project will address three questions:

(1) How will pre-positioning affect the responsiveness of the port during the recovery phase?

(2) What are the optimal stocking quantities and location of resources given the uncertainty associated with a disaster (e.g hurricane, terrorist attack etc.)?

(3) What is the benefit of private, non-profits and government agencies working together to provide support?

**1.5 Thesis Overview**

The remainder of this thesis is outlined as follows. The second chapter gives an overview of previous research on pre-positioning. The third chapter discusses the agency coordination in port environment. The fourth chapter explains the problem statement, model formulation and approach. The fifth chapter gives a numerical example of the preliminary model. The sixth chapter provides the experimental design created to answer the research questions posed. The seventh chapter provides results and data analysis of this research. The eighth chapter gives the conclusion and further directions for research.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

This chapter consists of two sections. The first provides an overview of modeling that has been done in relation to ports, aids to navigation and pre-positioning. The differences between prior and proposed research are also addressed. The second section describes examples of various prepositioning models using realistic scenarios. The models are described in terms of specific input and output parameters, as well as objectives.

## 2.2 Overview of Port Modeling

Wright (2006) provides a literature review of various operations research models developed to address emergency preparedness and response, threat analysis, critical infrastructure protection and border/transportation security. The models are classified according to the Department of Homeland Security (DHS) research framework. DHS represents different government agencies that are responsible for securing the homeland. It contains five directorates: border and transportation security, emergency preparedness and response, science and technology, information and analysis and infrastructure protection, and management. Research performed at DHS can be found under the science and technology directorate. They focus on three main areas: countermeasures portfolios, component-support portfolio, and cross-cutting portfolios. Under this framework there is very little research on port prepositioning. There has been some research on container security and inter-modal transportation (Lewis, 2003; Ozdamar, 2004).

## 2.3 Overview of Pre-positioning

Pre-positioning is defined by the Department of Air Force as “the stockpiling of equipment and supplies at, or near the point of planned use. It began with the military in which different weapons and ships needed to be moved for war (Johnstone et. al, 2004). As more large scale natural disasters arise many agencies and organizations have adopted this method to create better humanitarian relief efforts. For example, the Care International organization is one of the largest relief organizations that disperse supplies and resources to countries in need. They considered the effects of pre-positioning in regards to response time and determined the optimal configuration of the demand network to increase the response time of getting items to an affected area (Duran et. al, 2008).

Although pre-positioning is accepted, there have been instances where it has not been very favorable. Balick & Beamon (2008) state that pre-positioning can be costly and only a few organizations can support having distribution centers to store and distribute relief commodities (e.g. World Food Programme, World Vision International and United Nations Humanitarian Response Depot).

In order to determine the best pre-positioning approach the location and quantity of commodities must be considered. Depending on the length of time or type of commodities being stockpiled, organizations or agencies should weigh usability and potential danger of locations based on the damage that can occur if a disaster strikes. Various models are presented to show the diversity of pre-positioning models and will be described under the following categories:

1. Location Selection
    - Humanitarian Relief
    - Military
2. Location and Commodity Quantity Selection
    - Humanitarian Relief
    - Military

**2.4 Pre-positioning at Ports**

Many ports have hurricane preparedness plans set in place ahead of a storm. The plan provides the preparation activities in 12 hour increments (i.e. 12 hrs., 24hrs., 36hrs., 72hrs.) until it shuts down completely. One of the main discrepancies post storm is the safety and navigability of waterways. ATONs are known for aiding in safety for boats, vessels and mariners on the waterways. If a disaster or emergency damages the aids to navigation then a team is sent out to fix them or the ATONs are sent to a facility where it can be refurbished.

The USCG currently has nine facilities dedicated to the repair of aids to navigation which are all located near a port. Most of the supplies needed to repair the aids are not sent out until after the hurricane occurs. The aids to navigation teams prioritize the damage to the aids by the discrepancy response factor score. This score is a number given to an ATON to show the criticality of damage and determines the level of correction. The higher the score the more critical the damage is to the ATON and the higher the level of correction. Many states within a Coast Guard district only have one team. Depending on the amount of damages, it could take long periods of time to repair. This example shows one reason that pre-positioning is needed at ports to help keep the waterways safe.

## 2.5 Pre-positioning Models

### *2.5.1 Location Selection*

#### *2.5.1.1 Humanitarian Relief*

Synder (2006) gives an overview of the various facility location models that deal with location selection with some level of uncertainty. They classify the models by the particular approach to solve for uncertainty and the type of facility location problem. They do not focus on models that involve congested facilities such as (e.g emergency services). Although there are many facility locations problems, they do not address large-scale emergencies.

Jia et. al (2005) refer to large-scale emergencies as “rare events that overwhelm local emergency responders and require regional and/or national assistance such as natural disasters.” Most of the local responders only have enough capacity to handle small scale emergencies or frequent incidents. Since large-scale emergencies can also be classified as low frequency with high impact, this requires some changes in the facility coverage. For example, having redundant facility medical stocks (e.g. protective equipment and antidotes) and determining how to position local staging centers. These staging centers should be able to receive, repackage and distribute medical supplies from a strategic national stockpile for a major natural disaster or a bioterrorist attack. The general goal of the model is to decide on the number and location of facilities.

Klose and Drexl (2004) also provide a literature review in which they give a list of criteria to classify traditional facility location models. Based on these criteria, three classifications of facility location models are discussed for emergency services. These models include: covering model, P-median model and P-center model. The covering model for emergency services is to provide coverage to demand points. A demand point is considered covered if serviced by a facility within a specified distance. There are two types of covering models: location set covering model and maximal covering location problem. A location set covering model tries to locate the least amount of facilities that are required to cover all demand points. The maximal covering location problem looks for maximal coverage with a given number of facilities. The stochastic covering models also incorporate scenario planning to represent parameters over a certain time period.

The P-median model determines the location of P facilities to minimize the average distance between demands and facilities. When the total distance decreases, it increases the effectiveness and accessibility of the facilities. The P-center model seeks to minimize the worst case performance of the system and address certain situations where unfair service is more important than the average system performance. It also minimizes the maximum distance between any demand point and the closest facility.

The model proposed in Jia et. al (2005) takes into account all the characteristics mentioned for a large-scale emergency. There are a set of demand points and possible facility locations. From these sets, there are three decisions that are made: whether to place a facility at a particular location, whether a facility services a demand point and whether demand is covered. The demand for this model is uncertain and dependent on the emergency scenario, impact of the emergency, and how likely the emergency will affect a demand point. The authors created two likelihood parameters one represents the likelihood that a certain emergency situation affects a demand point, the other is the impact that the emergency situation has on the population of a demand point and the last one captures the geographical effect of emergency situation in regards to the location of the event. Characteristics of the likelihood parameters are as follows: there can be more than one emergency occurring simultaneously; they do not sum to one over all demand points; and there can be multiple demand points simultaneously affected by an emergency. The decision variables are configured to optimize a function that represents the efficiency in covering the uncertain demand.

Three input parameters are considered: (1) the minimum number of facilities that must be assigned to a demand point so that it is consider covered, (2) the reduction in service capability of a facility under an emergency scenario and (3) the maximal number of facilities that can be placed in a set location. The model is formulated to locate facilities to address an emergency scenario, this requires that facilities service demand points with the same level of quality. The input parameters that are considered consist of the minimum number of facilities to be assigned to a demand point, the reduction in service capability of a facility under a particular emergency scenario, and the maximum number of facilities that can be placed in a certain location. The general objective function can either maximize or minimize the amount of facilities needed to address a certain demand area.

Ukkursuri & Yushimito (2008) propose a model to assist planners during the preparedness stage while designing logistics efforts for humanitarian relief that mitigates and reduces the risk of disruption within a humanitarian relief network. The focus of this research is pre-positioning supplies for post-disaster relief. The model is developed using the location routing problem which took into consideration the selection of locations for pre-positioning humanitarian supplies based on the reliability of the ground transportation network.  The probability of a route failing is independent but the proposed research accounts for all disruptions in a transportation network. All affected zones must be satisfied by a chosen pre-positioned location and an integer programming model chooses the pre-positioning facilities after evaluating the most reliable path in the network.

#### *2.5.1.2 Military*

Johnstone et. al(2004) developed a model to be used for pre-positioning using the Agile Combat System (ACS) with the addition of the afloat pre-positioning fleet (APF). Since the United States Air Force (USAF) cannot pre-position every commodity that is needed, they use a starter stock and swing stock. A starter stock is munitions that are loaded onto aircraft before a conflict begins. The swing stock uses the APF, the standard air munitions package (STAMP) and standard tank, racks, adapters, and pylons packages (STRAPP). These packages are put onto pallets and stored at a safe location until needed for deployment. The munitions inventory is very diverse from bombs to precision-guided weapons. The munitions levels are based on targets from the Joint Chiefs of Staff. Once these targets are met then they are moved into a storage location.

Using this method allows the USAF to keep the proper levels of stock in order to be operational at the appointed time. This model is a mixed integer program of munitions flow named Pre-Po. The USAF makes the following assumptions for their model: the APF stocks level of munitions and where they are moved to unload cargo; the ships depth requirements and the net explosive weight restriction (NEW) for each port that is visited. The net explosive weight is the actual weight of various explosives used to determine limits and quantities of explosives. They model the offload times based on ships and port configurations; the munitions are transported to the airbases based on the available transportation method; last they model the STAMP, STRAPP and theater hub munitions inventory which support the APF and try to reduce the unmet demand at an airbase. A theater is a large geographical area in which military operations are coordinated.

Brown et. al. (2005) presents a method for pre-positioning a defensive interceptor platform which is a platform, with anti-missile and other systems. This system is used by the United States to combat enemies using theater ballistic missiles (biological, high explosive, chemical or nuclear warheads) that can go over long distances. They used a bi-level optimization to solve the problem.  Bi-level optimization refers to two entities, each have information regarding each other’s plans but want to counter the attacks that will be made against them. The model first considers the enemies course of action and maximizes the expected damage that is known by the defensive strategy of the enemy.

Next, the model minimizes the maximum pre-positioning of the various defensive platforms that intercept these strategies. The results from this model aid the Joint Task Force's air defense commander in better defense planning and assessments.

Ghanmi & Shaw (2008) create a Monte Carlo simulation framework to model the various strategic lift and pre-positioning options under consideration by the Canadian forces. To understand comparisons between the different options, they used a common set of parameters within the simulation for a three year period. These parameters focused on deployment locations, frequency of flights and flying times for aircraft which were given stochastically. They also consider two different force packages: the first package is related to the taskforce which was based on a light battle group and the second package is related to the Disaster Assistance Response Team (DART).

For the strategic lift simulation, the focus is on the movement of equipment and supplies. Historical data is used from the Canadian Forces past operations, deployment locations, failing states and their airports/seaports. The pre-positioning option was developed as a subset of historical data of an operation conducted by the Canadian Forces. The different supplies are moved by different modes of transportation (e.g. air, sealift or combination) to a particular theater or area where supplies are needed. The performance of a pre-positioning option depends on the location and manifest (list of materials) that has been pre-positioned.

### *2.5.2 Location and Commodity Quantity Selection*

*2.5.2.1 Humanitarian Relief*

Rawls and Turnquist (2009) model a pre-positioning policy for emergency supply needed during a recovery effort. For this model, they use the Gulf Coast states to create their network. A set of damage scenarios are developed from past data on eight historical hurricanes that passed through this area. Each scenario is given a probability of occurrence. They focus on only three different supplies: water, food and medical kits. Their demands are based on the number of people sheltered in various locations for the historical storms. Based on this data, a table is constructed that shows the amount of each supply that is required in each city for each of the eight storms.

Damage to a transportation network can be shown by reductions in capacity on links or complete loss of capacity. Depending on where the storm hits, the supplies pre-positioned at a node can be partially or completely damaged. From these components, it is possible to determine where storage facilities are located, the capacity, and the amount of the commodity that should be stored. The formulation is developed using a multi-source, multi-sink flow network. The model determines the maximum flow across all the network of sources and sinks. The source represents the starting point of the entity and the sink represents the ending point of the entity. For this particular research, a network is created with a set of nodes with arc capacities and a set of maximum capacities. The set of maximum capacities can vary based on the type of scenario. Each node is assigned a set cost per unit, fixed unit cost and unit resource purchase cost. Each scenario shows the variability in forecasted demand at nodes in the network for specific commodities and arc capacities. The authors represent the loss of different commodities at a node by dividing it into twin nodes known as the excess supply (sink) and unmet demand (source). The links to the twin nodes have an infinite capacity and a link cost of zero. This occurs when a supply facility is destroyed due to a natural disaster causing commodities to be damaged.

The objective function minimizes the expected costs over all possible scenarios based on supplier locations, resource purchase and allocations to the supply facilities and the shipments of the supplies to the demand points, including the flow in the arcs that represent unmet demand and excess supplies. The first stage variables represent the location and capacity of the supply facilities and the resource quantity of each commodity to be allocated at each facility. This stage is not scenario dependent. The second stage variables consider the flow of commodities, arc capacities and costs that are constrained by the first stage decisions. Rawls and Turnquist noticed that there was a combination of structural elements used within the two-stage stochastic model that allowed the model to be solved using a specialized procedure. The benefit of this method is its ability to decompose the overall problem into smaller sub-problems that can be solved more easily.

Chapman (2007) develops a model that shows the benefits of pre-positioning different local commodities that are in a high-risk area. For this research, supply locations and capacities are known and contain some initial inventory to satisfy demand during normal operations. After a hurricane makes landfall, the initial inventory is used in the response phase to satisfy demand in the affected population. This demand level is unlike the demand seen during regular operations. Sometimes when an event strikes, there is a possibility that the stored initial supply will be damaged.

The goal of this model is to minimize the amount of supply that would be lost. This model is a single commodity, supply chain network that is modeled using a stochastic linear programming and network flow framework. The objective function minimizes the total cost of pre-positioning supplies, redistribution, distribution, transportation, supply loss, and shortage cost. This ensures that the minimal amount of supplies move from initial supply facilities to safer locations and that supplies; are efficiently redistributed to minimize unmet demand. First stage decisions consist of pre-positioning existing supplies to minimize the supply loss. Second stage decisions maximize the responsiveness of the system by allocating supplies to satisfy demand.

Duran et. al (2008) develop a model to study the effects of pre-positioning. Care International has a specific approach it uses to respond to disasters. First, they identify suppliers, conduct a procurement process, identify potential warehouse sites and they outsource their transportation. Two of the biggest challenges that Care International has when responding to a disaster is a lack of transportation and a low level of preparedness due to funding. To receive supplies, they consider local and international suppliers. However, they prefer local supplies because they have fast delivery and culturally acceptable products. Issues with procuring locally are the uncertainty in product quality, availability, and production capacity. Also, the prices may be inflated due to scarcity of a certain item. They explore the idea of using pre-positioning to improve their emergency response time. This strategy would allow them to store items in warehouses set up in strategic locations around the world to be deployed after the disaster.

The United Nations Humanitarian Response Depot has started to lease warehouse storage space to different international humanitarian organizations. Therefore, the pre-positioning network became feasible to try. They use a mixed integer programming inventory location model that considers a set of typical demand instances given a specified upfront investment. The model finds the configuration of the supply network that minimizes the average response time over all demand instances. They obtain demand from historical data of different natural disasters. The supply network consists of the number and location of warehouses and the quantity and type of items held in inventory in each warehouse. The objective of the model is to minimize the average of the weighted response time over 233 demand instances.

Balick & Beamon (2008) consider a distribution system where a relief organization locates a distribution center to satisfy the immediate needs of those affected by a disaster. Within the disaster area there would be uncertainties such as resources and damage. They address the issue of determining the quantity and location of the distribution centers and the amount of inventory to stock in order to maximize the relief provided to affected people. They use a facility location and stock pre-positioning model to address the problem. The objective of this model is to maximize the total expected demand covered by the chosen distribution centers. The inventory associated with the chosen distribution center cannot be smaller than the maximum amount of demand that the distribution center would encounter from a single disaster. The amount of inventory must not exceed capacity.

In addition, pre-disaster expenses that are related to a chosen distribution center and holding inventory must not exceed the pre-disaster budget. The results shows that transportation costs incurred between distribution centers and each disaster scenario are less than the expected post-disaster budget. The amount of supplies sent to satisfy the demand of a disaster scenario does not exceed the actual demand. A non-negativity constraint is set to proportion the demand satisfied.

Salmeron and Apte (2010) develop an enhanced pre-positioning model created by Tean (2006) to position relief assets to specified relief locations in order to supply affected areas. The affected areas are categorized into three major populations: critical, stay-back and transfer. It is assumed that if the critical population is not evacuated, their health will deteriorate. In addition, a percentage of the stay back population will not receive any supplies and eventually perish. For this research a multi-objective, two staged stochastic mixed integer optimization program is used.

The objective of this model is to minimize the number of casualties from the critical and stay back population. The second objective is to minimize the expected transfer population to temporary relief locations. The first stage decisions are to determine the location and capacity of relief assets. The second stage decisions are the consequences due to the knowledge received after the disaster has occurred. Included in this decision is the means of transportation used to evacuate the critical and transfer population to the various relief locations and delivering different commodities to the stay back population.

*2.5.2.2 Military*

Ee Shen (2006) modeled a pre-positioning policy that takes into consideration logistics and budget constraints. To test this model two different cases are used (earthquake and hurricane). First they develop a deterministic model that considers fundamental data such as: affected areas(AA)/ relief locations (RL), potential survivors in AAs, commodities needed in each AA, workers required to handle commodities in each AA, available help personnel and warehouse at each RL, available ramp space at each AA, available transportation means with associated capacity for survivors, commodities and relief workers, time to travel between the AAs/RLs and available operating hours and operation range and allocated budget for pre-positioning of additional health personnel. This data is used in the stochastic model.

The objective function maximizes the total expected number of rescued survivors by all transportation means from all AAs but, a penalty is applied if, unmet commodities at an AA occurs. The first stage decisions: expansion of warehouses, medical facilities and their health care personnel and ramp space to facilitate the supply of commodities by aircraft to the AAs. The second stage: logistics problem represented as a network, maximize the expected rescued survivors and delivery of required commodities. This is accomplished by various transportation means and relief workers. An unmet commodity penalty is built in the objective function to penalize the total number of rescued survivors.

### 2.6 Research Contribution

Table 1 summarizes the relevant parameters of prior research. Previous research has one common goal either to minimize cost, minimize response time, maximize covering demand, minimize damage, and maximize life. The research objective across all the articles focuses on evaluating pre-positioning policies. Each model has either a single or multiple commodities that should be pre-positioned. The basic context of the models, are humanitarian relief and military. The first set of papers focuses on pre-positioning models dedicated to location selection. The second set of papers, refer to pre-positioning models that focus on location and quantity selection. Some of the approaches used were stochastic linear programming, simulation, mixed-integer programming facility location models. The research proposed in this paper considers information from a weather related disaster and port preparation activities to help decision makers determine a pre-positioning policy. The contribution to the literature is developing a pre-positioning policy that uses multiple commodities for repairing aids to navigation to help provide reduced response time to port recovery tasks based on a natural disaster striking the area of a port. Throughout major disasters, various organizations come together to help with recovery. However, as seen with Hurricane Katrina, the level of coordination needed among agencies to respond to these situations has been low. This problem would not be classified as humanitarian relief but as business continuity. Business continuity planning considers disaster recovery, contingency planning and crisis management. This plan outlines the best way to recover from disruptions that can cause problems to critical functions needed in order to provide continued services for compensation. These key elements are not shown in prior literature.

**Table 1. Location selection humanitarian relief**

| **Location Selection** | **Objective Function** | **Model** | **Commodities** | **Level of Uncertainty** |
|---|---|---|---|---|
| ***Humanitarian Relief*** | | | | |
| Jia et. al (2005) | Minimize distance; Maximize covering demand | Facility Location | Facilities, equipment and drugs needed for different diseases | Facility location |
| Synder (2006) | | Facility Location | | Facility Location |
| Ukkurusi & Yushimito (2008) | Minimize the maximum reliability of reach a demand point | Location Routing | Facilities and inventory | Location |

**Table 2. Location/ quantity selection humanitarian relief**

| **Location/Quantity Selection** | **Objective function** | **Model** | **Commodities** | **Level of Uncertainty** |
|---|---|---|---|---|
| ***Humanitarian Relief*** | | | | |
| Rawls and Turnquist (2006) | Minimize Cost | Two-Staged Stochastic Mixed Integer | Water, food and medical kits | Demand, damage to facilities and roads |
| Chapman (2007) | Minimize Cost | Stochastic Linear Programming/ Network Flow Model | Supplies | Demand and available supply |
| Duran et. Al | Minimize Response Time | Mixed Integer Inventory Location Model | Food, water, shelter and sanitation | Location, inventory |
| Balick & Beamon (2008) | Maximize the benefit to affected people | Maximal Location Covering Model | Food, water, medicine and shelter | Number and location of distribution centers |
| Salmeron & Apte (2010) | Minimize the number of casualties and expected transfer population | Two-Staged Stochastic Mixed Integer Optimization Model | Relief units and assets | Location and capacity of relief assets, number of casualties |

**Table 3. Location selection military**

| **Location Selection** | **Objective Function** | **Model** | **Commodities** | **Level of Uncertainty** |
|---|---|---|---|---|
| ***Military*** | | | | |
| Johnstone et. al (2006) | Minimize Response time | Mixed Integer Program | Munitions | |
| Brown et. al (2005) | Minimize maximum total expected damage to targets | Bi-level Optimization | Ballistic missile defense platforms | Secrecy and deception from attacker and defender |
| Ghanmi &Shaw (2008) | Minimize movement costs and closure time | Monte Carlo Simulation/ Optimization Model | Equipment, personnel and packages | |

**Table 4. Location/ quantity selection military**

| **Location/ Quantity Selection** | **Objective Function** | **Model** | **Commodities** | **Level of Uncertainty** |
|---|---|---|---|---|
| ***Miltary*** | | | | |
| Ee Shen (2006) | Maximize expected number of survivors | Two-Staged Stochastic Optimization Model | Relief units and assets | Commodity demand and potential survivors |

# CHAPTER 3

# AGENCY COORDINATION

Ports and related organizations have created procedures and guidelines to help with the preparation and recovery process after terrorist attacks and hurricanes. They begin by preparing the port to terminate operations until safe to resume. Immediately after the disaster has ended the various assessment teams are deployed to capture data of damage in waterways and at the port. Many agencies and teams play a major role in the recovery process such as the United States Army Corps of Engineers (USACOE), United States Coast Guard (USCG), assessment teams, barge industry, and the logistics support center. The following, descriptions of these agencies and their role in the recovery process is unique to the ports located in the Gulf Coast. Figure 1 displays the different response organizations in the gulf coast and their coordination activities.

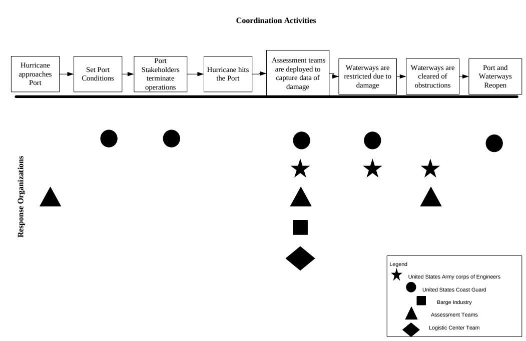



**Figure 1. Coordination among response organizations**

## 3.1 Federal Agencies

### *3.1.1 United States Coast Guard (USCG)*

The USCG was created to provide safety to the nation's maritime interest (e.g ports, sea). They are also responsible for protecting the maritime economy and environment, defending maritime borders and saving vessels, people or facilities that have been impacted by hurricanes, floods, or earthquakes (Guard,  2010). During the event of a hurricane, they coordinate communication of four port conditions (e.g. Whiskey, X-Ray, Yankee, Zulu) to port stakeholders. The purpose of port conditions is to inform stakeholders on what preparation activities need to be carried out to shutdown the port before the storm strikes land. In addition, they make judgments on when to open and close waterways. Prior to the strike of a storm, they discuss waterway closures with port stakeholders (e.g. port coordination team, vessel owners). Upon completion of the storm, they request participation from the air transportation industry and other agencies (e.g. NOAA, Navy) to collect data of waterway obstructions and provide additional planes to perform over-flight assessments. This information assists in creating deployment plans to conduct more detailed surveys. After finalizing the status of waterway closures they communicate this information to the USACOE (Team 2009).

### *3.1.2 United States Army Corps of Engineers (USACOE)*

The mission of the USACOE is to provide engineering services during peace and war to strengthen the nation's security, stimulate the economy and reduce risks associated with disasters. As the leader of waterway restoration, they assess and verify the channel conditions and assign other agencies (e.g. USCG, Navy) to assist with surveying areas.

Depending on the severity of channel obstructions they will issue emergency contracts to clear the shoaled areas. After verifying the channel, they develop a spreadsheet to hold the data of project depths and channel damage, this information is distributed to the USCG in order to communicate waterway restrictions. Besides handling destruction in waterways, they are responsible for shutting down and starting up lock structures that vessels travel through to get to other areas of the waterway. During the response phase, the USACOE communicates with the Logistics Center operated by the inland barge industry via the River Industry Executive Task Force (RIETF) to receive information on equipment and services (Team, 2009; CNN, 2010).

### 3.2 Assessment Teams

The assessment teams follow a command structure similar to the National Response Framework. This structure consists of an Incident Command that facilitates activities in command, operations, planning, logistics and finance/administration. The incident commander is responsible for all response activities such as: developing strategies and the order/ release of resources. They also manage the operations at the site of the incident (Security, 2008).

The assessment teams (e.g. Incident Command, Industry Command, Self Help) include various representatives from federal agencies and industry. Each team has unique functions such as: creating assignments for deployment, serving as liaisons between agencies, assisting in towing vessels, governing traffic flow of vessels to assess the waterways, and transporting/repositioning ATONs. All of these teams work together with the incident commander to create an effective response (Team, 2009).

### 3.3 Logistic Support Center Teams

The River Industry Executive Task Force (RIETF) a committee under the American Waterway Operators Association (AWOA) is responsible for setting up the Logistics Support Center. The Logistic Support Center provides an avenue for agencies and suppliers to communicate the types of equipment and supplies needed for response efforts. Many contacts are received from the barge industry due to their large network (Team, 2009; CNN, 2010).

### 3.4 Private Industry

#### *3.4.1 Barge Industry*

During the response phase the barge industry provides information to the Logistics Center that allows the USACOE and USCG to carry out their functions. This industry also provides personnel to the assessment teams to provide expertise on waterway towing services to increase response. They move equipment and supplies to disaster stricken areas, lock structures and vessels deployed before the storm. The information they solicit from fuel and coal shippers/terminals on critical supply inventory and vessel operations can assist in determining when the waterways will close or re-open (Team, 2009).

# CHAPTER 4

# METHODOLOGY

## 4.1 Problem Overview

For this research, we consider a hurricane hitting a particular area in which ATONs are damaged. Facilities are designated pre-storm in order to hold items to repair ATONs. Each facility is supplied by federal organizations as well as industry. Based on the level of damage and location of ATONs, items are pre-positioned after the storm for repair efforts. Aids to navigation will use a priority system of critical, urgent and routine when determining which aids to fix.

## 4.2 Problem Description and Assumptions

The following assumptions are considered for this research:

1. There will be four regions used: Alabama, Florida, Louisana and Mississippi because they are part of the gulf coast and prone to hurricanes.
2. Each region has a specified amount of safe locations for the various commodities needed to repair aids to navigation.
3. Each safe location has flashers, radar reflectors, discrepancy buoys and cutters that can be pre-positioned pre-disaster.

4. The process to repair aids to navigation will use the following priority system:
    a. Critical- based on damage requires the use of discrepancy buoy until original buoy is repaired;
    b. Urgent- the damage is able to be fixed on the scene;
    c. Routine- there is less damage and repair can take place after the most critical aids to navigation;
5. Commodities used for on scene repair are flashers and radar reflectors.
6. Commodities used in place of buoys are transferred back to safe location to be repaired are a discrepancy buoy.
7. Each teams gets a cutter, therefore the number of cutters needed is directly related to teams.
8. The demand for these commodities is unknown until after a disaster has occurred.
9. Aids to navigation teams are needed to move cutters to damaged areas.
10. Based on the path of the hurricane these commodities have the potential to be damaged.

### 4.3 Model Formulation

A two-stage stochastic facility location program is developed to solve this problem. A two-stage stochastic program uses first stage and second stage decisions. The first stage decisions, are represented by a vector. These decisions are taken without knowing the full information of some random event. The second stage decisions or recourse, or corrective actions based on the information received from the first stage decisions. According to (Birge, 1997), the general mathematical notation for this model with recourse is as follows:

$$\min c^T x + E_\xi \, Q(x, \xi) \tag{1}$$

$$s.t. \quad Ax = b \tag{2}$$

$$x \geq 0 \tag{3}$$

Recourse Function

$$Q(x, \xi) = min\{q^T y \big| W_y = h - T_{x,y} \geq 0\} \tag{4}$$

The objective function (1) minimizes the cost $c^T$ associated with the first stage decisions $x$ plus the expected cost of the second stage decisions. $\xi$ represents the full information of some random event and $Q(x, \xi)$ or recourse function represents the dependency of the random vector on different scenarios. Constraints (2, 3) are related to the first stage decisions of the model. Constraint (4) is related to the second stage decisions of the model.

***4.3.1 Overview of Stage 1***

Using this framework the model illustrates the processes a port takes to become operational based on the repair of ATONs while providing a rapid response time. The first stage decisions determine the amount of teams and commodities that are allocated to safe locations pre-landfall of a hurricane. That means, $x_i$ is the number of teams that are assigned to a safe location $i$ before the storm strikes land. The demand $D_{jv\omega}$ for each region $j$ for a priority $v$ is considered a random variable. A cost $c_k$ is associated with one unit of procuring repair items $k$.

#### *4.3.2 Overview of Stage 2*

The second stage decisions determine the amount of teams needed to fix ATONs that are damaged in each region, in regards to the repair type (i.e. critical, urgent, routine). Based on the demand there is a probability associated with each repair type scenario for each region. Table 3 represents the notation used for the parameters and variables of this model.

**Table 5. Model notation**

| Category | Symbol | Description |
|---|---|---|
| Index Sets | $L$ | Set of supply locations |
| | $I$ | Set of safe locations |
| | $K$ | Set of commodities used in repair activity |
| | $V$ | Set of possible ATON repair types (based on urgency) |
| | $J$ | Set of demand areas possibly affected |
| First Stage Decision Variables | $x_i$ | The number of teams assigned to safe location $i$ |
| | $s_{ik}$ | The number of supplies of commodity type $k$ assigned to safe location $i$ |
| | $y_{li}$ | The number of teams transferred from supply location $l$ to safe location $i$ |
| Second Stage Decision Variables | $z_{ij\omega}$ | The number of teams assigned from location $i$ to demand region $j$ in scenario ω |
| | $h_{ijk\omega}$ | The number of commodities of type k transferred from location $i$ to affected area j in scenario ω |
| | $u_{ijv\omega}$ | Unrepaired ATONs of type $v$ region $j$ in scenario ω by teams from safe location $i$. |
| | $r_{ijv\omega}$ | Repaired ATONs of type $v$ region $j$ in scenario ω by teams from safe location $i$. |

**Table 6. Model notation cont.**

| Category | Symbol | Description |
|---|---|---|
| Parameters | $M$ | Maximum load that each team can carry (lbs.) |
| | $w_k$ | Weight associated with commodity $k$ (lbs.) |
| | $N_l$ | Number of teams based at location $l$ |
| | $a_{vk}$ | Amount of commodity $k$ used in repair of type $v$ |
| | $B$ | Maximum allowable cost associated with pre-positioning commodities |
| | $\alpha_v$ | Criticality weight associated with ATON repair of type $v$ |
| | $c_k$ | Per unit cost associated with pre-positioning commodity $k$ |
| | $p_\omega$ | Scenario specific probability |
| | $e_{ij}$ | The travel time between safe location $i$ and demand region $j$ |
| | $t_{v\omega}$ | Scenario specific repair time for ATON of type $v$ |
| | $\gamma_k$ | The number of supplies available for commodity type $k$ |
| | $D_{jv\omega}$ | Amount of ATONS in need of repair of type $v$ in region $j$under scenario ω |

Using the notation above, a two-stage stochastic facility location model is formulated as follows:

$$\text{Max} \sum_v \sum_j \sum_\omega \sum_i p_\omega \alpha_v r_{ijv\omega} \tag{5}$$

s.t.

*Flow Balance (Pre-positioning)*

$$\sum_l y_{li} = x_i \quad \forall i \tag{6}$$

$$\sum_i y_{li} \leq N_l \ \forall l \tag{7}$$

*Supply Constraint*

$$\sum_{k} w_k s_{ik} \leq M x_i \quad \forall i \tag{8}$$

$$\sum_{i} s_{ik} \leq \gamma_k \quad \forall k \tag{9}$$

*Budget Constraint*

$$\sum_{k} \sum_{i} c_k s_{ik} \leq B \tag{10}$$

*Aid to Navigation Team Constraint*

$$\sum_{j} z_{ij\omega} \leq x_i \quad \forall i, \omega \tag{11}$$

*Repair Time Constraint*

$$\sum_{v} \sum_{i} t_{v\omega} r_{ijv\omega} \leq \sum_{i} z_{ij\omega} * (36 - e_{ij}) \quad \forall j, \omega \tag{12}$$

*Inventory Balance Constraint*

$$\sum_{i} (r_{ijv\omega} + u_{ijv\omega}) = D_{jv\omega} \quad \forall j, v, \omega \tag{13}$$

*Repaired ATONs to pre-positioned supplies Constraint*

$$\sum_{v} a_{vk} r_{ijv\omega} \leq h_{ijk\omega} \quad \forall i, j, k, \omega \tag{14}$$

*Affected Area Constraints*

$$\sum_{j} h_{ijk\omega} \leq s_{ik} \quad \forall i, k, \omega \tag{15}$$

$$\sum_{k} w_k * h_{ijk\omega} \leq M * z_{ij\omega} \quad \forall i, j, \omega \tag{16}$$

*Non-negativity Constraints*

$$x_i, s_{ik}, z_{ij\omega}, h_{ijk\omega}, u_{ijv\omega}, r_{i,j,v\omega}, y_{li} \geq 0 \qquad (17)$$

The objective function (5) maximizes the expected amount of aids to navigation that are repaired in the response phase. The first set of constraints (6, 7) represent the flow balance equations to ensure the amount of teams transferred from a supply location do not exceed the teams at the supply location and are equal to the amount teams at a safe location. Constraint (8) ensures that supplies stored at a safe location do not exceed the weight of the amount of items that a team can carry to that location. Constraint (9) shows the amount of supplies available for each commodity type. Constraint (10) ensures that the total number of items prepositioned cannot exceed the available budget. Constraint (11) makes certain the number of teams dispatched per location and scenario cannot exceed available team supply per location. Constraint (12) ensures the time to repair items at the demand region per scenario cannot exceed the available operation hours of teams allocated to an affected area. Constraint (13) makes certain that the amount of repaired and unrepaired ATONs equals the total demand. Constraint (14) represents the relationship between repaired ATONs and pre-positioned supplies. The next set of constraints (15,16) are dedicated to affected areas. The amount of supplies sent to an affected area cannot exceed available supply and commodities can only be allocated to an affected area if the teams are allocated to that area. The last constraint (17) makes sure the variables are not negative.

# CHAPTER 5

# NUMERICAL EXAMPLE

## 5.1 Numerical Example

Based on the model formulation given by equations (5)-(16) an example is illustrated. The supply chain data is represented by $l = 3$ supply location, $j = 4$ regions and $i = 3$ safe locations with three damage scenarios $(\omega)$ shown in 5. In Table 5 for scenario 1 the total demand is 485 ATONs, for scenarios 2 the total demand is 550 and for scenario 3 the total demand is 610. The total demand for damaged ATONs that are classified as critical is 545, routine is 605 and urgent is 495. For this example only one repair item is considered. The solution for this model is based on the data from Table 4 and 5 entered into GAMS linear programming software.

**Table 7. Model parameters for numerical example**

| Parameters | Levels | Values |
|---|---|---|
| $(\boldsymbol{M})$ the max lbs. a team can carry | 1 | 200 lbs. |
| $(\boldsymbol{w_k})$ the weight associated with commodity | 1 | 1 lb. |
| $(\boldsymbol{N_l})$ # of teams at a supply location | 3 | [50,20,30] |
| $(\boldsymbol{a_{vk}})$ amount of commodity used in a repair type | 3 | [1,0,0;1,0,0;1,0,0] |
| $(\boldsymbol{B}$ )the max cost associated with prepositioning commodities | 1 | $609,937 |

**Table 8. Model Parameters for numerical example cont.**

| Parameters | Levels | Values |
|---|---|---|
| ($\boldsymbol{\alpha_v}$) criticality weight of ATON Repair type | 3 | [3,2,1] |
| ($\boldsymbol{c_k}$) cost per unit commodity | 3 | [$40, $120, $90] |
| ($\boldsymbol{p_\omega}$) scenario specific probability | 3 | [0.6, 0.3, 0.1] |
| ($\boldsymbol{t_{v\omega}}$) scenario specific time repair | 3 | [2,1,0.75; 2,1,0.75; 2,1,0.75] |
| ($\boldsymbol{e_{ij}}$) travel time | 4 | [2, 2,3,1;2,4,3,2;2,2,4,3] |

**Table 9. Damage scenarios**

| Scenario | Region | Critical ATON Demand | Routine ATON Demand | Urgent ATON Demand |
|---|---|---|---|---|
| 1 | 1 | 20 | 15 | 50 |
| 1 | 2 | 35 | 40 | 25 |
| 1 | 3 | 25 | 15 | 75 |
| 1 | 4 | 55 | 70 | 60 |
| 2 | 1 | 55 | 75 | 45 |
| 2 | 2 | 40 | 15 | 30 |
| 2 | 3 | 15 | 45 | 20 |
| 2 | 4 | 65 | 95 | 50 |
| 3 | 1 | 70 | 30 | 50 |
| 3 | 2 | 90 | 80 | 35 |
| 3 | 3 | 60 | 80 | 30 |
| 3 | 4 | 15 | 45 | 25 |

## 5.2 Results

According to Figure 2, commodities are only sent to all three safe locations, one commodity is considered for this model. Since, the amount of teams is dependent on commodities each supply location must send a team to each safe location. In Figure 3, all safe locations are sent teams from only one supply location, which supports the amount of commodities received. Both of these figures also represent the decisions that are made within the first stage of the model.

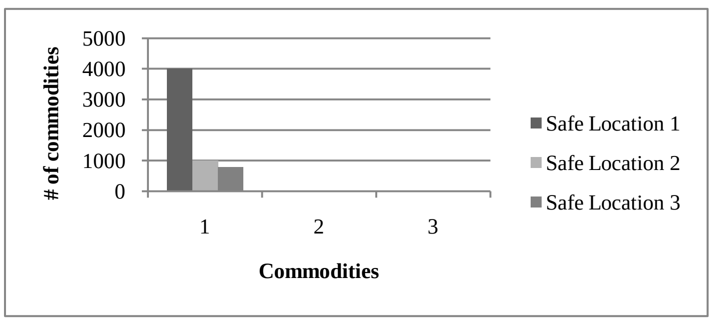



**Figure 2. Repair items sent to safe locations**

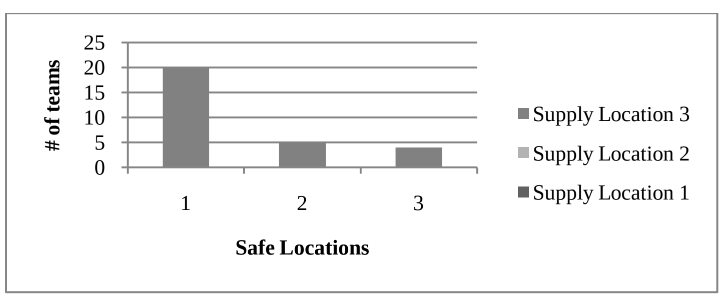



**Figure 3. Teams sent to safe locations**

The second stage decisions determine the amount of commodities and teams needed for each demand region per scenario. Figures 4(a)-4(d) depicts the amount of teams sent to the demand regions from a safe location. The results show that certain safe locations supply teams to specific regions. Safe location 1 supplies the most teams over all.

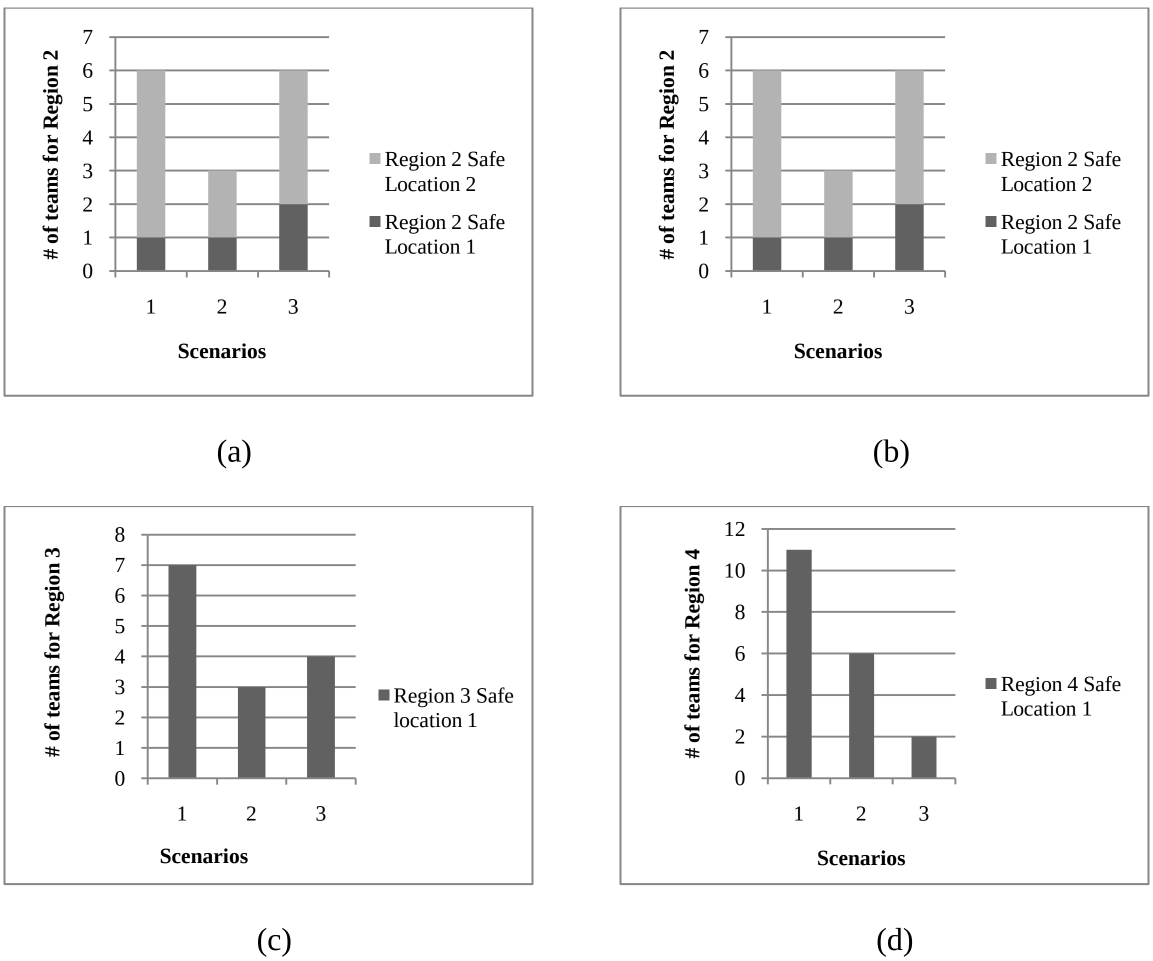
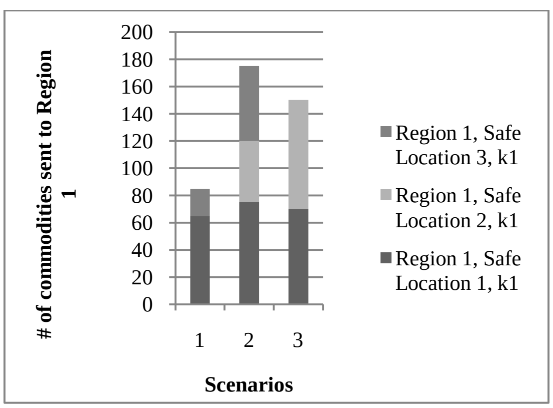
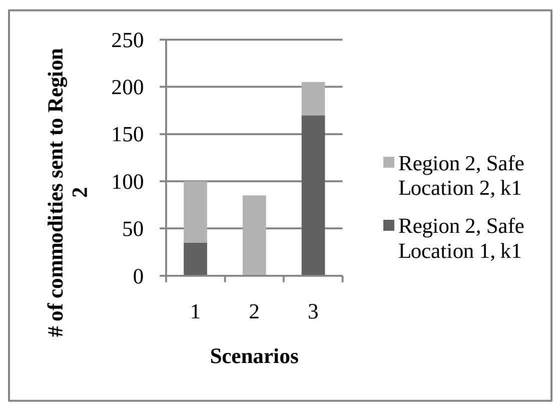



**Figure 4. Teams sent to demand regions (a) region 1, (b) region 2, (c) region 3, (d) region 4**

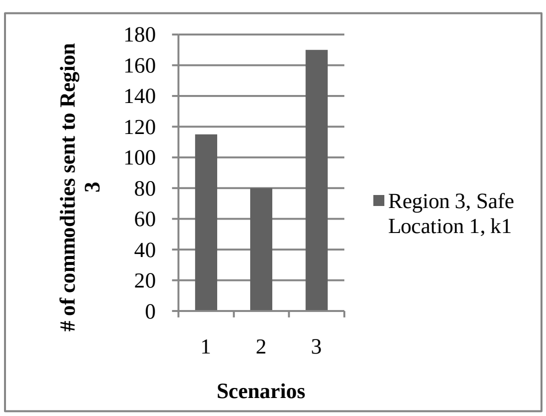
Figures 5(a)-5(d) represent the amount of commodities sent to a demand region from a safe location. The results show that all regions are supplied one commodity by specific safe locations. For regions one and two the amount of utilize the most commodities per scenario from more than one safe location. Regions three and four only utilize one safe location. Each region shows that the amount of teams sent matches up with commodities.



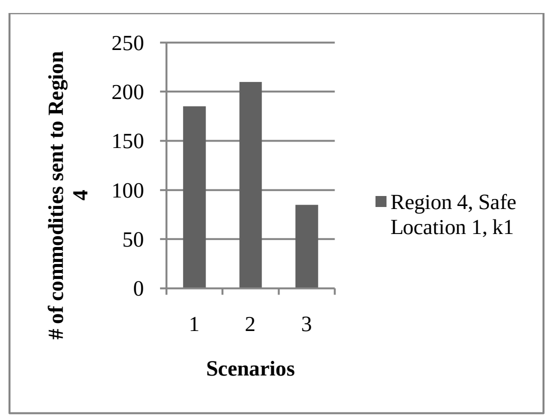

(a)




(b)



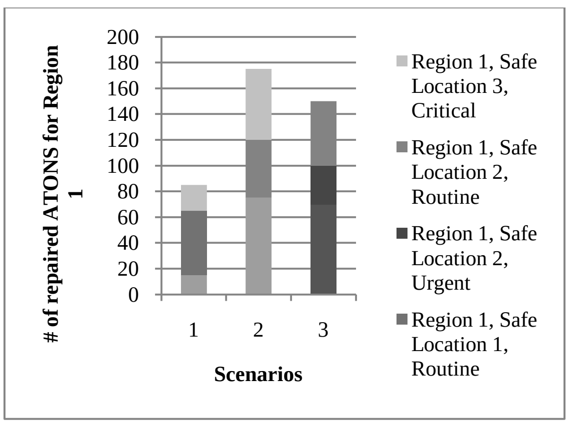

(c)



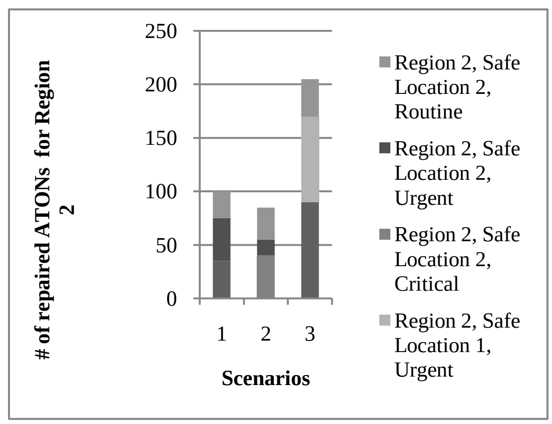

(d)

**Figure 5. Commodities sent to demand regions (a) region 1, (b) region 2, (c) region 3, (d) region 4**

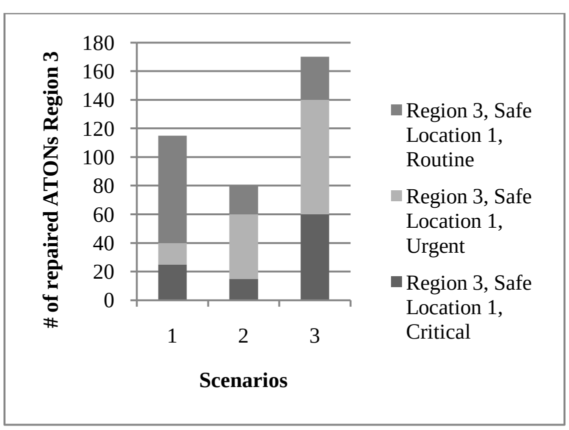
The next, set of decisions made within the second stage are the number of repaired and unrepaired items for each region. Figures 6(a)-6(d) show the amount of ATONs that are repaired for each region.  The results show that the all critical, urgent, routine ATONs are repaired for all regions leaving none unrepaired. This shows that there were enough commodities and teams sent to get all of the ATONs repaired.



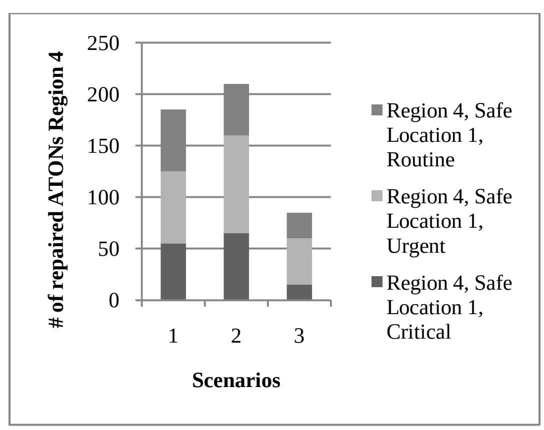

(a)




(b)




(c)




(d)

**Figure 6.  Number of repaired ATONs (a) region 1, (b) region 2, (c) region 3, (d) region 4**

## 5.3 Results Summary

The expected number of ATONs that required repair was 1393.5 for all demand regions and scenarios combinations. The optimal solution revealed there were on average 1008 ATONs repaired which is more than half of the expected demand. The figures, for each stage of the model, acknowledge that all safe locations are utilized but not all supply locations. However, all safe locations do not supply all regions for the scenario specific decisions. Our, objective is to maximize the expected number of ATONs over the response phase; the pre-positioning cost ($232,000) was below the budget of ($609,937).

# CHAPTER 6

# EXPERIMENTAL DESIGN

The objective of this research is to determine the effect of a prepositioning policy on the repair commodities in order to help with the recovery phase of waterways from a hurricane. Specifically, we will focus on the following:

1. The effect of parameters on the optimal pre-positioning policy;
2. The optimal stocking quantities and location of resources;
3. The benefit of the pre-positioning policy to the response phase.

Figure 7 illustrates the supply chain network of supply locations, safe locations and affected areas. Tables 10 and 11 show the actual names of locations and total time it takes to get to each one. The amount of hours between locations was calculated and the following ranking applied: **1-**(1-3hrs.), **2-**(4-6hrs.), **3**-(7-above). The ranking between supply and safe locations is negligible for this model. Each supply location is representative of USCG sectors within the eighth district. The eighth district represents states within the gulf coast region. The safe locations are different ports located within a region. The affected areas shown are regions that have ATONs that are damaged. Table 12 lists the parameters used for the model.

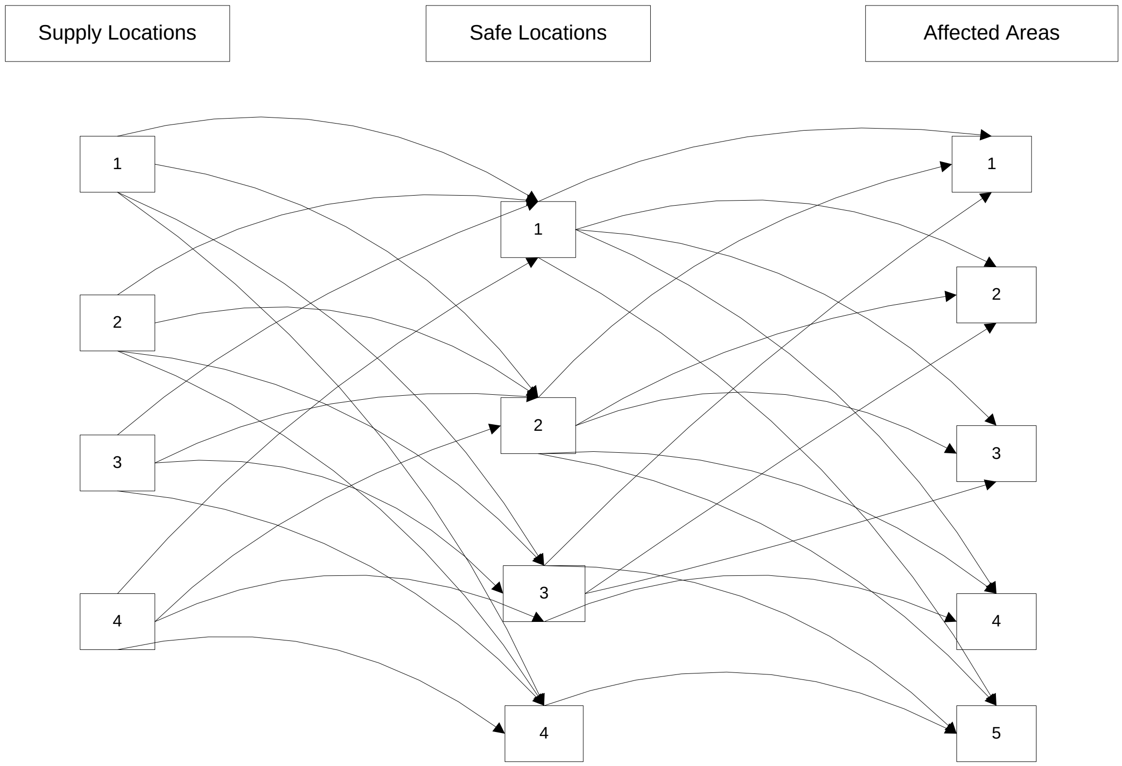



**Figure 7. Supply chain diagram**

**Table 10. Supply/safe locations and regions**

| **Supply Locations** | **Safe Locations** | **Region** |
|---|---|---|
| Sector New Orleans(l1) | Port of New Orleans(i1) | Alabama(j1) |
| Sector Mobile(l2) | Port of Mobile(i2) | Florida(j2) |
| Sector Lower Mississippi River (l3) | Port of Gulfport(i3) | Louisiana(j3) |
| Sector Upper Mississippi River(l4) | Port of Jacksonville(i4) | Mississippi(j4) |
| | | Mississippi/Louisiana(j5) |

**Table 11. Distance between safe locations and regions**

| Safe Locations/Regions | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| **i1** | 2 | 3 | 1 | 1 | 1 |
| **i2** | 1 | 3 | 2 | 1 | 1 |
| **i3** | 2 | 3 | 2 | 1 | 1 |
| **i4** | 3 | 1 | 3 | 3 | 3 |

**Table 12. Model parameters**

| Parameters | Levels | Values |
|---|---|---|
| ($\boldsymbol{M}$) the max lbs. a team can carry | 1 | 1500 lbs. |
| ($\boldsymbol{w_k}$) the weight associated with commodity | 1 | [190, 1, 6] lbs |
| ($\boldsymbol{N_l}$) # of teams at a supply location | 3 | [50,20,30,25] |
| ($\boldsymbol{a_{vk}}$) amount of commodity used in a repair type | 3 | [1,0,0;0,1,0;0,0,1] |
| ($\boldsymbol{\alpha_v}$) criticality weight of ATON Repair type | 3 | [3,2,1] |
| ($\boldsymbol{c_k}$) cost per unit commodity | 3 | [$350, $179, $139] |
| ($\boldsymbol{p_\omega}$) scenario specific probability | 3 | [0.05, 0.15, 0.25,0.25,0.30] |
| ($\boldsymbol{t_{v\omega}}$) scenario specific time repair | 3 | [2,1,0.75;2,1,0.75;2,1,0.75;2,1,0.75;2,1,0.75] (hrs.) |
| ($\boldsymbol{e_{ij}}$) travel time | 4 | [2,1,2,3,1;3,3,3,1;1,2,2,3;1,1,1,3;1,1,1,3] (hrs.) |

## 6.1 Model Data

The data for this model consists of information from various hurricanes and aids to navigation. The national hurricane center provides the path of hurricanes based on the Saffir/Simpson scale. They also give the strike probabilities of the hurricane in relation to the path of cities and states the hurricane will strike in a 24 hour period. The Light List provided by the USCG shows information on all aids to navigation throughout each district (United States Coast Guard, 2010).

Also, a list was provided from the USCG District 8 of damaged ATONs in the locations affected by Hurricane Katrina (Tables 34-38 Appendix 1). This information consists of the location measured in latitude and longitude, characteristics (e.g. flashers, bells, whistles) and other remarks of importance to the aid. This data was later formatted and clustered by region. The USCG website provides a table with various costs of the supplies used to repair ATONs (United States Coast Guard, 2010). Various manuals and documents were provided by the USCG to understand the entire ATON repair process.

## 6.2 Scenario Generation

The scenarios constructed for this case study are generated from realistic information. Each scenario is constructed using the projected storm path for Hurricane Katrina along with probabilities of the storm taking on a particular category (i.e. $\omega1$-tropical storm, $\omega2$-Category 1, $\omega3$-Category 2, $\omega4$-Category 3 and $\omega5$-Category 4/5). Figure 8 shows the actual forecast for Hurricane Katrina on August 26, 2005 at 11pm. The ATONs located inside the red circle are considered damaged.

The different colored circles represent the actual ATONs for different regions (i.e. blue-Louisiana, orange-Alabama, yellow-Mississippi/Louisiana, green-Florida, purple-Mississippi). The small green circles on the figure represent the safe locations. Based on the damage information received from the Coast Guard, the ATONs discrepancies were classified under the different repair types (e.g. critical, urgent and routine) for each region (Table 13). The repair items needed to fix the ATONs are discrepancy buoys(k1), flashers(k2) and radar reflectors(k3).

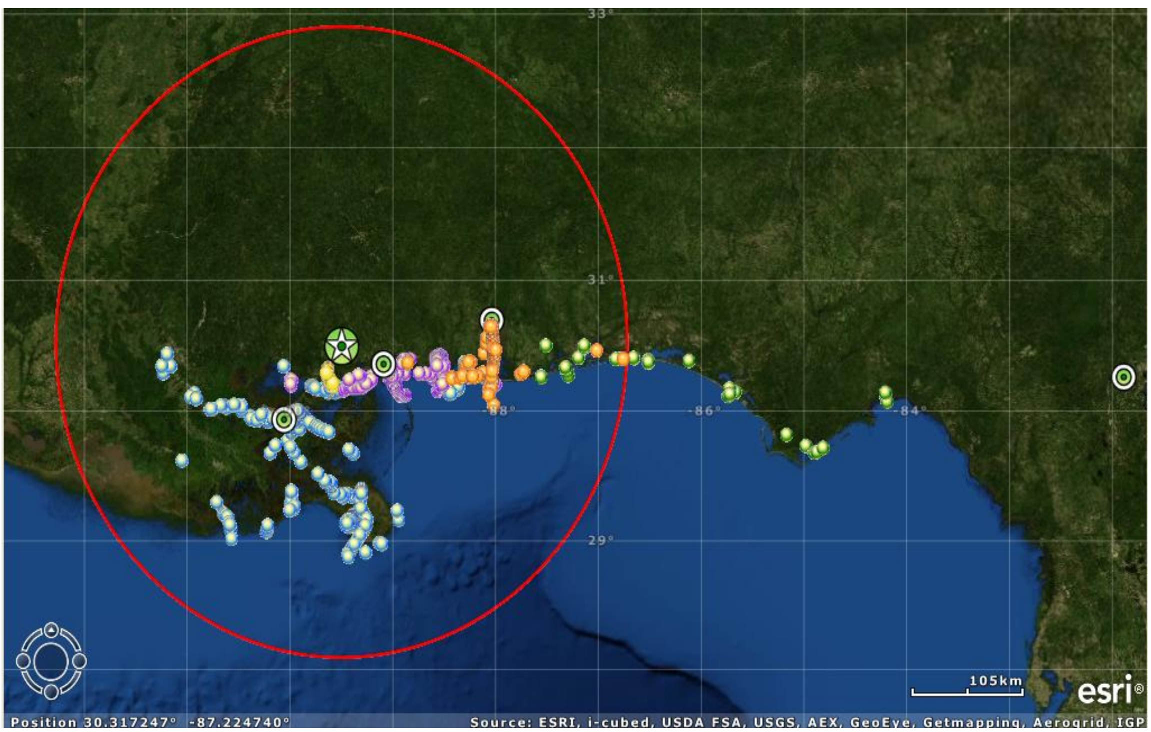



**Figure 8. ATONs inside the hurricane path**

**Table 13. ATON classification**

| Critical | Urgent | Routine |
|---|---|---|
| Light Extinguished | Dayboard Damaged | Buoy Damaged |
| Dayboard Destroyed | Topmark Damaged | |
| Missing | Missing/Dayboard Damaged | |
| Temporarily Replaced | Reduced Intensity | |
| Missing/Temporarily Replaced | | |
| Light Extinguished/ Dayboard Destroyed | | |
| Temporarily Replaced/Extinguished | | |
| Off station | | |
| Light Extinguished/ Improper Characteristics | | |
| Light Extinguished/ Dayboard Destroyed | | |
| Light Extinguished/Daybeacon Destroyed | | |
| Off station/ Light Extinguished | | |
| Daybeacon Destroyed | | |

A discrepancy factor was created to develop ATON damage estimates for each hurricane category (Table 14). Category three was used as the base since data was obtained from Hurricane Katrina to build case. The discrepancy factor for category three is calculated as follows the ratio of damaged ATONS to total ATONS per region. The other categories were scaled up or down from these numbers based on the intensity of the hurricane. This factor is multiplied by the total number of damaged ATONs in order to get the demand per region $\boldsymbol{D_{jv\omega}}$ (Table 15). The probabilities for each scenario are found in Table 16.

**Table 14. Discrepancy factor for each hurricane category**

| Category 1 | | | | | |
|---|---|---|---|---|---|
| **Repair type** | **Alabama** | **Florida** | **Louisiana** | **Mississippi** | **Mississippi/Louisiana** |
| **Critical** | 0.670 | 0.526 | 0.593 | 0.837 | 0.455 |
| **Urgent** | 0.168 | 0.263 | 0.204 | 0.062 | 0.364 |
| **Routine** | 0.162 | 0.211 | 0.204 | 0.100 | 0.182 |
| **Category 2** | | | | | |
| **Repair type** | **Alabama** | **Florida** | **Louisiana** | **Mississippi** | **Mississippi/Louisiana** |
| **Critical** | 0.782 | 0.763 | 0.699 | 0.861 | 0.591 |
| **Urgent** | 0.151 | 0.158 | 0.170 | 0.091 | 0.318 |
| **Routine** | 0.067 | 0.079 | 0.131 | 0.048 | 0.091 |
| **Category 3** | | | | | |
| **Repair type** | **Alabama** | **Florida** | **Louisiana** | **Mississippi** | **Mississippi/Louisiana** |
| **Critical** | 0.905 | 0.842 | 0.869 | 0.919 | 0.818 |
| **Urgent** | 0.095 | 0.105 | 0.131 | 0.077 | 0.182 |
| **Routine** | 0.000 | 0.053 | 0.000 | 0.005 | 0.000 |
| **Category 4/5** | | | | | |
| **Repair type** | **Alabama** | **Florida** | **Louisiana** | **Mississippi** | **Mississippi/Louisiana** |
| **Critical** | 0.961 | 0.921 | 0.973 | 0.957 | 0.909 |
| **Urgent** | 0.039 | 0.053 | 0.027 | 0.043 | 0.091 |
| **Routine** | 0.000 | 0.026 | 0.000 | 0.000 | 0.000 |

Table 15. Demand for base case

| Category1 | | | | | | |
|---|---|---|---|---|---|---|
| **Repair type** | **Alabama** | **Florida** | **Louisiana** | **Mississippi** | **Mississippi/ Louisiana** | **Total Repair Type** |
| **Critical** | 109 | 5 | 177 | 15 | 90 | 396 |
| **Urgent** | 3 | 1 | 6 | 0 | 2 | 12 |
| **Routine** | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | 112 | 6 | 183 | 15 | 92 | |
| **Category2** | | | | | | |
| **Repair type** | **Alabama** | **Florida** | **Louisiana** | **Mississippi** | **Mississippi/ Louisiana** | **Total Repair Type** |
| **Critical** | 127 | 8 | 208 | 171 | 11 | 525 |
| **Urgent** | 3 | 0 | 5 | 1 | 1 | 10 |
| **Routine** | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | 130 | 8 | 213 | 172 | 12 | |
| **Category3** | | | | | | |
| **Repair type** | **Alabama** | **Florida** | **Louisiana** | **Mississippi** | **Mississippi/ Louisiana** | **Total Repair Type** |
| **Critical** | 147 | 8 | 259 | 182 | 15 | 611 |
| **Urgent** | 2 | 0 | 4 | 0 | 1 | 7 |
| **Routine** | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | 149 | 8 | 263 | 182 | 16 | |
| **Category4/5** | | | | | | |
| **Repair type** | **Alabama** | **Florida** | **Louisiana** | **Mississippi** | **Mississippi/ Louisiana** | **Total Repair Type** |
| **Critical** | 156 | 9 | 290 | 189 | 16 | 661 |
| **Urgent** | 1 | 0 | 1 | 0 | 0 | 2 |
| **Routine** | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | 157 | 9 | 291 | 189 | 16 | |

**Table 16. Scenario probabilities based on hurricane advisory**

| Scenarios | Probability |
|---|---|
| **Tropical Storm** | 0.05 |
| **Category 1** | 0.15 |
| **Category 2** | 0.25 |
| **Category 3** | 0.25 |
| **Category 4&5** | 0.30 |

### 6.3 Performance Measures

During recovery or response phases there are many tasks to complete. The performance measures considered for this model are the impact of responsiveness based on the repair of ATONs and value of coordination among agencies and organizations. Based on pre-positioning, the responsiveness is defined as a ratio

$$Response\ Ratio = \frac{\sum_v \sum_j \sum_\omega \sum_i p_\omega \alpha_v r_{ijv\omega}}{\sum_\omega \sum_v \sum_j p_\omega \alpha_v D_{jv\omega}} \tag{17}$$

Where ( $\sum_v \sum_j \sum_\omega \sum_i p_\omega \alpha_v r_{ijv\omega}$) is the expected number of ATONs that are repaired during the response phase and ($\sum_\omega \sum_v \sum_j p_\omega \alpha_v D_{jv\omega}$) the expected number of ATONs needing repair. The value of supply is calculated by using the following formula $relative\ value = \frac{f(base\ case) - f(experiment)}{f(base\ case)}$ which corresponds to the amount of ATONs repaired. The collaboration between different agencies or industry is imperative and expected to be of benefit to each party involved. The value of coordination is established by leaving out the first stage pre-positioning decisions associated with material, adding extra time account for acquiring supplies after the event, and changing the budget constraint to be scenario specific rather than applied to the first stage prepositioning decision. This policy is tested against the original model for consistency.

## 6.4 Sensitivity Analysis

The following inputs are varied throughout the experiment: the supply, the workers response time, budget and supply acquisition time. The supply is changed based on the need of supplies for damaged ATONs due to the storm and the availability of supplies. The criteria used for the supply variations are increase, decrease and no change. An increase in supply could be necessary if the storm path strikes numerous regions or if damage is significant. A decrease in supply might be due to regions receiving no damage or supply locations being low on supplies. No change in supply can be due to no damage or supplies are evenly distributed.

The workers response time is changed based on the same time used for hurricane forecast. Since, damage within this model is uncertain, the budget will be changed to fit the need of the various scenarios. The supply acquisition time is used to decrease the response time for cases where pre-positioning is not taken to account. The following parameters as summarized in Tables (17 and 18) will be used in the experimental design.

**Table 17. Experimental design**

| Experiment # | Supply | Response Time | Budget | Supply Acquisition Time |
|---|---|---|---|---|
| 1 (base case) | Normal | 36 | $609,937 | None |
| 2 | Increase 10% | 36 | $609,937 | None |
| 3 | Increase 20% | 36 | $609,937 | None |
| 4 | Increase 30% | 36 | $609,937 | None |
| 5 | Decrease 10% | 36 | $609,937 | None |
| 6 | Decrease 20% | 36 | $609,937 | None |
| 7 | Decrease 30% | 36 | $609,937 | None |
| 8 | Normal | 36 | $607,655 | None |
| 9 | Normal | 36 | $1,002,000 | None |
| 10 | Normal | 36 | $609,937 | 0hrs. |
| 11 | Normal | 36 | $609,937 | 12hrs. |
| 12 | Normal | 36 | $609,937 | 24hrs. |
| 13 | Normal | 72 | $609,937 | None |
| 14 | Increase 10% | 72 | $609,937 | None |
| 15 | Increase 20% | 72 | $609,937 | None |
| 16 | Increase 30% | 72 | $609,937 | None |
| 17 | Decrease 10% | 72 | $609,937 | None |

**Table 18. Experimental design cont.**

| **Experiment #** | **Supply** | **Response Time** | **Budget** | **Supply Acquisition Time** |
|---|---|---|---|---|
| 18 | Decrease 20% | 72 | $609,937 | None |
| 19 | Decrease 30% | 72 | $609,937 | None |
| 20 | Normal | 72 | $607,655 | None |
| 21 | Normal | 72 | 1,002,000 | None |
| 22 | Normal | 72 | $609,937 | 0hrs. |
| 23 | Normal | 72 | $609,937 | 12hrs. |
| 24 | Normal | 72 | $609,937 | 24hrs. |
| 25 | Normal | 72 | $609,937 | 48hrs. |

# CHAPTER 7

# RESULTS

## 7.1 Overview

The results generated from the experimental design for the model determine the optimal policy for pre-positioning repair items for ATONs and maximizes the expected ATONs repaired during the response phase. This chapter consists of four sections to give detailed analysis of the experiments. The first section shows results from the base model. The second section discusses the performance measures used to assess the effect of pre-positioning on the responsiveness during the response phase and the value of coordination among organizations. The third section summarizes the sensitivity analysis on the supply, worker response time, budget and travel time. The last section shows the actual optimal policies.

## 7.2 Base Model

Table 15 shows the total demand of ATONs for each region and repair type. All three repair items are considered in this model (discrepancy buoy-k1, flasher-k2 and radar reflector-k3). The optimal quantities of teams and repair items for experiment 1 are shown in Figures 9 and 10. All safe locations are utilized to hold repair items for ATONs except safe location 2. For this model only discrepancy buoys and flashers are sent to each of the safe locations. The total supply prepositioned for discrepancy buoys are 707 and for flashers are 12. The radar reflectors are not demanded. The supply locations are all utilized but, they do not send commodities to every safe location.

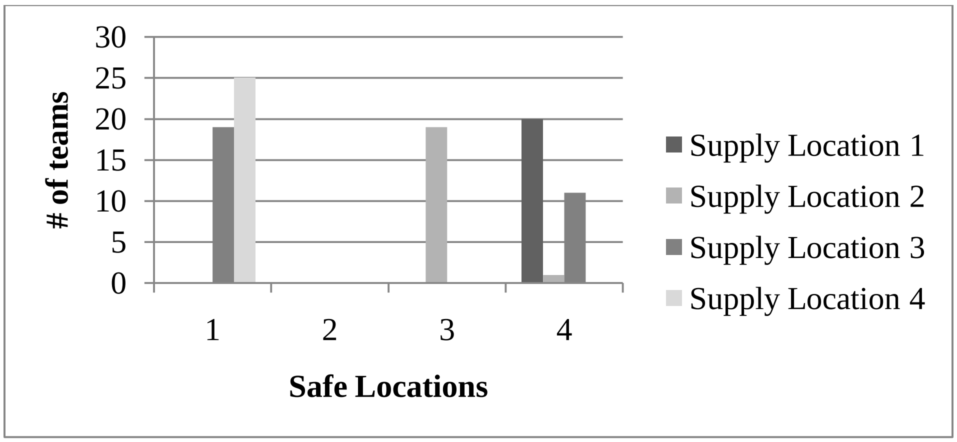



**Figure 9. Number of teams sent to safe locations**

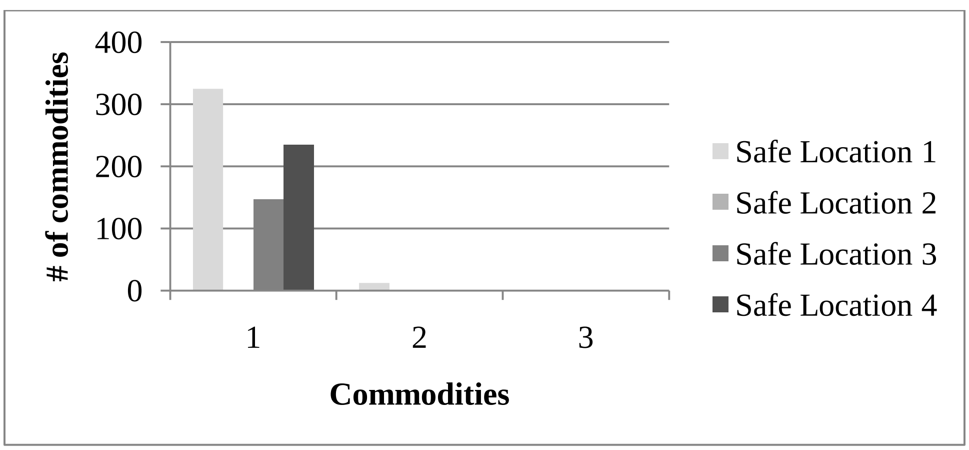
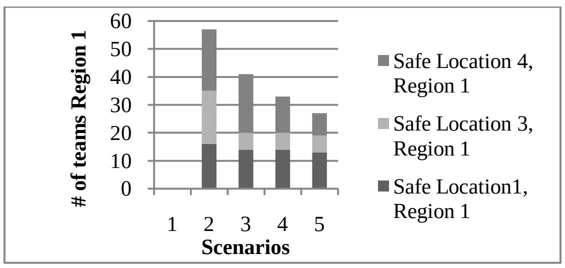
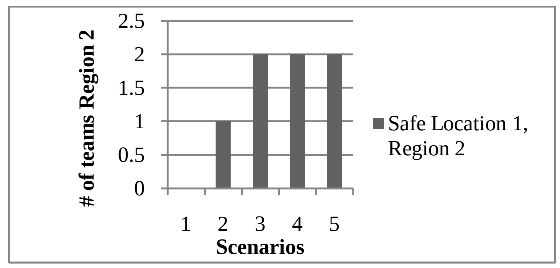



**Figure 10. Number of commodities sent to safe locations**

Figures 11a-11e illustrates the optimal quantities of teams sent to the actual affected areas with ATONs. For scenario two, which refers to a Category one storm, regions one (Figure 11a) and five (Figure 11e) receive the majority of the teams. The other regions have more teams sent for a category five storm.

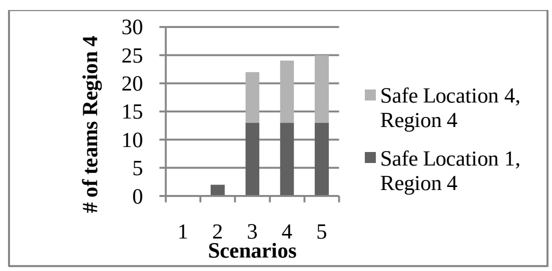



(a)

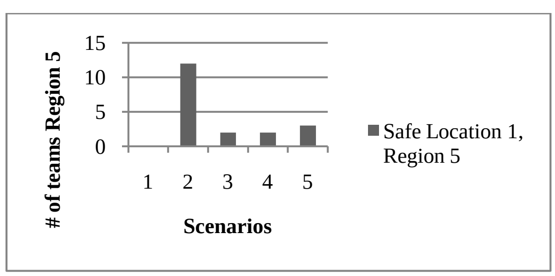



(b)


(c)



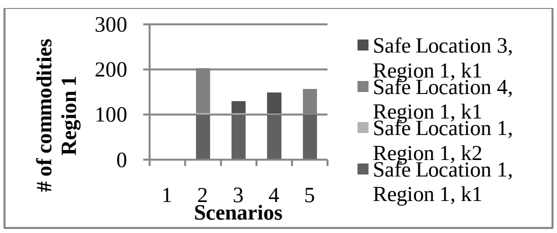

(d)



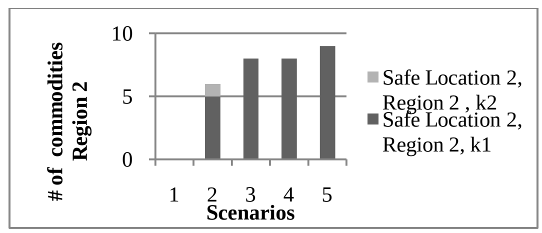

(e)

**Figure 11. Number of teams sent to demand regions (a) region 1, (b) region 2, (c) region 3, (d) region 4, (e) region 5**

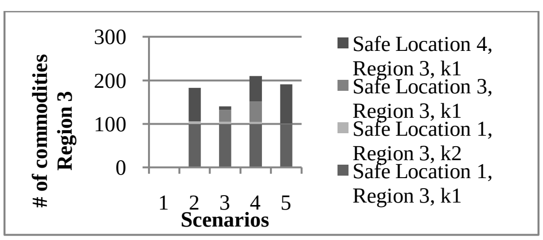
Figures 12(a)-12(e) represents the optimal quantities of repair items sent to each affected area. The amount of commodities for region one (Alabama) and five (Mississippi/Louisiana) for Category one match up with large amount of teams found in Figures 11(a) and 11(e). This increased amount could be due to total demand. Throughout all the regions we can see that the discrepancy buoy (k1) is sent the most which means that a lot of ATONs are damaged beyond repaired.



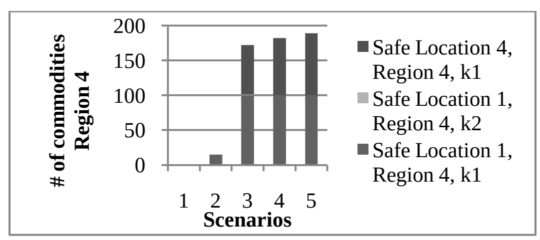

(a)



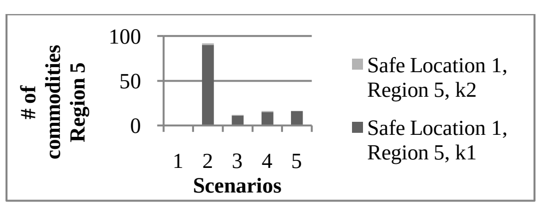

(b)




(b)



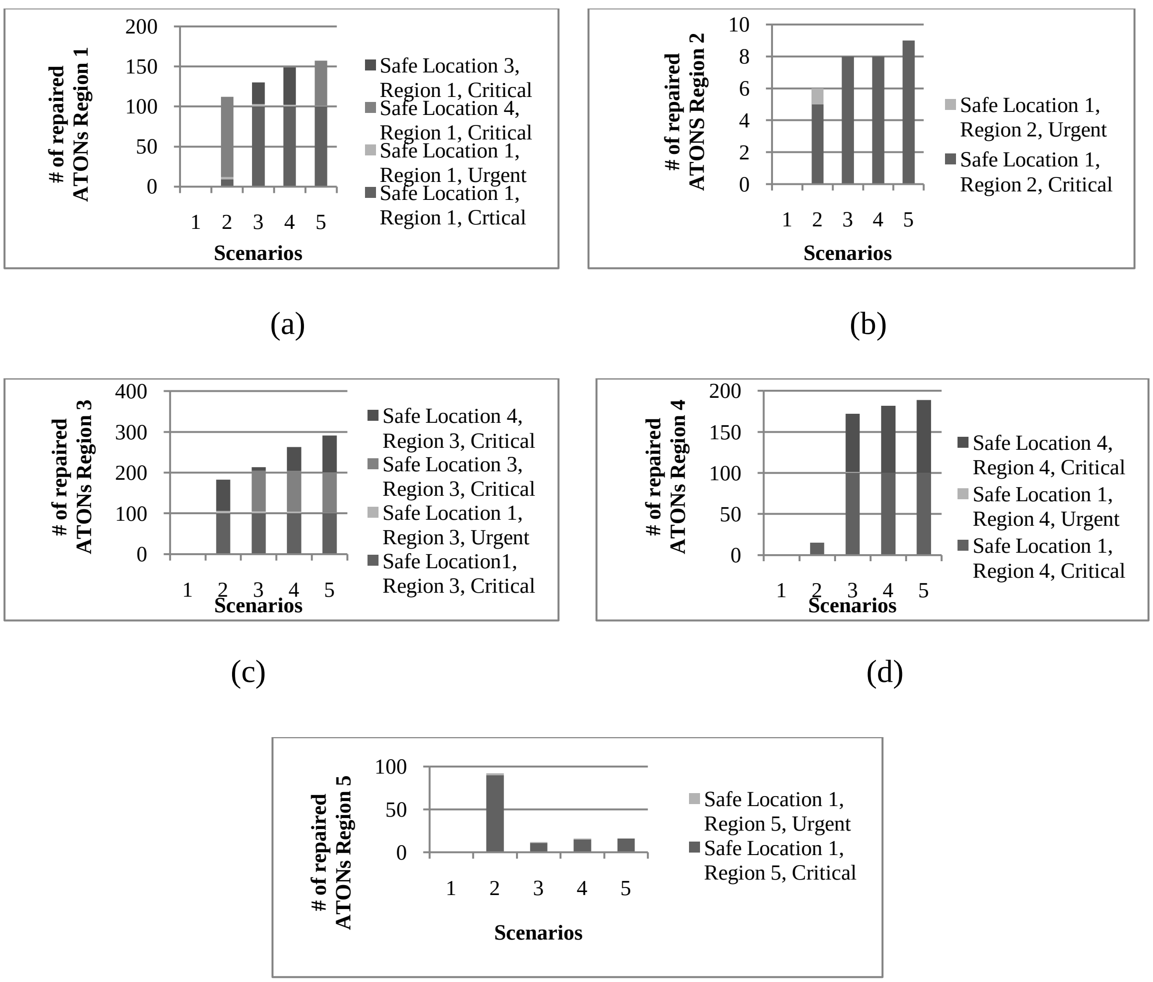

(d)




(e)

**Figure 12. Number of commodities sent to affected regions (a) region 1, (b) region 2, (c) region 3, (d) region4, (e) region 5**

Figures 13a-13e show the amount of ATONs repaired within each region. Each region repairs only the critical and urgent ATONs. Figures 13(a), 13(b) and 13(d) Category 5 has the most critical ATONs which are due to the intensity of the storm. In figure 13(e) shows that region 5 scenario 2 has the most ATONs being repaired this is due to the demand.  Based on the demand there are no routine ATONs repaired.




(e)

**Figure 13. Number of repaired ATONs for each region (a) region 1, (b) region 2, (c) region 3, (d) region 4, (e) region 5**

## 7.3 Sensitivity Analysis

### *7.3.1 Supply, Worker Response Time, Budget*

Tables 19 gives a list of the variation of supply from the base model for the different response times based on the unconstrained supply model. This model tells the optimal amount of supply given the model parameters. Tables 20 and 21 show the results of putting the supply numbers back into the supply constrained model under gamma(k) as a parameter. The experiments listed below only use two different response times (i.e. 36 hrs. and 72 hrs.). At the different response time of (Table 20 and 21) the increase in supply has no effect on the overall policy, a change does not occur until the supply is decreased. The amount of supplies used for the increased supply remains the same this is because the model gives the best amount of supply available given the time.

**Table 19. Supply variation for unconstrained supply model**

| Supply | Response Time | Supplies | | Total Supply Available gamma(k) |
|---|---|---|---|---|
| | | k1 | k2 | |
| base case(normal) | 36 | 707 | 12 | 719 |
| 10% | 36 | 778 | 13 | 791 |
| 20% | 36 | 848 | 14 | 862 |
| 30% | 36 | 919 | 16 | 935 |
| -10% | 36 | 636 | 11 | 647 |
| -20% | 36 | 566 | 10 | 576 |
| -30% | 36 | 495 | 8 | 503 |
| Normal | 72 | 762 | 17 | 779 |
| 10% | 72 | 838 | 19 | 857 |
| 20% | 72 | 914 | 20 | 934 |
| 30% | 72 | 991 | 22 | 1013 |
| -10% | 72 | 686 | 15 | 701 |
| -20% | 72 | 610 | 14 | 624 |
| -30% | 72 | 533 | 12 | 545 |

**Table 20. Supply variation for 36 hour response time**

| Experiment # | Supply | Response Time | Supplies | | Supply pre-positioned S(i,k) | Expected Number repaired |
|---|---|---|---|---|---|---|
| | | | k1 | k2 | | |
| 1 | base case(normal) | 36 | 707 | 12 | 719 | 1638 |
| 2 | 10% | 36 | 707 | 12 | 719 | 1638 |
| 3 | 20% | 36 | 707 | 12 | 719 | 1638 |
| 4 | 30% | 36 | 707 | 12 | 719 | 1638 |
| 5 | -10% | 36 | 636 | 11 | 647 | 1616 |
| 6 | -20% | 36 | 566 | 10 | 576 | 1519 |
| 7 | -30% | 36 | 495 | 8 | 503 | 1377 |

**Table 21. Supply variation for 72 hour response time**

| Experiment # | Supply | Response Time | k1 | k2 | Supply Pre-positioned S(i,k) | Expected Number Repaired |
|---|---|---|---|---|---|---|
| 13 | Normal | 72 | 762 | 17 | 779 | 1638 |
| 14 | 10% | 72 | 706 | 12 | 718 | 1638 |
| 15 | 20% | 72 | 706 | 12 | 718 | 1638 |
| 16 | 30% | 72 | 706 | 12 | 718 | 1638 |
| 17 | -10% | 72 | 686 | 12 | 698 | 1638 |
| 18 | -20% | 72 | 610 | 12 | 622 | 1592 |
| 19 | -30% | 72 | 533 | 12 | 545 | 1465 |

Tables 22 and 23 give the relative value of the total supply available for each case which further proves that a decrease in supply has an effect on the total amount of items repaired. Table 24 shows the amount of ATONs damaged or repaired per region. Throughout each case we can see that the amount ATONs expected to be repaired and damaged for each region is the same. Based on Figures 13(a)-13(e) this proves true because all ATONs are repaired.

**Table 22. Value of supply for 36 hour response time**

| Supply | Response Time | Value of Supply |
|---|---|---|
| base case(normal) | 36 | 0 |
| 10% | 36 | 0 |
| 20% | 36 | 0 |
| 30% | 36 | 0 |
| -10% | 36 | .013 |
| -20% | 36 | .072 |
| -30% | 36 | .159 |

**Table 23. Value of supply for 72 hour response time**

| Supply | Response Time | Value of supply |
|---|---|---|
| Normal | 72 | 0 |
| 10% | 72 | 0 |
| 20% | 72 | 0 |
| 30% | 72 | 0 |
| -10% | 72 | 0 |
| -20% | 72 | .020 |
| -30% | 72 | .105 |

**Table 24. Expected number of damaged/repaired ATONs for base case per region (Experiment #1)**

| **Base Case** | | |
|---|---|---|
| **Region** | **Expected Number of ATONs Damaged** | **Expected Number of ATONs Repaired** |
| Alabama | 399 | 399 |
| Florida | 24 | 24 |
| Louisiana | 697 | 697 |
| Mississippi | 442 | 442 |
| Mississippi/Louisiana | 76 | 76 |
| Total | 1638 | 1638 |

The budget was varied three times through all experiments. The numbers used for the budget are half the cost of the United States Coast Guard Budget for ATONs and waterways; for the 2010 and 2011. The other budget is calculated using the cost within the model inflated by 10%.  Table 25 gives a list of the budget and the amount of the budget actually used, determined from the model. The budget remains the same which results in no effect on the supply.  The budget was not exceeded anytime because only the amount of commodities needed was purchased.

**Table 25. Actual budget vs. Budget used**

| **Experiment #** | **Actual Budget** | **Budget Used** | **% of budget used** |
|---|---|---|---|
| 1 | $609,937 | 249,600 | 40.92% |
| 8 | $607,655 | 249,600 | 41.08% |
| 9 | $1,002,000 | 249,600 | 24.91% |
| 13 | $609,937 | 269,740 | 44.22% |
| 20 | $607,655 | 269,740 | 44.39% |
| 21 | $1,002,000 | 269,740 | 26.92% |

### 7.4 Performance Measure

#### *7.4.1 Response Ratio*

To examine the impact of pre-positioning on the recovery phase the response ratios is considered. Table 26 shows the total expected number of ATONs and the total expected number of damaged ATONs used to determine the overall response ratio. The response ratio is 100% which shows that all ATONs are repaired and that teams are responding in a timely manner to each discrepancy. Tables 27 and 28 show the response ratio for the variation in supply. When the supply decreases the response ratio is reduced. When the supply is increased the response ratio is the same as the base case.

**Table 26. Response ratio base case**

| Total Expected Repaired ATONs | Total Expected Number Damaged | Response Ratio |
|---|---|---|
| 1638 | 1638 | 100% |

**Table 27. Response ratio based on supply variation with response time 36 hours**

| Experiment # | Supply | Response Time | Expected Number Repaired | Expected Number Damaged | Response Ratio |
|---|---|---|---|---|---|
| 1 | base case(normal) | 36 | 1638 | 1638 | 100% |
| 2 | 10% | 36 | 1638 | 1638 | 100% |
| 3 | 20% | 36 | 1638 | 1638 | 100% |
| 4 | 30% | 36 | 1638 | 1638 | 100% |
| 5 | -10% | 36 | 1616 | 1638 | 98% |
| 6 | -20% | 36 | 1519 | 1638 | 93% |
| 7 | -30% | 36 | 1377 | 1638 | 84% |

**Table 28. Response ratio based on supply variation with response time 72 hours**

| Experiment # | Supply | Response Time | Expected Number Repaired | Expected Number Damaged | Response Ratio |
|---|---|---|---|---|---|
| 13 | Normal | 72 | 1638 | 1638 | 100% |
| 14 | 10% | 72 | 1638 | 1638 | 100% |
| 15 | 20% | 72 | 1638 | 1638 | 100% |
| 16 | 30% | 72 | 1638 | 1638 | 100% |
| 17 | -10% | 72 | 1638 | 1638 | 100% |
| 18 | -20% | 72 | 1592 | 1638 | 97% |
| 19 | -30% | 72 | 1465 | 1638 | 90% |

### *7.4.2 Value of Coordination*

To understand the impact of coordination during the response phase the first stage pre-positioning constraints were removed from the model. All supplies are not accounted for until the second stage of the model. The same parameters from the base model were used except the supply acquisition time is used to reduce the response time.

Tables 29 and 31 are two cases that show the value of coordination. This coordination is measured by taking the difference between the expected number ATONs repaired without pre-positioning, within the response phase against the base model. The lack of coordination is considered when the time to acquire supplies is increased and no pre-positioning occurs. The supply acquisition reduces the amount of time it takes to respond and repair ATONs. Therefore, the number of ATONs repaired decreases as the supply acquisition time increases. In Tables 29 and 31, decreasing, the 36 hr. case by 48 hr. supply time is not considered for this test. For the 72 hr. response time the amount of

ATONs repaired remains the same when realistic data is used, since it allows more time to respond to ATONs.

Table 29 shows there is no value of coordination and the supply constrained model yields the same results as the base model since this is the best policy. This is because increasing the time and supply has no effect on the amount of ATONs repaired and shows the response ratio is unchanged. For the test case, the amount of teams was changed from (i.e. 50, 20, 30, and 25) to (i.e. 10, 15), from this some value of coordination is shown in Tables 31 and 32. For example, the 36 hr. case with a 24 hr. supply time results in a decrease in the response ratio by 17%. As the supply acquisition time increases the amount of ATONs repaired decreases (Table 31).

**Table 29. Value of coordination for realistic data**

| Response Time | Base Case | 12hrs. | 24hrs. | 48hrs. |
|---|---|---|---|---|
| **36hrs.** | 1638 | 1638 | 1634 | 0 |
| **72hrs.** | 1638 | 1638 | 1638 | 1638 |

**Table 30. Relative value for realistic data**

| Response Time | Base Case | 12rs. | 24hrs. | 48hrs. |
|---|---|---|---|---|
| **36hrs.** | 1638 | 0 | 0 | 0 |
| **72hrs.** | 1638 | 0 | 0 | 0 |

**Table 31. Test case value of coordination**

| Response Time | Base Case | 12hrs. | 24hrs. | 48hrs. |
|---|---|---|---|---|
| **36hrs.** | 1126 | 1125 | 930 | 0 |
| **72hrs.** | 1126 | 1126 | 1126 | 1125 |

**Table 32. Relative value for test case**

| Response Time | Base Case | 12hrs. | 24hrs. | 48hrs. |
|---|---|---|---|---|
| **36hrs.** | 1126 | .0008 | .174 | 0 |
| **72hrs.** | 1126 | 0 | 0 | .174 |

# CHAPTER 8

# CONCLUSION

This research utilized a stochastic programming model to solve a real world problem involving emergency preparedness and response in relation to ports and ATONs. The findings of this research show that amount of repaired ATONs during the response decreases with variation of response time and supply acquisition time. The relationship between the available supply and worker response time affect the optimal solution of the amount of ATONs that are actually repaired. For some regions the Category one hurricane had more damaged ATONs than a Category five. This could be due to the amount of ATONs damaged for the particular experiment. The response ratio proved to be reasonable for the amount of ATONs that were repaired. These results show the motivation for researching the pre-positioning policy in relation to ports but further improvements can provide more insight.

Further research would include receiving more data from the Coast Guard of the damage acquired by ATONs due to a hurricane for each category type. This will help to build robust scenarios. Utilizing more hurricane paths will help to see the variation among damage within the scenarios at different levels; only one hurricane forecast was used for this model. Another improvement for this model is to consider the teams making multiple trips to the affected area during the response phase. This model only assumes one trip.

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## APPENDIX 1.

## NUMERICAL EXAMPLE DATA

**Table 33. Light list/ cluster data (Louisiana)**

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 367 | light | on research cage FI Y 4s | 29.9775 | 88.6050 | 5 |
| 370 | buoy | red, horn, Q, R | 29.5847 | 88.6828 | 5 |
| 397 | buoy | white, FI W 4s, lighted mooring buoy | 28.1602 | 89.2633 | 5 |
| 400 | buoy | white with orange bands, wreck buoy | 29.1668 | 88.8836 | 5 |
| 402 | buoy | Green , Q, Lighted horn buoy | 29.2390 | 88.8837 | 5 |
| 405 | buoy | red, lighted bell buoy , FI R 6s | 29.2380 | 88.9578 | 5 |
| 410 | buoy | red, lighted bell buoy, FI R 2.5s | 29.1649 | 88.9423 | 5 |
| 414 | buoy | white with blue bands,Q,W | 29.1172 | 88.8583 | 5 |
| 416 | buoy | white with orange bands, ocean energy buoy | 28.9887 | 89.0818 | 2 |
| 417 | buoy | red,lighted horn, Q,R | 28.9881 | 89.0824 | 2 |
| 425 | light | reef light, FI Y 2.5s, NY on pile | 30.2021 | 89.0811 | 5 |
| 430 | light | FI (5) W 60sskeleton tower, white below gallery, black above, Q,W | 29.0152 | 89.1667 | 2 |
| 435 | beacon | On texaco platform, Q,W, RACON | 28.8661 | 89.2608 | 5 |
| 445 | buoy | red, lighted bell buoy, FI R 2.5s | 28.9787 | 89.1087 | 2 |
| 455 | light | tower on white dwelling on piles, FI W 10s, Racon | 28.9059 | 89.4286 | 5 |
| 460 | beacon | on texaco platform A, Racon | 28.8336 | 89.4534 | 5 |
| 465 | buoy | red and white stripes with red spherical topmark, lighted whistle, Mo(A) W | 28.8775 | 89.4319 | 5 |
| 467 | buoy | white with orange bands lighted, FI W 2.5s | 28.8298 | 89.5265 | 5 |
| 468 | buoy | white with orange bands lighted, FI W 2.5s | 28.8770 | 89.5357 | 5 |

**Table 33. Light list/ cluster data (Louisiana) cont.**

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 470 | buoy | white with orange bands lighted, FI W 2.5s | 28.7970 | 89.5583 | 5 |
| 481 | buoy | red, private aid lighted, Q, R | 28.9972 | 89.5283 | 5 |
| 482 | beacon | on shell-WD-143-platform 1, Q, W , RACON | 28.6617 | 89.5511 | 5 |
| 490 | buoy | lighted bell, FI G 4s, green | 29.2238 | 89.6149 | 5 |
| 491 | buoy | lighted FI W 2.5s, white with orange bands, Exxon | 28.9442 | 89.7111 | 5 |
| 493 | buoy | lighted, FI W 2.5s, white with orange bands, | 28.9565 | 89.7520 | 5 |
| 495 | buoy | LSU oceangraphic lighted, FI Y4s, yellow | 30.3843 | 86.7633 | 5 |
| 500 | buoy | red and white stripes with red spherical topmark, lighted whistle, Mo(A) W | 29.2328 | 89.9020 | 1 |
| 510 | buoy | BP America lighted, FI W 2.5s, white with orange bands | 29.0314 | 89.8859 | 5 |
| 513 | beacon | articulated beacon A , FI Y 4s, ny on pillar buoy, (NIGHT) FI Y 4s | 29.1933 | 89.8833 | 4 |
| 513.1 | beacon | Articulated beacon B, FI Y 4s, ny on pillar buoy | 29.1933 | 89.8950 | 4 |
| 513.2 | beacon | articulated beacon C, FI Y 4s, ny on pillar buoy | 29.1850 | 89.8983 | 4 |
| 513.3 | beacon | articulated beacon D, FI Y 4s, ny on pillar buoy | 29.1817 | 89.8883 | 4 |
| 513.4 | beacon | Articulated beacon E, FI Y 4s, ny on pillar buoy | 29.1850 | 89.8800 | 4 |
| 530 | light | FI W 10s, on platform, RACON, Q, W, Horn | 28.8850 | 90.0250 | 4 |
| 535 | buoy | Lighted horn buoy, FI G 6s, green | 28.8100 | 89.9167 | 5 |
| 538 | buoy | lighted buoy FI W 2.5s, white with orange bands | 28.6856 | 89.9592 | 5 |
| 540 | buoy | lighted buoy FI R 6s | 28.8383 | 89.8983 | 5 |
| 545 | buoy | lighted buoy FI G 6s, green | 28.8358 | 90.0400 | 4 |
| 550 | buoy | lighted buoy, FI R 6s, red | 28.9144 | 89.9500 | 5 |
| 555 | buoy | lighted mooring buoy, Q,W, white deck with yellow sides | 28.8883 | 89.9997 | 4 |

**Table 33. Light list/ cluster data (Louisiana) cont.**

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 560 | buoy | lighted mooring buoy, Q,W, white deck with yellow sides | 28.8711 | 90.0050 | 4 |
| 565 | buoy | lighted mooring buoy,Q,W, white deck with yellow sides | 28.8625 | 90.0233 | 4 |
| 570 | buoy | lighted mooring buoy, FI W 4s , white | 28.8883 | 90.0200 | 4 |
| 575 | buoy | lighted mooring buoy, FI W 4s, white | 28.8833 | 90.0333 | 4 |
| 580 | buoy | lighted mooring buoy, FI W 4s, white | 28.8900 | 90.0453 | 4 |
| 590 | buoy | lighted buoy, FI Y 6s, yellow | 28.8683 | 89.8783 | 5 |
| 595 | buoy | lighted buoy, FI Y 6s, yellow | 28.9017 | 89.9433 | 5 |
| 597 | buoy | lighted buoy, FI W 2.5s, white with orange bands | 28.7699 | 89.9721 | 5 |
| 600 | light | FI W 4s on pile, horn | 29.1000 | 90.1133 | 4 |
| 605 | light | FI W 4s on pile, | 29.1017 | 90.1150 | 4 |
| 615 | buoy | lighted buoy, FI W 2.5s, white with orange bands | 28.4299 | 90.1348 | 5 |
| 625 | buoy | lighted buoy, Q,W, red | 28.6864 | 90.1528 | 5 |
| 630 | buoy | Shell flare pipe buoy, white with orange bands | 28.9750 | 90.1767 | 5 |
| 631 | buoy | lighted buoy, FI W 2.5s, white with orange bands | 28.4432 | 90.1846 | 5 |
| 633 | buoy | lighted buoy, FI W 2.5s, white with orange bands | 28.2799 | 90.2393 | 5 |
| 9477 | light | NOAA shell beach tide monitoring platform light, FI Y 2.5s, | 29.8681 | 89.6732 | 3 |
| 9495 | light | FI W 6s, nb on dolphin, radar reflector | 29.9463 | 89.7084 | 5 |
| 9500 | light | FI W 2.5s, nb on dolphin, radar reflector | 30.0196 | 89.7199 | 5 |
| 9565 | light | FI R 6s , TR on dolphin, radar reflector | 30.1610 | 89.6521 | 2 |
| 9570 | light | FI G 4s, SG on dolphin, radar reflector | 30.1733 | 89.6888 | 2 |
| 9575 | light | FI R 4s, TR on dolphin | 30.1669 | 89.7167 | 2 |
| 9577 | buoy | LSU oceanographic lighted buoy, FL Y 4s, Yellow | 30.1720 | 89.7300 | 2 |

**Table 33. Light list/ cluster data (Louisiana) cont.**

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 9580 | light | FI G 6s, SG on pile, radar reflector | 30.1646 | 89.7360 | 2 |
| 9585 | light | FI G 4s, SG on dolphin, radar reflector | 30.1749 | 89.7431 | 2 |
| 9590 | light | FI R 2.5s, TR on pile, radar reflector | 30.1771 | 89.7546 | 2 |
| 9595 | beacon | NW on pile worded Danger Rocks | 30.1653 | 89.7492 | 2 |
| 9600 | beacon | NW on pile worded Danger Rocks | 30.1645 | 89.7492 | 2 |
| 9715 | light | FI G 6s, green, SG on pile, radar reflector | 30.1416 | 89.8588 | 5 |
| 9603 | beacon | NW on pile worded Danger do not proceed | 30.2292 | 89.7465 | 2 |
| 9810 | light | Q, R, on concrete platform | 30.1518 | 89.8964 | 5 |
| 9935 | light | Q,W | 30.0600 | 90.0300 | 5 |
| 9937 | light | FI Y 4s, on pile | 30.1644 | 90.0819 | 5 |
| 9992 | light | FI (2)W 5s, on skeleton pole | 30.0272 | 90.1132 | 5 |
| 10050 | light | Q,W, on concrete slab. | 30.3609 | 90.0940 | 3 |
| 10055 | light | Q,W, on concrete slab. | 30.3591 | 90.0949 | 3 |
| 10240 | light | F R, on square platform | 30.0317 | 90.1750 | 5 |
| 10281 | light | FI Y 4s, on pile | 30.0322 | 90.1955 | 5 |
| 10360 | light | Q,W,on power line structure | 30.0817 | 90.4017 | 5 |
| 10362 | light | steel dolphins | 30.0441 | 90.2369 | 5 |
| 10363 | light | FI G 2.5s, steel dolphin | 30.0333 | 90.2333 | 5 |
| 10365 | light | Q,W, on power line structures | 30.3831 | 90.1975 | 5 |
| 10367 | light | Lumcon environmental monitoring station light,FI Y 2.5s, on platform | 30.3146 | 90.2805 | 5 |
| 10426 | beacon | NW on pile worded : Danger barricade ahead | 30.3311 | 90.4117 | 2 |
| 10427 | buoy | lighted buoy, white with orange bands and open face diamond | 30.3314 | 90.4119 | 2 |
| 10428 | beacon | NW on pile worded: Danger barricade ahead | 30.3353 | 90.4125 | 1 |
| 10685 | light | pipeline light, Q, G, SG on piles | 29.5227 | 89.1687 | 4 |

**Table 33. Light list/ cluster data (Louisiana) cont.**

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 10690 | light | pipeline light, Q, R, TR on piles | 29.5249 | 89.1662 | 4 |
| 10695 | light | pipeline light, Q,R pile structure | 29.5243 | 89.1713 | 4 |
| 10700 | light | pipeline light, Q, R pile structure | 29.5263 | 89.1695 | 4 |
| 10795 | light | FI G 4s, SG on dolphin | 29.6331 | 89.3262 | 2 |
| 10815 | light | FI G 4s, SG on dolphin | 29.6522 | 89.3536 | 2 |
| 10825 | beacon | SG on pile | 29.6567 | 89.3671 | 2 |
| 10830 | beacon | TR on pile, radar reflector | 29.6555 | 89.3656 | 2 |
| 10835 | beacon | SG on pile | 29.6589 | 89.3644 | 2 |
| 10840 | beacon | TR on pile radar reflector | 29.6584 | 89.3638 | 2 |
| 10860 | light | Q R TR on pile, radar reflector | 29.6779 | 89.3856 | 2 |
| 10880 | light | FI R 4s, TR on pile | 29.7071 | 89.4280 | 5 |
| 10980 | light | Q,G, SG on pile | 29.8401 | 89.6238 | 4 |
| 10985 | light | Q, R, TR on pile radar reflector | 29.8421 | 89.6230 | 4 |
| 10990 | light | FI G 2.5s, SG on pile, radar reflector | 29.8463 | 89.6458 | 4 |
| 10995 | light | FI R 2.5s, TR on dolphin | 29.8490 | 89.6453 | 4 |
| 11000 | light | FI G 2.5s , SG on pile | 29.8566 | 89.6804 | 3 |
| 11005 | light | FI R 2.5s, TR on skeleton tower on piles | 29.8585 | 89.6799 | 3 |
| 11010 | light | Q,G, SG on skeleton tower on piles | 29.8648 | 89.7091 | 3 |
| 11015 | light | Q,R, TR on skeleton tower on plies | 29.8667 | 89.7081 | 3 |
| 11020 | light | FI G 2.5s, SG on pile | 29.8748 | 89.7293 | 3 |
| 11025 | light | FI R 2.5s, TR on dolphin | 29.8767 | 89.7283 | 3 |
| 11030 | light | FI G 4s SG on skeleton tower on piles. | 29.8847 | 89.7490 | 3 |
| 11035 | light | FI R 4s TR on pile, radar reflector | 29.8864 | 89.7475 | 3 |
| 11040 | light | FI G 2.5s, SG on pile | 29.9030 | 89.7844 | 4 |
| 11045 | light | FI R 2.5s,TR on skeleton tower on piles | 29.9049 | 89.7835 | 4 |

**Table 33. Light list/ cluster data (Louisiana) cont.**

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 11050 | light | Q, G, SG on skeleton tower on piles | 29.9162 | 89.8102 | 4 |
| 11055 | light | Q, R, TR on skeleton tower on piles | 29.9178 | 89.8087 | 4 |
| 11060 | light | FI G 2.5s, SG on pile | 29.9416 | 89.8419 | 4 |
| 11065 | light | FI R 2.5s, TR on pile | 29.9433 | 89.8401 | 4 |
| 11070 | light | FI G 6s, SG on pile | 29.9553 | 89.8591 | 4 |
| 11075 | light | FI R 6s, TR on pile | 29.9568 | 89.8568 | 4 |
| 11080 | light | FI G 4s, SG on dolphin, radar reflector | 29.9733 | 89.8809 | 4 |
| 11085 | light | FI R 4s, TR on skeleton tower on piles | 29.9748 | 89.8794 | 4 |
| 11090 | light | FI G 6s, SG on pile | 29.9855 | 89.8965 | 4 |
| 11095 | light | FI Y 2.5s, nw on pile | 29.9889 | 89.9011 | 4 |
| 11100 | light | FI R 6s, TR on pile | 29.9871 | 89.8982 | 4 |
| 11105 | light | FI Y 2.5s, nw on pile | 29.9908 | 89.8992 | 4 |
| 11110 | light | FI G 4s, SG on dolphin | 30.0006 | 89.9149 | 4 |
| 11115 | light | FI R 4s, TR on skeleton tower on piles | 30.0012 | 89.9119 | 4 |
| 11120 | light | FI G 2.5s, SG on dolphin | 30.0054 | 89.9233 | 4 |
| 11125 | light | FI R 2.5s, TR on dolphin | 30.0051 | 89.9172 | 4 |
| 11130 | light | FI (2+1) R 6s, JR-SY on skeleton tower on piles | 30.0077 | 89.9217 | 4 |
| 11135 | light | FI G 4s, SG-SY on pile | 30.0054 | 89.9317 | 4 |
| 11140 | light | FI R 2.5s | 30.0067 | 89.9342 | 4 |
| 11145 | light | FI R 2.5s, on dolphin | 30.0039 | 89.9497 | 4 |
| 11150 | light | FI R 2.5s, TR-TY on skeleton tower on piles | 30.0029 | 89.9551 | 4 |
| 11152 | light | FI R 2.5s , on dolphins | 29.9978 | 90.0097 | 5 |
| 15195 | light | FI G 2.5s , SG on dolphin | 29.3728 | 89.6658 | 5 |
| 15200 | light | FI G 4s, SG on dolphin | 29.3795 | 89.6413 | 5 |
| 15225 | buoy | FI G 4s, green | 29.3716 | 89.6017 | 5 |
| 15323 | buoy | Green Can | 29.2412 | 89.9129 | 1 |
| 15325 | buoy | Red nun | 29.2430 | 89.9117 | 1 |
| 15328 | buoy | Green Can | 29.2472 | 89.9203 | 1 |
| 15330 | buoy | Red nun | 29.2489 | 89.9183 | 1 |
| 15338 | Buoy | Green Can | 29.2522 | 89.9266 | 1 |

Table 33. Light list/ cluster data (Louisiana) cont.

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 15340 | buoy | FI R 6s , Red | 29.2547 | 89.9251 | 1 |
| 15343 | buoy | Green Can | 29.2561 | 89.9316 | 1 |
| 15345 | buoy | Red nun | 29.2583 | 89.9303 | 1 |
| 15347 | buoy | Green Can | 29.2631 | 89.9391 | 1 |
| 15348 | buoy | Red nun | 29.2648 | 89.9372 | 1 |
| 15350 | buoy | Green Can | 29.2686 | 89.9453 | 1 |
| 15355.5 | light | On pipe FL Y 2.5s | 29.2728 | 89.9468 | 1 |
| 15356 | beacon | nw on pile worded Danger rocks | 29.2723 | 89.9435 | 1 |
| 15356.1 | light | FL W 2.5s, nw on pile worded Danger rocks | 29.2720 | 89.9439 | 1 |
| 15356.2 | light | FL W 2.5s, nw on pile worded Danger rocks | 29.2719 | 89.9451 | 1 |
| 15356.3 | beacon | nw on piles worded Danger rocks | 29.2727 | 89.9463 | 1 |
| 15356.4 | beacon | nw on pile worded Danger rocks | 29.2730 | 89.9464 | 1 |
| 15357 | light | on four pile cluster | 29.2712 | 89.9447 | 1 |
| 15360 | light | FL W 3s end of fishing piers on pilings | 29.2611 | 89.9500 | 1 |
| 15365 | light | QR on pile structure | 29.2624 | 89.9489 | 1 |
| 15366 | beacon | NW on pile. Worded danger breakwater | 29.2580 | 89.9483 | 1 |
| 15366.01 | beacon | NW on pile. Worded danger breakwater | 29.2562 | 89.9510 | 1 |
| 15485 | light | FL Y 2.5s nw on pile do not anchor or dredge | 29.2653 | 89.9719 | 1 |
| 15545 | beacon | Shell Reef Daybeacon, NW on pile. Worded danger, radar reflector | 29.3444 | 89.9408 | 1 |
| 15525 | light | FL Y 4s nw on pile | 29.3975 | 89.7958 | 2 |
| 15530 | light | FL Y 4s nw on pile | 29.3981 | 89.7961 | 2 |
| 15535 | light | Q, W | 29.3925 | 89.7933 | 2 |
| 15540 | light | Q, R, on pile | 29.3919 | 89.7981 | 2 |
| 15595 | light | Q, W, nw on pile worded do not anchor or dredge | 29.2767 | 89.9567 | 1 |
| 15600 | light | FI G 4s, SG on dolphin, radar reflector | 29.2783 | 89.9586 | 1 |

**Table 33. Light list/ cluster data (Louisiana) cont.**

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 15605 | light | Q, R, TR on pile, radar reflector | 29.2793 | 89.9575 | 1 |
| 15610 | light | FI y 2.5s, nw on pile worded do no anchor or dredge | 29.2801 | 89.9579 | 1 |
| 15615 | light | FI Y 2.5s, nw on pile worded do not anchor or dredge | 29.2783 | 89.9591 | 1 |
| 15620 | Buoy | red nun | 29.2805 | 89.9601 | 1 |
| 15625 | beacon | SG on pile, radar reflector | 29.2832 | 89.9653 | 1 |
| 15630 | beacon | TR on pile, radar reflector | 29.2842 | 89.9646 | 1 |
| 15635 | beacon | Black diamond daymark on pile, FI W | 29.2850 | 89.9650 | 1 |
| 15640 | beacon | Black diamond daymark on pile,FI W | 29.2917 | 89.9717 | 1 |
| 15650 | beacon | Black diamond daymark on pile, FI W | 29.2917 | 89.9733 | 1 |
| 15665 | light | FI G 2.5s, SG on pile, radar reflector | 29.2903 | 89.9741 | 1 |
| 15670 | light | FI R 2.5s, TR on pile, radar reflector | 29.2908 | 89.9728 | 1 |
| 15675 | beacon | SG on pile, radar reflector | 29.2987 | 89.9786 | 1 |
| 15680 | beacon | TR on pile, radar reflector | 29.2993 | 89.9774 | 1 |
| 15685 | light | FI R 2.5s, TR on pile, radar reflector | 29.3063 | 89.9810 | 1 |
| 15690 | beacon | SG on pile, radar reflector | 29.3060 | 89.9818 | 1 |
| 15695 | beacon | TR on pile, radar reflector | 29.3120 | 89.9835 | 1 |
| 15700 | beacon | SG on pile, radar reflector | 29.3112 | 89.9842 | 1 |
| 15705 | light | FI G 4s, SG on pile, radar reflector | 29.3188 | 89.9860 | 1 |
| 15710 | light | FI R 4s, TR on pile, radar reflector | 29.3188 | 89.9835 | 1 |
| 15715 | light | FI G 6s, SG on pile, radar reflector | 29.3329 | 89.9856 | 1 |
| 15720 | beacon | TR on pile, radar reflector | 29.3329 | 89.9846 | 1 |
| 15730 | light | FI R 6s, Tr on pile, radar reflector | 29.3489 | 89.9842 | 1 |
| 15735 | light | FI G 2.5s, SG on pile, radar reflector | 29.3639 | 89.9846 | 3 |
| 15740 | light | FI R 2.5s, TR on pile, Radar reflector | 29.3641 | 89.9834 | 3 |

**Table 33. Light list/ cluster data (Louisiana) cont.**

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 15745 | beacon | SG on pile, radar reflector | 29.3689 | 89.9851 | 3 |
| 15750 | beacon | TR on pile, radar reflector | 29.3696 | 89.9838 | 3 |
| 15755 | beacon | SG on pile, radar reflector | 29.3761 | 89.9861 | 3 |
| 15760 | light | FI R 4s, TR on pile, radar reflector | 29.3751 | 89.9844 | 3 |
| 15765 | light | FI G 4s, SG on pile, radar reflector | 29.3830 | 89.9869 | 3 |
| 15770 | beacon | TR on pile, radar reflector | 29.3828 | 89.9855 | 3 |
| 15775 | beacon | SG on pile, radar reflector | 29.3889 | 89.9876 | 3 |
| 15780 | light | FO R 2.5s, TR on pile, radar reflector | 29.3890 | 89.9865 | 3 |
| 15825 | beacon | SG on pile, radar reflector | 29.3955 | 89.9886 | 3 |
| 15830 | beacon | TR on pile, radar reflector | 29.3957 | 89.9876 | 3 |
| 15835 | light | FI G 6s, SG on pile, radar reflector | 29.4059 | 89.9902 | 3 |
| 15840 | light | FI R 6s, Tr on pile, radar reflector | 29.4059 | 89.9891 | 3 |
| 15845 | beacon | SG on pile, radar reflector | 29.4163 | 89.9918 | 3 |
| 15850 | beacon | TR on pile, radar reflector | 29.4209 | 89.9916 | 3 |
| 15855 | beacon | SG on pile, radar reflector | 29.4271 | 89.9936 | 3 |
| 15860 | light | Q, G, SG on pile, radar reflector | 29.4250 | 89.9999 | 3 |
| 15865 | light | FI R 4s, TR on pile, radar reflector | 29.4378 | 89.9942 | 3 |
| 15870 | beacon | SG on pile, radar reflector | 29.4416 | 89.9960 | 3 |
| 15875 | beacon | TR on pile, radar reflector | 29.4534 | 89.9970 | 3 |
| 15880 | light | Q, G, SG on pile, radar reflector | 29.4668 | 90.0004 | 2 |
| 15885 | light | Q, R, TR on pile, radar reflector | 29.4674 | 89.9998 | 2 |
| 15890 | buoy | Green Can | 29.4716 | 90.0038 | 2 |
| 15895 | buoy | Red nun | 29.4715 | 90.0027 | 2 |
| 15900 | light | FI G 2.5s, SG on pile, Radar reflector | 29.4753 | 90.0073 | 2 |
| 15905 | light | FI R 2.5s, TR on pile, radar reflector | 29.4761 | 90.0061 | 2 |
| 15910 | beacon | TR on pile, radar reflector | 29.4806 | 90.0111 | 2 |
| 15915 | beacon | SG on pile, radar reflector | 29.4882 | 90.0171 | 2 |

**Table 33. Light list/ cluster data (Louisiana) cont.**

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 15920 | buoy | red nun | 29.4922 | 90.0170 | 2 |
| 15925 | light | FI R 4s, TR on pile, radar reflector | 29.4949 | 90.0184 | 2 |
| 15930 | light | FI G 4s , SG on pile, radar reflector | 29.4989 | 90.0214 | 2 |
| 15933 | light | FI Y 2.5s, NW on dolphin worded Danger | 29.4528 | 90.0325 | 2 |
| 15934 | light | FI Y 2.5s, NB on dolphin worded danger submerged pipeline | 29.4517 | 90.0400 | 2 |
| 15935 | light | on dolphin | 29.5533 | 90.0433 | 2 |
| 15936 | light | on dolphin | 29.5533 | 90.0450 | 2 |
| 15938 | light | FL Y 2.5s nw on dolphin worded danger submerged pipeline | 29.5819 | 90.0618 | 2 |
| 15939 | light | FL Y 2.5s nw on dolphin worded danger submerged pipeline | 29.5819 | 90.0607 | 2 |
| 15940 | light | FL Y 2.5s on dolphin | 29.5831 | 90.0611 | 2 |
| 15945 | light | FL Y 2.5s on dolphin | 29.5833 | 90.0597 | 2 |
| 15948 | light | FL G 4s SG on pile, radar reflector | 29.5779 | 90.0592 | 2 |
| 15949 | light | FL R 4s TR on pile, radar reflector | 29.5877 | 90.0640 | 2 |
| 15950 | light | FL G 2.5s SG on pile, radar reflector | 29.6009 | 90.0728 | 2 |
| 15955 | light | FL R 2.5s TR on pile, radar reflector | 29.6012 | 90.0720 | 2 |
| 15960 | beacon | SG on pile, radar reflector | 29.6112 | 90.0790 | 2 |
| 15965 | beacon | TR on pile radar reflector | 29.6115 | 90.0780 | 2 |
| 15970 | light | FL G 4s SG on pile, radar reflector | 29.6232 | 90.0859 | 2 |
| 15975 | light | FL R 4s TR on pile, radar reflector | 29.6237 | 90.0847 | 2 |
| 15980 | light | FL R 2.5s TR on pile, radar reflector | 29.6457 | 90.0980 | 2 |
| 15985 | light | FL G 4s SG on pile, radar reflector | 29.6663 | 90.1120 | 2 |
| 15990 | light | FL R 4s TR on pile, radar reflector | 29.6670 | 90.1122 | 2 |

**Table 33. Light list/ cluster data (Louisiana) cont.**

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 16205 | light | Q, R, on dolphin | 29.1991 | 90.0411 | 5 |
| 16210 | light | FI Y 2.5s, NW on dolphin worded Do not anchor or dredge | 29.2094 | 90.0433 | 5 |
| 16217 | beacon | NW on pile worded danger submerged oyster reef | 29.3506 | 90.1318 | 5 |
| 16218 | beacon | white with orange band worded danger barricade ahead | 29.3551 | 90.0893 | 5 |
| 16220 | light | Q, W , SG on pile | 29.5325 | 90.1642 | 4 |
| 16225 | light | Q,W, SG on pile | 29.5325 | 90.1600 | 4 |
| 16230 | light | Q,W, SG on pile | 29.5322 | 90.1550 | 4 |
| 16235 | ligh | Q,W,SG on pile | 29.5472 | 90.1664 | 4 |
| 16240 | light | Q,W, TR on pile | 29.5467 | 90.1608 | 4 |
| 16245 | light | FI W 4s TR on pile | 29.0711 | 90.1797 | 3 |
| 16515 | buoy | lighted bell buoy, Q, R, Red | 29.5172 | 90.2279 | 4 |
| 16530 | buoy | Q,G, Green | 29.0717 | 90.2314 | 3 |
| 16535 | light | Q, G, KRW on platform | 29.0986 | 90.2232 | 3 |
| 16535.01 | light | Iso G 6s, KRW on platform | 29.1234 | 90.2176 | 3 |
| 16540 | light | FI G 2.5s, SG on pile, Radar reflector | 29.0794 | 90.2294 | 3 |
| 16547 | light | FI R 2.5s, TR on pile, radar reflector | 29.0789 | 90.2257 | 3 |
| 16550 | light | FI R 4s TR on pile, radar reflector | 29.0845 | 90.2253 | 3 |
| 16555 | light | FI R 6s , TR on pile, radar reflector | 29.0910 | 90.2241 | 3 |
| 16560 | light | Q,W on pile | 29.0863 | 90.5571 | 1 |
| 16570 | light | Q,W, on pile | 29.1001 | 90.5296 | 1 |
| 16575 | light | Q,W, SG on pile | 29.0964 | 90.5283 | 1 |
| 16580 | beacon | SG on pile | 29.0961 | 90.5283 | 1 |
| 16585 | beacon | SG on pile | 29.0942 | 90.5281 | 1 |
| 16590 | beacon | SG on pile | 29.0922 | 90.5278 | 1 |
| 16595 | beacon | SG on pile | 29.0908 | 90.5272 | 1 |
| 16600 | beacon | SG on pile | 29.0894 | 90.5267 | 1 |
| 16605 | beacon | SG on pile | 29.0886 | 90.5267 | 1 |
| 16610 | beacon | SG on pile | 29.0881 | 90.5264 | 1 |

Table 33. Light list/ cluster data (Louisiana) cont.

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 16615 | light | Q,W on pile | 29.1078 | 90.5055 | 1 |
| 16620 | light | Q,W on pile | 29.1121 | 90.4970 | 1 |
| 16625 | light | Q,W on pile | 29.1116 | 90.4856 | 1 |
| 16630 | light | Q,W on pile | 29.1115 | 90.4846 | 1 |
| 16635 | beacon | TR on pile | 29.0922 | 90.4964 | 1 |
| 16640 | beacon | TR on pile | 29.0917 | 90.4950 | 1 |
| 16645 | beacon | TR on pile | 29.0911 | 90.4933 | 1 |
| 16650 | beacon | TR on pile | 29.0903 | 90.4917 | 1 |
| 16655 | light | TR on pile | 29.0747 | 90.4700 | 1 |
| 16660 | beacon | TR on pile | 29.0733 | 90.4706 | 1 |
| 16665 | beacon | TR on pile | 29.0719 | 90.4708 | 1 |
| 16670 | beacon | TR on pile | 29.0706 | 90.4714 | 1 |
| 16675 | beacon | TR on pile | 29.0697 | 90.1797 | 3 |
| 16684 | light | On wooden structure FL 2.5s Y | 29.1273 | 90.5142 | 1 |
| 16684.01 | light | Q,Q, TR on four pile platform | 29.0789 | 90.4556 | 1 |
| 16685 | beacon | TR on piles | 29.0706 | 90.4542 | 1 |
| 16690 | beacon | TR on piles | 29.0694 | 90.4539 | 1 |
| 16695 | beacon | TR on piles | 29.0681 | 90.4539 | 1 |
| 16696.01 | beacon | SG on pile, radar reflector | 29.1656 | 90.5818 | 5 |
| 16696.03 | light | FI G 4s, SG on pile | 29.1651 | 90.5637 | 5 |
| 16696.07 | light | FI G 6s, SG on pile | 29.1642 | 90.5275 | 5 |
| 16696.11 | light | FI G 4s SG on pile | 29.1632 | 90.4914 | 5 |
| 16696.15 | light | FI G 6s , SG on pile | 29.1623 | 90.4552 | 5 |
| 16696.19 | light | FI G 4s, SG on pile | 29.1613 | 90.4190 | 5 |
| 16696.23 | light | FI G 6s , SG on pile | 29.1604 | 90.3828 | 5 |
| 16696.27 | light | Q, G, SG on pile, radar reflector | 29.1594 | 90.3467 | 5 |
| 16696.29 | beacon | SG on pile, radar reflector | 29.1507 | 90.3322 | 5 |
| 16696.31 | light | FI G 4s, SG on pile | 29.1418 | 90.3178 | 5 |
| 16696.33 | beacon | SG on pile, radar reflector | 29.1328 | 90.3034 | 5 |
| 16696.36 | light | Q, R, TR on pile, radar reflector | 29.1233 | 90.2892 | 5 |
| 16696.38 | light | FI R 4s, TR on pile, radar reflector | 29.1278 | 90.2760 | 5 |

**Table 33. Light list/ cluster data (Louisiana) cont.**

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 16696.4 | light | FI R 6s, Tr on pile, radar reflector | 29.1324 | 90.2630 | 5 |
| 16696.42 | light | Q, R, TR on pile, radar reflector | 29.1370 | 90.2494 | 5 |
| 16699 | buoy | FI(2+1)R 6s Red with green band | 29.1652 | 90.6000 | 5 |
| 16780 | light | FI G 4s SG on dolphin | 29.1939 | 90.3496 | 5 |
| 16785 | light | FI R 4s TR on dolphin | 29.1864 | 90.4186 | 5 |
| 16790 | light | FI W 4s, SG on dolphin | 29.2025 | 90.2689 | 3 |
| 16795 | light | FI W 4s, SG on dolphin | 29.2275 | 90.3000 | 3 |
| 16800 | buoy | Green Can | 29.2289 | 90.2989 | 3 |
| 16805 | buoy | Green Can | 29.2306 | 90.2978 | 3 |
| 16810 | buoy | Green Can | 29.2319 | 90.2964 | 3 |
| 16815 | buoy | Green Can | 29.2333 | 90.2953 | 3 |
| 16820 | buoy | Green Can | 29.2350 | 90.2942 | 3 |
| 16825 | buoy | Green Can | 29.2364 | 90.2931 | 3 |
| 16830 | buoy | Green Can | 29.2378 | 90.2919 | 3 |
| 16835 | buoy | Green Can | 29.2394 | 90.2908 | 3 |
| 16840 | buoy | Green Can | 29.2411 | 90.2903 | 3 |
| 16845 | light | FI W 4s, SG on piles | 29.2464 | 90.2825 | 3 |
| 16850 | buoy | Green Can | 29.2464 | 90.2806 | 3 |
| 16855 | buoy | Green Can | 29.2461 | 90.2786 | 3 |
| 16860 | buoy | Green Can | 29.2458 | 90.2767 | 3 |
| 16865 | buoy | Green Can | 29.2458 | 90.2744 | 3 |
| 16870 | buoy | Green Can | 29.2456 | 90.2725 | 3 |
| 16875 | buoy | Green Can | 29.2453 | 90.2706 | 3 |
| 16880 | buoy | Green Can | 29.2450 | 90.2683 | 3 |
| 16885 | buoy | Green Can | 29.2450 | 90.2664 | 3 |
| 16890 | buoy | Green Can | 29.2447 | 90.2644 | 3 |
| 16895 | buoy | Green Can | 29.2444 | 90.2622 | 3 |
| 16900 | buoy | Green Can | 29.2444 | 90.2603 | 3 |
| 16905 | buoy | Green Can | 29.2442 | 90.2583 | 3 |
| 16910 | buoy | Green Can | 29.2439 | 90.2439 | 3 |
| 16915 | light | Q, R, on pile | 29.2393 | 90.1797 | 5 |
| 16920 | beacon | SG on pile | 29.2910 | 90.3512 | 4 |

Table 33. Light list/ cluster data (Louisiana) cont.

| Number | ATON Type | ATON Characteristics | Latitude | Longitude | Cluster |
|---|---|---|---|---|---|
| 16925 | beacon | SG on pile | 29.2943 | 90.3475 | 4 |
| 16930 | beacon | SG on pile | 29.2949 | 90.3453 | 4 |
| 16935 | beacon | SG on pile | 29.2949 | 90.3407 | 4 |
| 16940 | beacon | SG on pile | 29.2958 | 90.3375 | 4 |
| 16945 | beacon | SG on pile | 29.2984 | 90.3348 | 4 |
| 16950 | beacon | SG on pile | 29.3008 | 90.3346 | 4 |
| 16955 | beacon | SG on pile | 29.3030 | 90.3352 | 4 |
| 16960 | beacon | SG on pile | 29.3055 | 90.3382 | 4 |
| 16965 | beacon | SG on pile | 29.3076 | 90.3404 | 4 |
| 16967 | light | SG on pile | 29.5435 | 90.4002 | 5 |
| 16990 | light | FI G 4s, SG on dolphin, radar reflector | 29.2727 | 90.4753 | 5 |
| 16995 | light | FI R 4s, TR on pile, radar reflector | 29.3204 | 90.4376 | 5 |
| 17000 | light | FI G 4s, SG on pile, radar reflector | 29.1821 | 90.5835 | 5 |
| 17005 | light | FI R 2.5s, TR on dolphin, radar reflector | 29.2072 | 90.5806 | 5 |
| 17010 | light | FI R 4s, TR on dolphin, radar reflector | 29.2250 | 90.5961 | 5 |
| 17015 | light | FI G 6s, SG on dolphin, radar reflector | 29.2324 | 90.6032 | 5 |
| 17020 | light | FI G 4s, SG on dolphin, radar reflector | 29.2439 | 90.5914 | 5 |
| 17025 | light | FI G 2.5s, SG on dolphin, radar reflector | 29.2489 | 90.5777 | 5 |
| 17030 | light | FI W 4s, NB on pile, radar reflector | 29.2887 | 90.5407 | 5 |

**Table 34. Damaged aids to navigation for Hurricane Katrina (Alabama)**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 6190 | 30.47667 | 88.01197 | Alabama | Missing |
| 6030 | 30.25461 | 88.05721 | Alabama | Temporarily Replaced by Unlighted Buoy |
| 5770 | 30.37023 | 88.85473 | Alabama | LT EXT |
| 5440 | 30.63964 | 88.03333 | Alabama | LT EXT |
| 6025 | 30.2537 | 88.0563 | Alabama | TRUB |
| 6050 | 30.25359 | 88.0619 | Alabama | DBN DEST |
| 6055 | 30.25257 | 88.06353 | Alabama | TRUB/DBD DES |
| 6075 | 30.25226 | 88.07207 | Alabama | DBN DEST |
| 6080 | 30.25201 | 88.07577 | Alabama | DBN DEST |
| 6095 | 30.24993 | 88.07333 | Alabama | TRUB/LT EXT/DBD DEST |
| 6100 | 30.25009 | 88.06828 | Alabama | TRLB |
| 6160 | 30.45393 | 88.1039 | Alabama | LT EXT |
| 6167 | 30.45064 | 88.10864 | Alabama | DBN DEST |
| 6180 | 30.44398 | 88.1123 | Alabama | DBN DEST |
| 6185 | 30.44436 | 88.11333 | Alabama | DBN DEST |
| 5295 | 30.47742 | 88.01902 | Alabama | DBN DEST |
| 6220 | 30.48727 | 88.03249 | Alabama | TRLB/LT EXT/DBD DEST |
| 6230 | 30.49487 | 88.04551 | Alabama | TRLB/LT EXT/DBD DEST |
| 6235 | 30.49652 | 88.0442 | Alabama | TRLB/LT EXT/DBD DEST |
| 6245 | 30.50458 | 88.05858 | Alabama | TRLB |
| 6250 | 30.51023 | 88.07252 | Alabama | TRLB/LT EXT/DBD DEST |
| 6260 | 30.51497 | 88.08136 | Alabama | TRLB/LT EXT/DBD DEST |
| 6275 | 30.51908 | 88.0836 | Alabama | DBN DEST |
| 6280 | 30.51943 | 88.08858 | Alabama | TRUB/DBD DEST |
| 6295 | 30.52353 | 88.09213 | Alabama | TRLB/LT EXT/DBD DEST |
| 6460 | 30.54597 | 88.02684 | Alabama | MISSING/TRUB |
| 6465 | 30.54695 | 88.02762 | Alabama | DBN DEST |
| 6470 | 30.55501 | 88.04118 | Alabama | LT EXT/DBD DEST |
| 6475 | 30.5554 | 88.04089 | Alabama | DBN DEST |
| 6480 | 30.56379 | 88.05555 | Alabama | DBN DEST |
| 6490 | 30.56635 | 88.07023 | Alabama | MISSING/TRUB |
| 6495 | 30.56676 | 88.07019 | Alabama | LT EXT |
| 6505 | 30.56644 | 88.07348 | Alabama | DBN DEST |
| 6510 | 30.56698 | 88.07336 | Alabama | DBN DEST |

**Table 34. Damaged aids to navigation for Hurricane Katrina (Alabama) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 6515 | 30.56678 | 88.07649 | Alabama | LT EXT/DBD DEST |
| 6520 | 30.5672 | 88.07651 | Alabama | DBN DEST |
| 6530 | 30.56641 | 88.08163 | Alabama | DBN DEST |
| 6535 | 30.56487 | 88.08451 | Alabama | LT EXT/DBD DEST |
| 6540 | 30.56564 | 88.08469 | Alabama | DBN DEST |
| 6640 | 30.30246 | 88.26683 | Alabama | MISSING |
| 6643 | 30.30497 | 88.27405 | Alabama | MISSING |
| 6648 | 30.25936 | 88.4278 | Alabama | MISSING/TRUB |
| 32684 | 30.24773 | 88.42565 | Alabama | MISSING/TRUB |
| 32682 | 30.2546 | 88.34594 | Alabama | MISSING/TRUB |
| 6660 | 30.27473 | 88.31618 | Alabama | MISSING |
| 6666 | 30.29789 | 88.30712 | Alabama | MISSING |
| 6670 | 30.31285 | 88.30058 | Alabama | MISSING |
| 6695 | 30.37218 | 88.27526 | Alabama | LT EXT |
| 6255 | 30.51245 | 88.07248 | Alabama | TRLB/LT EXT/DBD DEST |
| 6674 | 30.32891 | 88.29407 | Alabama | MISSING |
| 6678 | 30.34436 | 88.28757 | Alabama | MISSING |
| 6225 | 30.48873 | 88.03095 | Alabama | TRLB/LT EXT/DBD DEST |
| 6285 | 30.52151 | 88.08798 | Alabama | TRLB/LT EXT/DBD DEST |
| 6485 | 30.56595 | 88.05734 | Alabama | LT EXT |
| 6525 | 30.56588 | 88.08158 | Alabama | DBD DMGD/ DBD DEST |
| 6040 | 30.25412 | 88.05974 | Alabama | TRUB |
| 6060 | 30.25333 | 88.06379 | Alabama | TRUB |
| 6065 | 30.25218 | 88.06703 | Alabama | TRUB |
| 6070 | 30.25286 | 88.06706 | Alabama | TRUB |
| 6035 | 30.25279 | 88.05932 | Alabama | TRUB/ DBN DEST |
| 5110 | 30.21587 | 88.04426 | Alabama | LT EXT |
| 5260 | 30.43996 | 88.01217 | Alabama | MISSING/TRLT |
| 5265 | 30.45796 | 88.00957 | Alabama | LT EXT/DBD DEST |
| 5267 | 30.45796 | 88.00957 | Alabama | LT EXT/DBD DEST |
| 5237 | 30.41132 | 88.00971 | Alabama | MISSING |
| 5236 | 30.41132 | 88.00971 | Alabama | MISSING |
| 5415 | 30.6076 | 88.03332 | Alabama | MISSING/TRLT |
| 5417 | 30.6076 | 88.03332 | Alabama | MISSING |
| 5075 | 30.26221 | 88.04227 | Alabama | MISSING |
| 4950 | 30.205 | 88.03411 | Alabama | TRLT/LT IMCH |

**Table 34. Damaged aids to navigation for Hurricane Katrina (Alabama) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 4953 | 30.205 | 88.03411 | Alabama | TRLT/REDUCED INT |
| 5070 | 30.25723 | 88.04128 | Alabama | MISSING |
| 5433 | 30.63018 | 88.03423 | Alabama | MISSING |
| 5420 | 30.59385 | 88.0338 | Alabama | MISSING/TRLT |
| 5423 | 30.59385 | 88.0338 | Alabama | MISSING |
| 5430 | 30.63018 | 88.03423 | Alabama | MISSING |
| 6195 | 30.46906 | 87.99875 | Alabama | MISSING |
| 4970 | 30.14132 | 88.06333 | Alabama | MISSING |
| 4975 | 30.14037 | 88.06049 | Alabama | OFF STA |
| 4980 | 30.14823 | 88.06022 | Alabama | OFF STA |
| 4985 | 30.14739 | 88.05772 | Alabama | OFF STA |
| 5030 | 30.20022 | 88.04363 | Alabama | OFF STA |
| 5035 | 30.19982 | 88.0413 | Alabama | OFF STA |
| 5065 | 30.21361 | 88.03759 | Alabama | MISSING |
| 5085 | 30.22418 | 88.03747 | Alabama | OFF STA |
| 5095 | 30.23824 | 88.03875 | Alabama | OFF STA |
| 5100 | 30.23895 | 88.03622 | Alabama | OFF STA |
| 5155 | 30.30696 | 88.03291 | Alabama | MISSING |
| 4990 | 30.15722 | 88.05627 | Alabama | MISSING |
| 4995 | 30.15646 | 88.05397 | Alabama | OFF STA |
| 5000 | 30.16507 | 88.05325 | Alabama | OFF STA |
| 5005 | 30.16421 | 88.05069 | Alabama | OFF STA |
| 5010 | 30.17257 | 88.05095 | Alabama | OFF STA |
| 5015 | 30.17234 | 88.06519 | Alabama | OFF STA |
| 5025 | 30.18332 | 88.04564 | Alabama | OFF STA |
| 5160 | 30.30662 | 88.04644 | Alabama | MISSING |
| 5165 | 30.32247 | 88.03068 | Alabama | DBD DMGD/LT EXT |
| 5170 | 30.32213 | 88.02754 | Alabama | DBD DMGD/LT EXT |
| 5175 | 30.33811 | 88.02841 | Alabama | DBD DMGD/LT EXT |
| 5180 | 30.33786 | 88.02528 | Alabama | MISSING |
| 5185 | 30.34348 | 88.02447 | Alabama | MISSING |
| 5190 | 30.36023 | 88.02525 | Alabama | MISSING |
| 5195 | 30.35989 | 88.02191 | Alabama | MISSING |
| 5200 | 30.04551 | 88.02257 | Alabama | MISSING |
| 5205 | 30.04517 | 88.01942 | Alabama | MISSING |
| 5210 | 30.39296 | 88.02064 | Alabama | MISSING |

**Table 34. Damaged aids to navigation for Hurricane Katrina (Alabama) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 5215 | 30.3926 | 88.01739 | Alabama | MISSING |
| 5220 | 30.40995 | 88.01809 | Alabama | MISSING |
| 5225 | 30.40961 | 88.01494 | Alabama | MISSING |
| 5240 | 30.42921 | 88.01531 | Alabama | DBD DMGD/LT EXT |
| 5245 | 30.42902 | 88.01247 | Alabama | MISSING |
| 5250 | 30.43746 | 88.01522 | Alabama | MISSING |
| 5270 | 30.44562 | 88.01512 | Alabama | MISSING |
| 5275 | 30.44574 | 88.01237 | Alabama | DBD DMGD/LT EXT |
| 5280 | 30.46452 | 88.01693 | Alabama | DBD DMGD/LT EXT |
| 5285 | 30.46473 | 88.0144 | Alabama | MISSING |
| 5290 | 30.47704 | 88.01566 | Alabama | DBD DMGD/LT EXT |
| 5305 | 30.48288 | 88.01992 | Alabama | TRLB/LT EXT/DBD DEST |
| 5310 | 30.48953 | 88.01958 | Alabama | MISSING |
| 5320 | 30.50447 | 88.0214 | Alabama | TRLB |
| 5325 | 30.50468 | 88.01887 | Alabama | DBD DMGD/LT EXT |
| 5330 | 30.52235 | 88.02348 | Alabama | DBD DMGD |
| 5340 | 30.52247 | 88.02081 | Alabama | MISSING |
| 5345 | 30.53902 | 88.02527 | Alabama | MISSING |
| 5350 | 30.53923 | 88.02275 | Alabama | MISSING |
| 5355 | 30.55491 | 88.02706 | Alabama | DBD DMGD/LT EXT |
| 5360 | 30.55512 | 88.02453 | Alabama | DBD DMGD/LT EXT |
| 5365 | 30.57399 | 88.0292 | Alabama | MISSING |
| 5370 | 30.5742 | 88.02667 | Alabama | DBD DMGD |
| 5375 | 30.58995 | 88.03099 | Alabama | DBD DMGD/LT EXT |
| 5380 | 30.59016 | 88.02846 | Alabama | MISSING |
| 5385 | 30.60572 | 88.03276 | Alabama | MISSING |
| 5390 | 30.60594 | 88.03023 | Alabama | MISSING |
| 5400 | 30.61844 | 88.03419 | Alabama | HAZ NAV/LT EXT/DBD DMGD |
| 5405 | 30.61847 | 88.03129 | Alabama | DBD DMGD/LT EXT |
| 5425 | 30.62928 | 88.03124 | Alabama | DBD DMGD/LT EXT |
| 5455 | 30.64967 | 88.03049 | Alabama | MISSING |
| 6555 | 30.64279 | 88.03703 | Alabama | TRLB |
| 6595 | 30.64814 | 88.05456 | Alabama | DBD DMGD |
| 32655 | 30.2635 | 88.25394 | Alabama | TRUB/DBD DEST |
| 32665 | 30.2623 | 88.26723 | Alabama | TRLB/LT EXT/DBD DEST |
| 32645 | 30.26464 | 88.23931 | Alabama | MISSING |

**Table 34. Damaged aids to navigation for Hurricane Katrina (Alabama) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 32637 | 30.26441 | 88.22424 | Alabama | MISSING |
| 32627 | 30.2657 | 88.20955 | Alabama | MISSING |
| 32625 | 30.26704 | 88.20959 | Alabama | TRUB/DBD DEST |
| 32605 | 30.271 | 88.14992 | Alabama | MISSING |
| 32520 | 30.25912 | 88.1156 | Alabama | LT EXT/DBD DEST |
| 32515 | 30.25952 | 88.11531 | Alabama | DBD DEST |
| 32510 | 30.26246 | 88.12298 | Alabama | LT EXT/DBD DEST |
| 32500 | 30.26552 | 88.12962 | Alabama | DBD DEST |
| 32495 | 30.26606 | 88.12947 | Alabama | DBD DEST |
| 32490 | 30.26922 | 88.13618 | Alabama | MISSING/TRUB |
| 32485 | 30.27145 | 88.14243 | Alabama | DBD DEST |
| 32480 | 30.27507 | 88.14873 | Alabama | DBD DEST |
| 32475 | 30.27854 | 88.155 | Alabama | DBD DEST |
| 32450 | 30.25823 | 88.21316 | Alabama | LT EXT/DBD DEST |
| 32445 | 30.26656 | 88.19041 | Alabama | DBD DEST |
| 32377 | 30.29389 | 88.12141 | Alabama | DBD DMGD/LT EXT |
| 6215 | 30.48172 | 88.02301 | Alabama | TRLB/LT EXT/DBD DEST |
| 6655 | 30.27054 | 88.32127 | Alabama | MISSING/TRUB |
| 6750 | 30.37608 | 88.24147 | Alabama | DBD DEST |
| 6710 | 30.37626 | 88.26265 | Alabama | LT EXT/DBD DEST |
| 32600 | 30.26881 | 88.17745 | Alabama | TRLB/LT EXT/DBD DEST |
| 32635 | 30.26587 | 88.22404 | Alabama | TRUB |
| 5120 | 30.25251 | 88.03798 | Alabama | OFF STA |
| 5125 | 30.26293 | 88.03855 | Alabama | OFF STA |
| 5445 | 30.6413 | 88.031 | Alabama | TRLB/DBD DMGD/LT EXT |
| 255 | 30.12527 | 88.06867 | Alabama | MISSING |
| 6197 | 30.46906 | 87.99875 | Alabama | MISSING |
| 5155 | 30.30696 | 88.03291 | Alabama | LIGHT EXTINGUISHED |
| 6590 | 30.64783 | 88.04991 | Alabama | TRUB/DBN DEST |
| 31140 | 30.39975 | 86.75904 | Alabama | OFF STATION |
| 6575 | 30.64519 | 88.04451 | Alabama | MISSING/TRLB |
| 6610 | 30.65006 | 88.05917 | Alabama | LIGHT EXTINGUISHED |
| 5585 | 30.28398 | 87.75642 | Alabama | TRLB |
| 5280 | 30.46452 | 87.01693 | Alabama | TRLB |
| 5700 | 30.30328 | 87.72714 | Alabama | TRUB |
| 6560 | 30.64372 | 88.03671 | Alabama | MISSING |
| 6580 | 30.64623 | 88.04464 | Alabama | DBN DEST |

**Table 35. Damaged aids to navigation Hurricane Katrina (Florida)**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 3265 | 30.14492 | 85.66659 | Florida | LT EXT |
| 3795 | 30.38923 | 86.51369 | Florida | OFF STA |
| 3805 | 30.39106 | 86.51552 | Florida | OFF STA |
| 165 | 30.37075 | 86.515 | Florida | OFF STA |
| 3755 | 30.37501 | 86.51401 | Florida | OFF STA |
| 1608 | 30.11537 | 84.20377 | Florida | OFF STA |
| 1610 | 30.11771 | 84.20239 | Florida | BUOY DMGD |
| 1595 | 30.11093 | 84.20308 | Florida | OFF STA |
| 1470 | 30.07137 | 84.19115 | Florida | BUOY DMGD |
| 1695 | 30.13959 | 84.20781 | Florida | MISSING |
| 205 | 30.25854 | 87.55676 | Florida | OFF STA |
| 3955 | 30.29476 | 87.31195 | Florida | OFF STA |
| 185 | 30.27103 | 87.29247 | Florida | OFF STA |
| 3965 | 30.30111 | 87.30113 | Florida | OFF STA |
| 31625 | 30.33355 | 87.31746 | Florida | OFF STA |
| 30050 | 30.38371 | 86.11861 | Florida | OFF STA |
| 3200 | 30.11366 | 85.73988 | Florida | OFF STA |
| 3210 | 30.12097 | 85.72909 | Florida | MISSING |
| 3351 | 30.17216 | 85.72475 | Florida | LT EXT/DBN DMGD |
| 29280 | 29.8172 | 85.16936 | Florida | DBD DMGD/LT EXT |
| 29120 | 29.73189 | 84.98144 | Florida | MISSING |
| 28910 | 29.68003 | 84.90077 | Florida | MISSING |
| 28880 | 29.68423 | 84.87927 | Florida | MISSING |
| 28875 | 29.68534 | 84.87136 | Florida | MISSING |
| 28765 | 29.7156 | 84.81401 | Florida | MISSING |
| 3195 | 30.11485 | 85.74094 | Florida | OFF STA |
| 4175 | 30.40711 | 87.19321 | Florida | MISSING |
| 31627 | 30.33276 | 87.32031 | Florida | OFF STA |
| 3215 | 30.12431 | 85.72421 | Florida | OFF STATION |
| 3220 | 30.12852 | 85.7207 | Florida | OFF STATION |
| 31165 | 30.39697 | 86.79433 | Florida | MISSING/TRLB |
| 4705 | 30.49969 | 87.51055 | Florida | DBD DMGD |
| 4700 | 30.4884 | 87.13408 | Florida | MISSING/TRLB |

**Table 35. Damaged aids to navigation Hurricane Katrina (Florida) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 4710 | 30.50009 | 87.13819 | Florida | DBD DEST |
| 3760 | 30.375 | 86.51279 | Florida | OFF STATION |
| 30930 | 30.40258 | 86.65316 | Florida | LIGHT EXTINGUISHED |
| 30945 | 30.40626 | 86.65926 | Florida | LIGHT EXTINGUISHED |
| 31180 | 30.39712 | 86.83181 | Florida | REDUCED INT |

**Table 36. Damaged aids to navigation Hurricane Katrina (Louisiana)**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 4810 | 30.26978 | 87.55806 | Louisiana | TRLT |
| 14705 | 30.29508 | 91.23364 | Louisiana | LT EXT/DBD DEST |
| 12955 | 29.1742 | 89.25701 | Louisiana | LT EXT/DBD DEST |
| 12990 | 29.20202 | 89.27146 | Louisiana | TRLT |
| 13415 | 29.7782 | 90.02512 | Louisiana | MISSING |
| 13430 | 29.83846 | 89.98412 | Louisiana | MISSING |
| 13460 | 29.87345 | 89.97142 | Louisiana | MISSING |
| 13780 | 29.94599 | 90.16637 | Louisiana | MISSING |
| 13815 | 29.92168 | 90.21319 | Louisiana | MISSING |
| 13825 | 29.97224 | 90.24555 | Louisiana | MISSING |
| 13900 | 29.93096 | 90.32953 | Louisiana | MISSING |
| 13935 | 29.94195 | 90.37252 | Louisiana | MISSING |
| 14180 | 30.04589 | 90.66976 | Louisiana | MISSING |
| 14400 | 30.10138 | 90.91341 | Louisiana | MISSING |
| 12915 | 29.16475 | 89.25246 | Louisiana | LT EXT/DBD DEST |
| 12980 | 29.1924 | 89.26433 | Louisiana | LT EXT/DBD DEST |
| 12995 | 29.2401 | 89.29842 | Louisiana | MISSING |
| 13000 | 29.24671 | 89.3173 | Louisiana | LT EXT/DBD DEST |
| 13045 | 29.34596 | 89.40276 | Louisiana | LT EXT/DBD DEST |
| 13050 | 29.36227 | 89.43204 | Louisiana | LT EXT/DBD DEST |
| 13070 | 29.36673 | 89.45114 | Louisiana | LT EXT/DBD DEST |
| 13075 | 29.36345 | 89.46125 | Louisiana | LT EXT/DBD DEST |
| 13085 | 29.33995 | 89.48237 | Louisiana | LT EXT/DBD DEST |
| 13100 | 29.35906 | 89.50997 | Louisiana | LT EXT/DBD DEST |
| 13125 | 29.37227 | 89.57162 | Louisiana | LT EXT/DBD DEST |

**Table 36. Damaged aids to navigation Hurricane Katrina (Louisiana) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 13145 | 29.41861 | 89.60239 | Louisiana | LT IMCH/DBD DEST |
| 13155 | 29.43831 | 89.60263 | Louisiana | MISSING |
| 13160 | 29.44248 | 89.59549 | Louisiana | LT EXT/DBD DEST |
| 13170 | 29.448 | 89.59727 | Louisiana | LT EXT/DBD DEST |
| 13175 | 29.45599 | 89.60898 | Louisiana | LT EXT/DBD DEST |
| 13185 | 29.45666 | 89.65375 | Louisiana | LT EXT/DBD DEST |
| 13190 | 29.46644 | 89.66179 | Louisiana | LT EXT/DBD DEST |
| 13255 | 29.61194 | 89.89501 | Louisiana | LT EXT/DBD DEST |
| 13365 | 29.6817 | 89.96037 | Louisiana | DBD DMGD |
| 13405 | 29.72636 | 89.99619 | Louisiana | LT EXT/DBD DEST |
| 13470 | 29.88413 | 89.96863 | Louisiana | DBD DMGD |
| 13475 | 29.87803 | 89.96026 | Louisiana | DBD DMGD |
| 13490 | 29.86446 | 89.90986 | Louisiana | DBD DMGD |
| 13500 | 29.92392 | 89.92442 | Louisiana | DBD DMGD |
| 13807 | 29.92544 | 90.20401 | Louisiana | DBD DMGD |
| 13958 | 29.96463 | 90.3922 | Louisiana | DBD DMGD |
| 14035 | 30.00632 | 90.47018 | Louisiana | DBD DMGD |
| 14050 | 30.04707 | 90.4743 | Louisiana | DBD DMGD |
| 14225 | 30.0182 | 90.75685 | Louisiana | DBD DMGD |
| 14240 | 30.01603 | 90.77833 | Louisiana | DBD DMGD |
| 14430 | 30.13958 | 90.93331 | Louisiana | DBD DMGD |
| 14480 | 30.11401 | 90.96673 | Louisiana | DBD DMGD |
| 14770 | 30.34728 | 91.16299 | Louisiana | DBD DMGD |
| 635 | 29.0711 | 90.22787 | Louisiana | OFF STA |
| 16530 | 29.07168 | 90.2314 | Louisiana | TRLB |
| 16550 | 29.08445 | 90.22534 | Louisiana | MISSING |
| 16555 | 29.09097 | 90.22407 | Louisiana | TRLB |
| 13515 | 29.91998 | 89.96739 | Louisiana | DBD DMGD |
| 11150 | 30.0029 | 89.95506 | Louisiana | DBD DMGD |
| 13633 | 29.95525 | 90.0553 | Louisiana | DBD DMGD |
| 11040 | 29.90299 | 89.7844 | Louisiana | MISSING |
| 11045 | 29.90495 | 89.78348 | Louisiana | MISSING |
| 11060 | 29.94159 | 89.84187 | Louisiana | MISSING |
| 11065 | 29.94326 | 89.84006 | Louisiana | MISSING |
| 11070 | 29.95525 | 89.85906 | Louisiana | MISSING |
| 11075 | 29.95678 | 89.85684 | Louisiana | MISSING |

**Table 36. Damaged aids to navigation Hurricane Katrina (Louisiana) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 11080 | 29.97326 | 89.8809 | Louisiana | MISSING |
| 11085 | 29.97481 | 89.87938 | Louisiana | MISSING |
| 11090 | 29.98548 | 89.89653 | Louisiana | MISSING |
| 11100 | 29.98709 | 89.89449 | Louisiana | MISSING |
| 11110 | 30.00064 | 89.91487 | Louisiana | MISSING |
| 11115 | 30.00118 | 89.91188 | Louisiana | MISSING |
| 11120 | 30.00535 | 89.92327 | Louisiana | DBD DMGD/LT EXT |
| 11125 | 30.00509 | 89.91721 | Louisiana | LT EXT/DBN DMGD |
| 12355 | 29.40463 | 89.30798 | Louisiana | LT EXT/DBN DMGD |
| 12360 | 29.40455 | 89.30944 | Louisiana | LT EXT/DBN DMGD |
| 12365 | 29.39924 | 89.30724 | Louisiana | LT EXT/DBN DMGD |
| 12370 | 29.39591 | 89.30837 | Louisiana | DBN DMGD |
| 12375 | 29.39321 | 89.3065 | Louisiana | LT EXT/DBD DEST |
| 12380 | 29.38936 | 89.30723 | Louisiana | LT EXT/DBD DEST |
| 12385 | 29.38418 | 89.30502 | Louisiana | LT EXT/DBD DEST |
| 12390 | 29.38432 | 89.30663 | Louisiana | DBN DMGD |
| 12400 | 29.37833 | 89.3056 | Louisiana | DBD DMGD/LT EXT |
| 12405 | 29.37484 | 89.30367 | Louisiana | DBN DMGD |
| 12410 | 29.37298 | 89.30467 | Louisiana | DBN DMGD |
| 12425 | 29.36248 | 89.30159 | Louisiana | DBN DMGD |
| 12430 | 29.3627 | 89.30305 | Louisiana | LT EXT/DBN DMGD |
| 12440 | 29.35976 | 89.30257 | Louisiana | LT EXT/DBD DEST |
| 12445 | 29.32076 | 89.31529 | Louisiana | DBN DMGD |
| 12447 | 29.31421 | 89.31993 | Louisiana | DBN DMGD |
| 12415 | 29.36787 | 89.30247 | Louisiana | LT EXT/DBD DEST |
| 12420 | 29.36761 | 89.30385 | Louisiana | LT EXT/DBN DMGD |
| 33090 | 30.14765 | 89.62921 | Louisiana | MISSING |
| 33085 | 30.14591 | 89.62943 | Louisiana | MISSING |
| 33045 | 30.14575 | 89.55981 | Louisiana | MISSING |
| 9140 | 30.1558 | 89.52487 | Louisiana | MISSING |
| 15165 | 29.22854 | 89.34847 | Louisiana | TRLB |
| 15160 | 29.22411 | 89.34955 | Louisiana | TRUB |
| 15157 | 29.22002 | 89.35074 | Louisiana | MISSING |
| 15156 | 29.21524 | 89.35064 | Louisiana | MISSING |
| 15155 | 29.21535 | 89.34987 | Louisiana | TRLB |
| 15150 | 29.21292 | 89.35099 | Louisiana | TRUB |

**Table 36. Damaged aids to navigation Hurricane Katrina (Louisiana) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 15147 | 29.20982 | 89.35184 | Louisiana | MISSING |
| 15145 | 29.20555 | 89.35313 | Louisiana | TRUB |
| 15140 | 29.20575 | 89.35404 | Louisiana | MISSING |
| 15135 | 29.19817 | 89.35613 | Louisiana | MISSING |
| 15130 | 29.19866 | 89.35673 | Louisiana | TRUB |
| 15125 | 29.19489 | 89.35837 | Louisiana | TRLB |
| 15120 | 29.19527 | 89.35939 | Louisiana | MISSING |
| 15110 | 29.19116 | 89.3612 | Louisiana | MISSING |
| 15100 | 29.18806 | 89.36332 | Louisiana | MISSING |
| 15095 | 29.18386 | 89.36326 | Louisiana | MISSING |
| 15090 | 29.18199 | 89.36479 | Louisiana | MISSING |
| 15085 | 29.17805 | 89.36445 | Louisiana | MISSING |
| 15080 | 29.17826 | 89.36533 | Louisiana | MISSING |
| 15070 | 29.17437 | 89.36708 | Louisiana | MISSING |
| 15060 | 29.17169 | 89.3692 | Louisiana | MISSING |
| 15055 | 29.16709 | 89.37442 | Louisiana | MISSING |
| 15050 | 29.16857 | 89.37403 | Louisiana | MISSING |
| 15045 | 29.17948 | 89.37905 | Louisiana | MISSING |
| 15040 | 29.16344 | 89.37975 | Louisiana | MISSING |
| 15035 | 29.15767 | 89.38886 | Louisiana | MISSING |
| 15030 | 29.15848 | 89.38903 | Louisiana | MISSING |
| 15027 | 29.15513 | 89.39256 | Louisiana | MISSING |
| 15025 | 29.15408 | 89.39536 | Louisiana | MISSING |
| 15020 | 29.15226 | 89.39654 | Louisiana | MISSING |
| 15015 | 29.15276 | 89.39877 | Louisiana | MISSING |
| 15013 | 29.15183 | 89.40069 | Louisiana | MISSING |
| 15010 | 29.15057 | 89.40712 | Louisiana | MISSING |
| 15005 | 29.15142 | 89.4069 | Louisiana | MISSING |
| 15002 | 29.14807 | 89.41297 | Louisiana | MISSING |
| 15000 | 29.14523 | 89.41533 | Louisiana | MISSING |
| 14995 | 29.14481 | 89.41814 | Louisiana | MISSING |
| 14990 | 29.14225 | 89.42196 | Louisiana | MISSING |
| 14985 | 29.14339 | 89.42185 | Louisiana | MISSING |
| 14980 | 29.1411 | 89.42445 | Louisiana | MISSING |
| 14975 | 29.14211 | 89.42491 | Louisiana | MISSING |
| 14970 | 29.13884 | 89.42977 | Louisiana | MISSING |

**Table 36. Damaged aids to navigation Hurricane Katrina (Louisiana) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 14965 | 29.13978 | 89.43033 | Louisiana | MISSING |
| 14950 | 29.13603 | 89.44171 | Louisiana | MISSING |
| 14945 | 29.13808 | 89.44236 | Louisiana | MISSING |
| 14395 | 30.09949 | 90.91293 | Louisiana | MISSING |
| 14390 | 30.09647 | 90.91221 | Louisiana | MISSING |
| 14380 | 30.0963 | 90.91481 | Louisiana | MISSING |
| 13005 | 29.25239 | 89.31191 | Louisiana | LT EXT/DBD DEST |
| 13840 | 29.9752 | 90.26674 | Louisiana | DBD DMGD |
| 14040 | 30.03276 | 90.46921 | Louisiana | DBD DMGD |
| 11055 | 29.91784 | 89.80865 | Louisiana | MISSING |
| 11135 | 30.00539 | 89.93166 | Louisiana | DBD DMGD |
| 11050 | 30.91617 | 89.81019 | Louisiana | MISSING |
| 11130 | 30.00766 | 89.92167 | Louisiana | MISSING |
| 13225 | 29.52115 | 89.72923 | Louisiana | LT EXT/DBD DEST |
| 13940 | 30.94355 | 90.37578 | Louisiana | MISSING |
| 13945 | 30.94415 | 89.3775 | Louisiana | MISSING |
| 15167 | 30.23516 | 89.35767 | Louisiana | MISSING |
| 15065 | 30.17125 | 88.36828 | Louisiana | MISSING |
| 15075 | 30.174 | 88.36609 | Louisiana | MISSING |
| 15105 | 30.18767 | 88.36238 | Louisiana | MISSING |
| 15115 | 30.19012 | 88.36069 | Louisiana | TRUB |
| 14935 | 30.13859 | 88.45134 | Louisiana | MISSING |
| 14940 | 30.13637 | 88.45166 | Louisiana | MISSING |
| 14955 | 30.13818 | 88.43631 | Louisiana | MISSING |
| 14960 | 30.13682 | 88.43602 | Louisiana | MISSING |
| 12395 | 30.37844 | 88.30415 | Louisiana | LT EXT/DBD DEST |
| 12435 | 30.35972 | 88.30102 | Louisiana | LT EXT/DBD DEST |
| 14805 | 30.34821 | 91.24644 | Louisiana | LT EXT |
| 17330 | 29.30149 | 90.71376 | Louisiana | DBD DEST |
| 17320 | 29.21692 | 90.64907 | Louisiana | DBD DEST |
| 17315 | 29.20905 | 90.63826 | Louisiana | DBD DEST |
| 17297 | 29.17998 | 90.59972 | Louisiana | LT EXT/DBD DEST |
| 17295 | 29.17998 | 90.59972 | Louisiana | DBD DMGD/LT EXT |
| 17250 | 29.17075 | 90.6049 | Louisiana | DBD DEST |
| 17190 | 29.10598 | 90.57925 | Louisiana | MISSING |
| 17185 | 29.09962 | 90.57554 | Louisiana | MISSING |

**Table 36. Damaged aids to navigation Hurricane Katrina (Louisiana) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 17180 | 29.09913 | 90.57754 | Louisiana | MISSING |
| 14150 | 30.04119 | 90.62999 | Louisiana | LT EXT |
| 14145 | 30.03638 | 90.62212 | Louisiana | LT EXT |
| 14140 | 30.02915 | 90.61889 | Louisiana | LT EXT |
| 14095 | 30.05085 | 90.5433 | Louisiana | DBD DEST |
| 13850 | 29.97242 | 90.28156 | Louisiana | LT EXT |
| 33445 | 29.62244 | 91.05228 | Louisiana | MISSING |
| 33345 | 29.68155 | 90.19335 | Louisiana | MISSING |
| 33335 | 29.73903 | 90.14285 | Louisiana | MISSING |
| 14890 | 30.44129 | 91.19645 | Louisiana | MISSING |
| 14885 | 30.43762 | 91.1966 | Louisiana | MISSING |
| 14190 | 30.04348 | 90.67498 | Louisiana | MISSING |
| 14185 | 30.04403 | 90.67381 | Louisiana | MISSING |
| 13805 | 29.94332 | 90.16575 | Louisiana | MISSING |
| 13790 | 29.94268 | 90.16997 | Louisiana | MISSING |
| 13785 | 29.94491 | 90.16763 | Louisiana | MISSING |
| 12950 | 29.17291 | 89.26106 | Louisiana | LT EXT |
| 12550 | 28.98657 | 89.133 | Louisiana | OFF STA |
| 12547 | 28.98147 | 89.12199 | Louisiana | OFF STA |
| 16535.01 | 29.12343 | 90.21761 | Louisiana | DBD DEST |
| 12910 | 29.16675 | 89.25361 | Louisiana | LT EXT/DBD DEST |
| 13890 | 29.93166 | 90.32254 | Louisiana | DBD DMGD |
| 13855 | 29.97378 | 90.2802 | Louisiana | LT EXT/DBD DEST |
| 14229 | 30.01934 | 90.76519 | Louisiana | LT EXT/DBD DEST |
| 14238 | 30.0185 | 90.76874 | Louisiana | LT EXT/DBD DEST |
| 12935 | 29.17302 | 89.25343 | Louisiana | LT EXT/DBD DEST |
| 12940 | 29.16986 | 89.25517 | Louisiana | LT EXT/DBD DEST |
| 12945 | 29.17327 | 89.25496 | Louisiana | LT EXT/DBD DEST |
| 12705 | 28.91787 | 89.41773 | Louisiana | LT EXT/DBD DEST |
| 12710 | 28.91971 | 89.41583 | Louisiana | LT EXT/DBD DEST |
| 12695 | 28.917 | 89.4193 | Louisiana | LT EXT/DBD DEST |
| 12697 | 28.91584 | 89.42051 | Louisiana | LT EXT/DBD DEST |
| 12700 | 28.92027 | 89.41585 | Louisiana | LT EXT/DBD DEST |
| 12715 | 28.91839 | 89.41849 | Louisiana | LT EXT/DBD DEST |
| 12720 | 28.92025 | 89.41651 | Louisiana | LT EXT/DBD DEST |
| 12661 | 28.91385 | 89.43143 | Louisiana | LT EXT/DBD DEST |

**Table 36. Damaged aids to navigation Hurricane Katrina (Louisiana) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 12670 | 28.91299 | 89.43246 | Louisiana | LT EXT/DBD DEST |
| 12870 | 29.13232 | 89.25683 | Louisiana | LT EXT/DBD DEST |
| 12873 | 29.13189 | 89.25672 | Louisiana | LT EXT/DBD DEST |
| 12645 | 28.91273 | 89.26531 | Louisiana | LT EXT/DBD DEST |
| 12925 | 29.171 | 89.25448 | Louisiana | LT EXT/DBD DEST |
| 10860 | 29.67787 | 89.38559 | Louisiana | MISSING |
| 10880 | 29.70709 | 89.42803 | Louisiana | MISSING |
| 10980 | 29.84006 | 89.62385 | Louisiana | MISSING |
| 10995 | 29.84895 | 89.6453 | Louisiana | MISSING |
| 11005 | 29.85854 | 89.6799 | Louisiana | MISSING |
| 11010 | 29.86476 | 89.70915 | Louisiana | MISSING |
| 11020 | 29.87479 | 89.72932 | Louisiana | LIGHT EXTINGUSIHED/DBD DEST |
| 11030 | 29.88465 | 89.74897 | Louisiana | LIGHT EXTINGUISHED/DBD DESET |
| 11035 | 29.88643 | 89.74756 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 12650 | 28.89479 | 89.43349 | Louisiana | MISSING |
| 12725 | 28.93643 | 89.41024 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 12730 | 28.9379 | 89.40347 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 12735 | 28.94748 | 89.40265 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 12740 | 28.95156 | 89.39389 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 12745 | 28.96586 | 89.38821 | Louisiana | TRLT |
| 12755 | 28.98115 | 89.37529 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 12760 | 28.99112 | 89.36081 | Louisiana | DBD DMGD |
| 12770 | 29.00225 | 89.3514 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 12785 | 29.02327 | 89.33504 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 12830 | 29.06157 | 89.31093 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 12840 | 29.08578 | 89.28638 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |

**Table 36. Damaged aids to navigation Hurricane Katrina (Louisiana) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 12845 | 29.0856 | 89.28061 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 12860 | 29.10742 | 89.26856 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 12865 | 29.11973 | 89.26695 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 12677 | 28.89975 | 89.43766 | Louisiana | DBD DMGD/LIGHT EXTINGUISHED |
| 12780 | 29.02208 | 89.34156 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 12810 | 29.04695 | 89.31954 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 11025 | 29.87666 | 89.72833 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 11015 | 29.86674 | 89.70814 | Louisiana | MISSING |
| 11000 | 29.8566 | 89.68043 | Louisiana | MISSING |
| 10990 | 29.84635 | 89.64585 | Louisiana | MISSING |
| 10985 | 29.84213 | 89.62297 | Louisiana | MISSING |
| 465 | 28.87753 | 89.43194 | Louisiana | OFF STATION |
| 12750 | 28.97653 | 89.37323 | Louisiana | LIGHT EXTINGUISHED/DBD DEST |
| 9645 | 30.19597 | 89.80067 | Louisiana | MISSING |
| 9640 | 30.196 | 89.79378 | Louisiana | DBN DEST |
| 9635 | 30.19596 | 89.78529 | Louisiana | DBN DEST |
| 9630 | 30.19588 | 89.77712 | Louisiana | DBN DEST |
| 9620 | 30.18517 | 89.76474 | Louisiana | DBN DEST |
| 9615 | 30.1809 | 89.7607 | Louisiana | MISSING |
| 9585 | 30.17487 | 89.74305 | Louisiana | MISSING |
| 9575 | 30.16686 | 89.71673 | Louisiana | MISSING |
| 9570 | 30.17329 | 89.68882 | Louisiana | DBD DMGD/ LIGHT EXTINGUISHED |
| 9565 | 30.16103 | 89.65206 | Louisiana | MISSING |
| 9460 | 30.16116 | 89.6495 | Louisiana | MISSING |
| 9290 | 30.20964 | 89.5895 | Louisiana | MISSING |
| 9285 | 30.20717 | 89.59284 | Louisiana | MISSING |
| 9280 | 30.20015 | 89.58979 | Louisiana | MISSING |
| 9275 | 30.19506 | 89.58592 | Louisiana | DBN DEST |
| 9272 | 30.19445 | 89.58847 | Louisiana | MISSING |

**Table 36. Damaged aids to navigation Hurricane Katrina (Louisiana) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 9265 | 30.18477 | 89.58016 | Louisiana | DBN DEST |
| 9260 | 30.18436 | 89.58076 | Louisiana | MISSING |
| 9255 | 30.18165 | 89.58211 | Louisiana | TMK DMGD |
| 9250 | 30.18106 | 89.586 | Louisiana | DBN DEST |
| 9245 | 30.18367 | 89.5858 | Louisiana | MISSING |
| 9240 | 30.1785 | 89.59513 | Louisiana | DBD DEST |
| 9235 | 30.17964 | 89.59561 | Louisiana | MISSING |
| 9215 | 30.17676 | 89.60125 | Louisiana | DBD DEST |
| 9210 | 30.17068 | 89.60978 | Louisiana | DBD DEST |
| 9195 | 30.16273 | 89.62617 | Louisiana | DBD DEST |
| 9190 | 30.16192 | 89.62496 | Louisiana | MISSING |
| 9185 | 30.16081 | 89.62804 | Louisiana | DBN DEST |
| 9180 | 30.15839 | 89.62792 | Louisiana | MISSING |
| 9175 | 30.15995 | 89.63037 | Louisiana | MISSING |
| 9160 | 30.18343 | 89.5245 | Louisiana | DBD DMGD/LIGHT EXTINGUISHED |
| 9155 | 30.17236 | 89.52391 | Louisiana | MISSING/TRUB |
| 9150 | 30.16473 | 89.52453 | Louisiana | MISSING/TRUB |
| 9220 | 30.17816 | 89.60061 | Louisiana | TMK DMGD |
| 9225 | 30.17776 | 89.60685 | Louisiana | DBN DEST |
| 9590 | 30.17711 | 89.75457 | Louisiana | MISSING |
| 9157 | 30.18285 | 89.52749 | Louisiana | MISSING |
| 9465 | 30.16189 | 89.64806 | Louisiana | MISSING |
| 9145 | 30.16034 | 89.52471 | Louisiana | MISSING/TRUB |
| 16540 | 29.07936 | 90.22943 | Louisiana | TRLB |
| 16535 | 29.09859 | 90.22316 | Louisiana | LT MICH |
| 16535.02 | 29.12343 | 90.21761 | Louisiana | LT MICH |
| 410 | 29.16495 | 88.94226 | Louisiana | OFF STATION |
| 445 | 28.97865 | 89.10868 | Louisiana | OFF STATION |
| 405 | 29.238 | 88.95782 | Louisiana | OFF STATION/LIGHT EXTINGUISHED |
| 17330 | 29.30149 | 90.71376 | Louisiana | DBD DEST |
| 17320 | 29.21692 | 90.64907 | Louisiana | DBD DEST |
| 17317 | 29.21164 | 90.64486 | Louisiana | MISSING |
| 17315 | 29.20904 | 90.63826 | Louisiana | DBD DEST |
| 17305 | 29.20023 | 90.62675 | Louisiana | MISSING |
| 17280 | 29.18654 | 90.61239 | Louisiana | DBD DEST |

**Table 36. Damaged aids to navigation Hurricane Katrina (Louisiana) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 17290 | 29.187 | 90.60933 | Louisiana | MISSING |
| 17230 | 29.14479 | 90.59393 | Louisiana | MISSING |
| 17210 | 29.11847 | 90.58292 | Louisiana | TRLB |
| 17175 | 29.09129 | 90.57977 | Louisiana | OFF STATION |
| 17115 | 29.01918 | 90.56815 | Louisiana | OFF STATION |
| 15410 | 29.26718 | 89.95977 | Louisiana | MISSING |
| 15375 | 29.27505 | 89.95604 | Louisiana | OFF STATION |
| 15380 | 29.27076 | 89.95738 | Louisiana | MISSING |
| 15390 | 29.26999 | 89.96034 | Louisiana | MISSING |
| 15385 | 29.26858 | 89.95915 | Louisiana | MISSING |
| 15435 | 29.26601 | 89.96098 | Louisiana | TRLB |
| 15445 | 29.26504 | 89.96155 | Louisiana | MISSING/TRLB |
| 15440 | 29.26447 | 89.97936 | Louisiana | DBD DEST |
| 15460 | 29.25158 | 89.99754 | Louisiana | DBD DEST |
| 15465 | 29.24673 | 89.97142 | Louisiana | DBD DEST |
| 15670 | 29.29079 | 89.97279 | Louisiana | DBD DEST |
| 15665 | 29.29029 | 89.97405 | Louisiana | DBD DEST |
| 15675 | 29.29874 | 89.99525 | Louisiana | DBD DEST |
| 15695 | 29.31195 | 89.98345 | Louisiana | DBD DEST |
| 15720 | 29.33294 | 89.98461 | Louisiana | DBD DEST |
| 15730 | 29.34887 | 89.98419 | Louisiana | DBD DEST |
| 15750 | 29.36959 | 89.98382 | Louisiana | DBD DEST |
| 15765 | 29.38296 | 89.98691 | Louisiana | MISSING |
| 15780 | 29.38897 | 89.98649 | Louisiana | TRLB |
| 10010 | 30.34696 | 90.0627 | Louisiana | MISSING/TRLB |
| 15710 | 29.3188 | 89.98491 | Louisiana | DBD DEST |
| 15700 | 29.31119 | 89.98415 | Louisiana | DBD DEST |
| 17215 | 29.1254 | 90.58455 | Louisiana | OFF STATION |
| 15405 | 29.26728 | 89.95938 | Louisiana | MISSING |
| 15470 | 29.24162 | 89.99852 | Louisiana | DBD DEST |
| 15475 | 29.24029 | 90.00375 | Louisiana | DBD DEST |
| 15770 | 29.38285 | 89.98553 | Louisiana | DBN DEST |
| 4815 | 30.26962 | 87.55675 | Louisiana | TRLT |
| 9230 | 30.17858 | 89.61077 | Louisiana | DBD DEST |

**Table 37. Damaged aids to navigation Hurricane Katrina (Mississippi)**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 6933 | 30.216 | 88.5043 | Mississippi | Missing |
| 33000 | 30.1583 | 89.4729 | Mississippi | MISSING/TRUB |
| 32997 | 30.1722 | 89.453 | Mississippi | MISSING/TRUB |
| 32995 | 30.1846 | 89.426 | Mississippi | MISSING |
| 335 | 30.2126 | 88.9664 | Mississippi | MISSING |
| 340 | 30.1194 | 88.8777 | Mississippi | MISSING |
| 32755 | 30.2754 | 89.0205 | Mississippi | LT EXT/DBD DEST |
| 32750 | 30.2755 | 89.0182 | Mississippi | LT EXT/DBD DEST |
| 32765 | 30.2843 | 89.028 | Mississippi | LT EXT/DBD DEST |
| 32760 | 30.2843 | 89.0257 | Mississippi | LT EXT/DBD DEST |
| 32971 | 30.1797 | 89.3772 | Mississippi | DBN DMGD/DBD DEST |
| 32970 | 30.1797 | 89.3649 | Mississippi | DBD DMGD/LT EXT |
| 32959 | 30.1796 | 89.352 | Mississippi | DBN DMGD/DBD DEST |
| 32935 | 30.2046 | 89.3553 | Mississippi | DBD DMGD/LT EXT |
| 32930 | 30.2296 | 89.2841 | Mississippi | DBD DMGD/LT EXT |
| 32926 | 30.233 | 89.2689 | Mississippi | DBD DMGD/TMK DMGD |
| 32916 | 30.2359 | 89.2505 | Mississippi | DBD DMGD/DBN DMGD |
| 32906 | 30.2399 | 89.2487 | Mississippi | DBD DMGD/DBN DMGD |
| 32901 | 30.2385 | 89.245 | Mississippi | DBD DMGD/TMK DMGD |
| 32897 | 30.2412 | 89.2456 | Mississippi | DBD DMGD/DBN DMGD |
| 32896 | 30.2419 | 89.245 | Mississippi | DBN DMGD/DBD DEST |
| 32891 | 30.2412 | 89.2431 | Mississippi | DBN DMGD/DBD DEST |
| 32886 | 30.2438 | 89.2445 | Mississippi | DBN DMGD/DBD DEST |
| 32881 | 30.2455 | 89.2372 | Mississippi | DBN DMGD/DBD DEST |
| 32875 | 30.2588 | 89.2165 | Mississippi | DBN DMGD/DBD DEST |
| 32871 | 30.2631 | 89.2039 | Mississippi | MISSING |
| 32860 | 30.1903 | 89.2882 | Mississippi | MISSING |
| 32855 | 30.1967 | 89.2745 | Mississippi | MISSING |
| 32850 | 30.1978 | 89.2755 | Mississippi | MISSING |
| 32840 | 30.2023 | 89.2675 | Mississippi | MISSING |
| 32835 | 30.2053 | 89.2591 | Mississippi | MISSING |
| 32825 | 30.2094 | 89.2518 | Mississippi | MISSING |
| 32815 | 30.2148 | 89.2462 | Mississippi | MISSING |
| 32812 | 30.2236 | 89.2315 | Mississippi | MISSING/TRUB |

**Table 37. Damaged aids to navigation Hurricane Katrina (Mississippi) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 32810 | 30.2219 | 89.23 | Mississippi | MISSING |
| 32805 | 30.2335 | 89.2164 | Mississippi | TRUB |
| 32800 | 30.2376 | 89.2085 | Mississippi | MISSING |
| 32990 | 30.1792 | 89.4023 | Mississippi | DBD DMGD/LT EXT |
| 32979 | 30.1796 | 89.3901 | Mississippi | DBD DMGD/LT EXT |
| 32955 | 30.1797 | 89.3348 | Mississippi | LT EXT/DBD DEST |
| 32940 | 30.1797 | 89.3036 | Mississippi | DBD DMGD/LT EXT |
| 32830 | 30.2065 | 89.2597 | Mississippi | MISSING |
| 7357 | 30.3357 | 88.5127 | Mississippi | DBD DMGD |
| 7435 | 30.3523 | 88.5061 | Mississippi | LT EXT/DBD DEST |
| 7370 | 30.2631 | 88.513 | Mississippi | LT EXT/DBD DEST |
| 7372 | 30.2627 | 88.513 | Mississippi | LT EXT/DBD DEST |
| 6955 | 30.2992 | 88.5145 | Mississippi | LT EXT/DBD DEST |
| 6960 | 30.3129 | 88.5162 | Mississippi | LT EXT/DBD DEST |
| 7073 | 30.271 | 88.4981 | Mississippi | LT EXT/DBD DEST |
| 6935 | 30.2118 | 88.5038 | Mississippi | LT EXT/DBD DEST |
| 7440 | 30.3593 | 88.5042 | Mississippi | LT EXT/TMK DMGD |
| 7365 | 30.2738 | 88.5129 | Mississippi | LT EXT/DBD DEST |
| 6930 | 30.216 | 88.5043 | Mississippi | DBD DMGD |
| 7070 | 30.271 | 88.4981 | Mississippi | LT EXT/DBD DEST |
| 7065 | 30.2824 | 88.5092 | Mississippi | LT EXT/DBD DEST |
| 7360 | 30.3434 | 88.5127 | Mississippi | DBD DMGD |
| 7470 | 30.3155 | 88.5162 | Mississippi | LT EXT/DBD DEST |
| 7465 | 30.3221 | 88.5144 | Mississippi | LT EXT/DBD DEST |
| 6925 | 30.2217 | 88.5077 | Mississippi | OFF STA |
| 6975 | 30.2411 | 88.5083 | Mississippi | LT EXT/DBD DEST |
| 7085 | 30.295 | 88.5227 | Mississippi | TRLB |
| 7090 | 30.2962 | 88.5212 | Mississippi | LT EXT/DBD DEST |
| 7100 | 30.3052 | 88.53 | Mississippi | LT EXT/DBD DEST |
| 7145 | 30.3133 | 88.5378 | Mississippi | LT EXT/DBD DEST |
| 7150 | 30.3213 | 88.5483 | Mississippi | LT EXT/DBD DEST |
| 7155 | 30.3225 | 88.5468 | Mississippi | LT EXT/DBD DEST |
| 7165 | 30.3311 | 88.5553 | Mississippi | LT EXT/DBD DEST |
| 7170 | 30.3387 | 88.5655 | Mississippi | LT EXT/DBD DEST |
| 7175 | 30.34 | 88.5638 | Mississippi | LT EXT/DBD DEST |

Table 37. Damaged aids to navigation Hurricane Katrina (Mississippi) cont.

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 7190 | 30.3437 | 88.5659 | Mississippi | LT EXT/DBD DEST |
| 7380 | 30.2955 | 88.5118 | Mississippi | LT EXT/DBD DEST |
| 7385 | 30.3037 | 88.5139 | Mississippi | LT EXT/DBD DEST |
| 7390 | 30.3037 | 88.5118 | Mississippi | LT EXT/DBD DEST |
| 7405 | 30.3122 | 88.5138 | Mississippi | LT EXT/DBD DEST |
| 7410 | 30.3122 | 88.5118 | Mississippi | LT EXT/DBD DEST |
| 7415 | 30.32 | 88.5138 | Mississippi | LT EXT/DBD DEST |
| 7425 | 30.3229 | 88.5119 | Mississippi | LT EXT/DBD DEST |
| 7427 | 30.3299 | 88.511 | Mississippi | LT EXT/DBD DEST |
| 7430 | 30.3276 | 88.5137 | Mississippi | LT EXT/DBD DEST |
| 7432 | 30.333 | 88.515 | Mississippi | LT EXT/DBD DEST |
| 7433 | 30.3346 | 88.5146 | Mississippi | LT EXT/DBD DEST |
| 7442 | 30.3524 | 95.4983 | Mississippi | LT EXT/DBD DEST |
| 7140 | 30.3121 | 88.5395 | Mississippi | LT EXT/DBD DEST |
| 7420 | 30.3159 | 88.5119 | Mississippi | LT EXT |
| 7045 | 30.2848 | 88.5137 | Mississippi | LT EXT |
| 7375 | 30.2956 | 88.514 | Mississippi | LT EXT/DBD DEST |
| 32715 | 30.2803 | 88.6358 | Mississippi | MISSING/TRLB |
| 32705 | 30.2553 | 88.6041 | Mississippi | MISSING/TRLB |
| 32700 | 30.2532 | 88.5791 | Mississippi | LT EXT |
| 8506.2 | 30.2428 | 89.0332 | Mississippi | DBD DMGD/LT EXT |
| 7340 | 30.4186 | 88.5247 | Mississippi | DBD DEST/TMK MISSING |
| 7330 | 30.4212 | 88.5326 | Mississippi | DBD DEST |
| 7315 | 30.4259 | 88.5411 | Mississippi | DBD DEST |
| 7310 | 30.423 | 88.5528 | Mississippi | MISSING/TRUB |
| 7305 | 30.4228 | 88.5587 | Mississippi | MISSING/TRUB |
| 7300 | 30.4205 | 88.5668 | Mississippi | MISSING/TRUB |
| 7295 | 30.4194 | 88.5728 | Mississippi | MISSING/TRUB |
| 7485 | 30.4123 | 88.5832 | Mississippi | MISSING/TRUB |
| 7280 | 30.4055 | 88.5845 | Mississippi | DBD DEST |
| 7275 | 30.4024 | 88.5825 | Mississippi | DBD DEST |
| 7270 | 30.3984 | 88.5778 | Mississippi | MISSING/TRUB |
| 7265 | 30.3936 | 88.5758 | Mississippi | DBD DEST |
| 7260 | 30.3887 | 88.5641 | Mississippi | DBD DEST |
| 7255 | 30.3829 | 88.5688 | Mississippi | MISSING/TRUB |

**Table 37. Damaged aids to navigation Hurricane Katrina (Mississippi) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 7250 | 30.3796 | 88.5667 | Mississippi | DBD DEST |
| 7000 | 30.2569 | 88.5084 | Mississippi | BUOY DMGD |
| 6895 | 30.2152 | 88.5108 | Mississippi | OFF STA |
| 6900 | 30.216 | 88.5078 | Mississippi | OFF STA |
| 32710 | 30.2518 | 88.6118 | Mississippi | MISSING/TRLB |
| 32720 | 30.2803 | 88.6356 | Mississippi | MISSING |
| 32725 | 30.2849 | 88.6848 | Mississippi | MISSING |
| 32730 | 30.2872 | 88.7451 | Mississippi | MISSING |
| 32740 | 30.2853 | 88.8859 | Mississippi | MISSING |
| 32745 | 30.2836 | 88.9532 | Mississippi | MISSING |
| 7042 | 30.2808 | 88.5189 | Mississippi | MISSING |
| 6890 | 30.2125 | 88.5096 | Mississippi | LT EXT |
| 6980 | 30.2413 | 88.5065 | Mississippi | OFF STA |
| 6950 | 30.2242 | 88.5069 | Mississippi | LT EXT |
| 8485 | 30.2663 | 89.0072 | Mississippi | LT EXT |
| 8490 | 30.3018 | 89.0156 | Mississippi | LT EXT/DBD DEST |
| 8493 | 30.3018 | 89.0156 | Mississippi | LT EXT/DBD DEST |
| 8565 | 30.2308 | 88.9816 | Mississippi | LT EXT/DBD DEST |
| 8570 | 30.2126 | 88.9663 | Mississippi | LT IMCH |
| 8650 | 30.3645 | 89.0949 | Mississippi | MISSING |
| 8395 | 30.1195 | 88.897 | Mississippi | OFF STA |
| 8400 | 30.1169 | 88.9123 | Mississippi | OFF STA |
| 8405 | 30.119 | 88.9124 | Mississippi | OFF STA |
| 8410 | 30.1185 | 88.9277 | Mississippi | OFF STA |
| 8415 | 30.1168 | 88.9306 | Mississippi | OFF STA |
| 8420 | 30.1206 | 88.9315 | Mississippi | OFF STA |
| 8425 | 30.1304 | 88.9419 | Mississippi | OFF STA |
| 8430 | 30.1314 | 88.9404 | Mississippi | OFF STA |
| 8435 | 30.1413 | 88.9508 | Mississippi | OFF STATION |
| 8440 | 30.1422 | 88.9493 | Mississippi | OFF STATION |
| 8445 | 30.1521 | 88.9599 | Mississippi | OFF STATION |
| 8450 | 30.1531 | 88.9582 | Mississippi | OFF STATION |
| 8455 | 30.163 | 88.9687 | Mississippi | OFF STATION |
| 8460 | 30.1639 | 88.9671 | Mississippi | OFF STATION |
| 8465 | 30.1738 | 88.9776 | Mississippi | OFF STATION |

**Table 37. Damaged aids to navigation Hurricane Katrina (Mississippi) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 8470 | 30.1748 | 88.976 | Mississippi | OFF STATION |
| 8475 | 30.1857 | 88.985 | Mississippi | OFF STATION |
| 8480 | 30.1888 | 88.9899 | Mississippi | OFF STATION |
| 8505 | 30.2037 | 88.9915 | Mississippi | OFF STATION |
| 8506 | 30.2026 | 88.0001 | Mississippi | LIGHT EXTINGUISHED |
| 8506.1 | 30.2428 | 88.0332 | Mississippi | LT MICH |
| 8510 | 30.2227 | 88.9978 | Mississippi | MISSING |
| 8515 | 30.223 | 88.9961 | Mississippi | MISSING |
| 8520 | 30.2309 | 88.9997 | Mississippi | MISSING |
| 8525 | 30.2312 | 88.998 | Mississippi | MISSING |
| 8540 | 30.2391 | 89.0017 | Mississippi | MISSING |
| 8545 | 30.2394 | 89.9998 | Mississippi | MISSING |
| 8550 | 30.2473 | 89.0037 | Mississippi | MISSING |
| 8555 | 30.2476 | 89.0017 | Mississippi | MISSING |
| 8560 | 30.2555 | 89.0055 | Mississippi | MISSING |
| 8562 | 30.2342 | 89.9833 | Mississippi | LIGHT EXTINGUISHED/DBD DMGD/DEST |
| 8580 | 30.2613 | 89.0084 | Mississippi | MISSING |
| 8585 | 30.2679 | 89.014 | Mississippi | MISSING |
| 8590 | 30.2689 | 89.0125 | Mississippi | MISSING |
| 8615 | 30.2901 | 89.033 | Mississippi | MISSING |
| 8620 | 30.2911 | 89.0314 | Mississippi | MISSING |
| 8575 | 30.2597 | 89.0045 | Mississippi | MISSING/DAYBOARD DESTROYED |
| 8625 | 30.2969 | 89.0387 | Mississippi | MISSING/DAYBOARD DESTROYED |
| 8495 | 30.1941 | 89.9892 | Mississippi | OFF STATION |
| 8500 | 30.2034 | 89.9933 | Mississippi | OFF STATION |
| 8630 | 30.2978 | 89.0372 | Mississippi | MISSING |
| 8635 | 30.3036 | 89.0444 | Mississippi | MISSING |
| 8640 | 30.3046 | 89.0429 | Mississippi | MISSING |
| 8645 | 30.3534 | 89.0854 | Mississippi | TRLT |
| 8655 | 30.3103 | 89.0501 | Mississippi | MISSING |
| 8660 | 30.311 | 89.0484 | Mississippi | MISSING |
| 8670 | 30.3169 | 89.0557 | Mississippi | MISSING |
| 8675 | 30.318 | 89.0543 | Mississippi | MISSING |
| 8690 | 30.3248 | 89.06 | Mississippi | MISSING |

**Table 37. Damaged aids to navigation Hurricane Katrina (Mississippi) cont.**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 8695 | 30.3305 | 89.0672 | Mississippi | MISSING |
| 8700 | 30.3315 | 89.0657 | Mississippi | MISSING |
| 8705 | 30.3372 | 89.073 | Mississippi | MISSING |
| 8710 | 30.3385 | 89.0717 | Mississippi | MISSING |
| 8715 | 30.344 | 89.0787 | Mississippi | MISSING |
| 8720 | 30.345 | 89.0771 | Mississippi | MISSING |
| 8725 | 30.3484 | 89.0824 | Mississippi | MISSING |
| 9079 | 30.2636 | 89.327 | Mississippi | TRLB |
| 9079.05 | 30.2666 | 89.3159 | Mississippi | TRLB |
| 9080 | 30.2732 | 89.3329 | Mississippi | TRLB |
| 8680 | 30.3227 | 89.0551 | Mississippi | MISSING |
| 8685 | 30.3237 | 89.0614 | Mississippi | MISSING |
| 9120 | 30.2383 | 89.4245 | Mississippi | MISSING |
| 7920 | 30.3935 | 88.8317 | Mississippi | MISSING |
| 7885 | 30.3881 | 88.8641 | Mississippi | MISSING |
| 7875 | 30.39 | 88.8707 | Mississippi | MISSING |
| 7870 | 30.3895 | 88.8768 | Mississippi | MISSING |
| 7830 | 30.3894 | 88.8991 | Mississippi | MISSING |
| 7810 | 30.3765 | 88.9016 | Mississippi | MISSING |
| 7805 | 30.3771 | 88.9028 | Mississippi | MISSING |
| 7800 | 30.3687 | 88.9018 | Mississippi | MISSING |
| 7795 | 30.3599 | 88.9021 | Mississippi | MISSING |
| 7790 | 30.3597 | 88.9037 | Mississippi | MISSING |
| 6810.1 | 30.1542 | 88.5667 | Mississippi | OFF STATION |
| 6810.2 | 30.153 | 88.5651 | Mississippi | OFF STATION |
| 6810.3 | 30.166 | 88.5548 | Mississippi | OFF STATION |
| 6810.4 | 30.1649 | 88.5532 | Mississippi | OFF STATION |
| 6810.5 | 30.1779 | 88.5429 | Mississippi | OFF STATION |
| 6810.6 | 30.1767 | 88.5413 | Mississippi | OFF STATION |
| 6855 | 30.1968 | 88.5237 | Mississippi | OFF STATION |
| 6865 | 30.2033 | 88.5173 | Mississippi | OFF STATION |
| 6870 | 30.2022 | 88.5159 | Mississippi | OFF STATION |
| 7080 | 30.3545 | 88.5793 | Mississippi | TRLT/LIGHT EXTINGUISHED |
| 7075 | 30.3458 | 88.5709 | Mississippi | LIGHT EXTINGUISHED |
| 7355 | 30.3357 | 88.5127 | Mississippi | LIGHT EXTINGUISHED |
| 7178 | 30.3421 | 88.5681 | Mississippi | LIGHT EXTINGUISHED |

**Table 38. Damaged aids to navigation Hurricane Katrina (Mississippi/Louisiana)**

| LLNR | Latitude | Longitude | Region | Discrepancy Summary |
|---|---|---|---|---|
| 9270 | 30.1884 | 89.5846 | Mississippi/Louisiana | DBD DMGD |
| 9435 | 30.3284 | 89.633 | Mississippi/Louisiana | DBN DGMD |
| 9430 | 30.3253 | 89.6308 | Mississippi/Louisiana | DBN DEST |
| 9420 | 30.3197 | 89.6311 | Mississippi/Louisiana | MISSING |
| 9415 | 30.3183 | 89.6309 | Mississippi/Louisiana | DBN DEST |
| 9405 | 30.3092 | 89.6327 | Mississippi/Louisiana | DBN DEST |
| 9400 | 30.3078 | 89.6364 | Mississippi/Louisiana | DBN DEST |
| 9375 | 30.288 | 89.6375 | Mississippi/Louisiana | DBN DEST |
| 9370 | 30.2856 | 89.6384 | Mississippi/Louisiana | MISSING |
| 9365 | 30.2785 | 89.63 | Mississippi/Louisiana | MISSING |
| 9360 | 30.2688 | 89.6331 | Mississippi/Louisiana | MISSING |
| 9355 | 30.2662 | 89.626 | Mississippi/Louisiana | DBN DEST |
| 9350 | 30.2617 | 89.632 | Mississippi/Louisiana | TRUB |
| 9340 | 30.2485 | 89.6226 | Mississippi/Louisiana | DBN DGMD |
| 9335 | 30.2469 | 89.6149 | Mississippi/Louisiana | DBN DGMD |
| 9330 | 30.226 | 89.6164 | Mississippi/Louisiana | TRUB |
| 9325 | 30.2223 | 89.6154 | Mississippi/Louisiana | TRUB |
| 9320 | 30.2208 | 89.6151 | Mississippi/Louisiana | TRLB |
| 9315 | 30.2181 | 89.6105 | Mississippi/Louisiana | TRUB |
| 9310 | 30.215 | 89.6014 | Mississippi/Louisiana | MISSING |
| 9295 | 30.2155 | 89.5869 | Mississippi/Louisiana | MISSING |
| 9385 | 30.2922 | 89.6473 | Mississippi/Louisiana | MISSING/TRUB |

**APPENDIX 2.**

**CODE**

**Numerical Example**

```
Sets
    l set of supply locations /l1*l3/
    i set of safe locations /i1*i3/
    k set of commodities used in repair activity /k1*k3/
    v set of possible Aids to Navigation repair types /v1*v3/
    j set of demand areas affected by the storm path /j1*j4/
    o set of scenarios /o1*o3/;
Parameters
    w(k) weight associated with commodity k (lbs)
        /k1 1
         k2 1
         k3 1/
    N(l) number of teams based at location l
        /l1 50
         l2 20
         l3 30/
    alpha(v) criticality weight associted with aton repair of type v
       /v1 3
        v2 2
```

```
        v3 1/

    c(k) per unit cost associated with pre-positioning commodity k
        /k1 40
         k2 120
         k3 190/
    p(o) scenario specific probabilties
        /o1 0.6
         o2 0.3
         o3 0.1/;

Scalar
*M is the weight associated with commodities
*B is the maximum allowable cost associated with prepositioned commodities
     M /200/
     B/609937/;

Table
a(v,k) amount of commodity k used in repair of type v
    k1  k2  k3
v1   1   0   0
v2   1   0   0
v3   1   0   0 ;
```

Table

D(j,v,o) amount of ATONs in need of repair of type v in region j under scenario w

| | v1.o1 | v1.o2 | v1.o3 | v2.o1 | v2.o2 | v2.o3 | v3.o1 | v3.o2 | v3.o3 |
|---|---|---|---|---|---|---|---|---|---|
| j1 | 20 | 55 | 70 | 15 | 75 | 30 | 50 | 45 | 50 |
| j2 | 35 | 40 | 90 | 40 | 15 | 80 | 25 | 30 | 35 |
| j3 | 25 | 15 | 60 | 15 | 45 | 80 | 75 | 20 | 30 |
| j4 | 55 | 65 | 15 | 70 | 95 | 45 | 60 | 50 | 25; |

Table

t(v,o) Repair time for ATONs

| | o1 | o2 | o3 |
|---|---|---|---|
| v1 | 2 | 1 | 0.75 |
| v2 | 2 | 1 | 0.75 |
| v3 | 2 | 1 | 0.75 ; |

Table

e(i,j) travel time

| | j1 | j2 | j3 | j4 |
|---|---|---|---|---|
| i1 | 2 | 2 | 3 | 1 |
| i2 | 2 | 1 | 3 | 1 |
| i3 | 2 | 2 | 4 | 3 ; |

Variables

x(i) the number of teams assigned to safe location

s(i,k) the number of supplies of commodity type k assigned to safe location

y(l,i) the number of teams transferred from supply location l to safe location i

z(i,j,o) the number of teams assigned from location i to demand region j in scenario w

h(i,j,k,o) the number of commodities of type k transferred from location i to affected area j in scenario w

u(i,j,v,o) Unrepaired ATONs of type v in region j in scenario w

r(i,j,v,o) Repaired atons of type v region j in scenario w ;

positive variable y,s,h,u,r;

integer variable x,z;

free variable q;

Equations

repaireditems objective function

con1 Flow balance pre-position constraint

con2 Flow balance pre-position constraint

con3 Number of supplies stored at safe location i cannot exceed more than what teams can carry

con4 Total items prepositioned cannot exceed budget constraint

con5 The number of teams dispatched per location per scenario cannot exceed available team supply per location

con6 Time to repair items at demand region per scenario cannot exceed daily operating time of teams allocated to affected area j con7 Inventory balance contraint

con8 Relationship between repaired ATONs and pre-positioned supplies

con9 Amount of supplies sent into affected areas cannot exceed available supply

con10 Commodities can only be allocated to an affected area if there are teams allocated to that area;

```
repaireditems..  q =e= sum(v,sum(j,sum(o,(p(o)*alpha(v)*sum(i,r(i,j,v,o))))));

con1(i).. sum(l,y(l,i)) =e= x(i);

con2(l).. sum(i,y(l,i)) =l= N(l);

con3(i)..sum(k,w(k)*s(i,k)) =l= M*x(i);

con4.. sum(k,sum(i,c(k)*s(i,k))) =l= B;

con5(i,o).. sum(j,z(i,j,o)) =l= x(i);

con6(j,o).. sum(v,sum(i,t(v,o)*r(i,j,v,o))) =l= sum(i,z(i,j,o)*(36-e(i,j)));

con7(j,v,o).. sum(i,r(i,j,v,o)+ u(i,j,v,o)) =e= D(j,v,o);

con8(i,j,k,o).. sum(v,a(v,k)*r(i,j,v,o)) =l= h(i,j,k,o);

con9(i,k,o).. sum(j,h(i,j,k,o)) =l= s(i,k);

con10(i,j,o).. sum(k,h(i,j,k,o)) =l= M*z(i,j,o);


Model ThesisModel1 /all/;

Solve ThesisModel1 using mip maximizing q;

Display x.l, s.l, y.l, z.l, h.l, r.l, u.l;
```

**Model with prepositioning and unconstrained supply**

Sets

l set of supply locations /l1*l4/

i set of safe locations /i1*i4/

k set of commodities used in repair activity /k1*k3/

v set of possible Aids to Navigation repair types /v1*v3/

j set of demand areas affected by the storm path /j1*j5/

o set of scenarios /o1*o5/;

Parameters

w(k) weight associated with commodity k (lbs)

/k1 190

k2 1

k3 6/

N(l) number of teams based at location l

/l1 50

l2 20

l3 30

l4 25/

alpha(v) criticality weight associted with aton repair of type v

/v1 3

v2 2

v3 1/

```
        c(k) per unit cost associated with pre-positioning commodity k
               /k1 350
                k2 179
                k3 139/
        p(o) scenario specific probabilties
               /o1 0.05
                o2 0.15
                o3 0.25
                o4 0.25
                o5 0.30/;

Scalar
*M is the weight associated with commodities
*B is the maximum allowable cost associated with prepositioned commodities
         M /1500/
         B/1002000/;
Table
a(v,k) amount of commodity k used in repair of type v
    k1   k2   k3
v1   1    0    0
v2   0    1    0
v3   0    0    1 ;
```

Table

D(j,v,o) amount of ATONs in need of repair of type v in region j under scenario w

| | v1.o1 | v1.o2 | v1.o3 | v1.o4 | v1.o5 | v2.o1 | v2.o2 | v2.o3 | v2.o4 | v2.o5 | v3.o1 | v3.o2 | v3.o3 | v3.o4 | v3.o5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| j1 | 0 | 120 | 140 | 162 | 172 | 0 | 3 | 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| j2 | 0 | 6 | 9 | 9 | 10 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| j3 | 0 | 195 | 229 | 285 | 319 | 0 | 7 | 6 | 4 | 1 | 0 | 0 | 0 | 0 | 0 |
| j4 | 0 | 17 | 188 | 200 | 208 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| j5 | 0 | 94 | 12 | 17 | 18 | 0 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0; |

Table

t(v,o) Repair time for ATONs

| | o1 | o2 | o3 | o4 | o5 |
|---|---|---|---|---|---|
| v1 | 0 | 1 | 1 | 2 | 2 |
| v2 | 0 | 1 | 1 | 2 | 2 |
| v3 | 0 | 1 | 1 | 2 | 2 ; |

Table

e(i,j) travel time

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i1 | 2 | 3 | 1 | 1 | 1 |
| i2 | 1 | 3 | 2 | 1 | 1 |
| i3 | 2 | 3 | 2 | 1 | 1 |
| i4 | 3 | 1 | 3 | 3 | 3; |

Variables

x(i) the number of teams assigned to safe location

s(i,k) the number of supplies of commodity type k assigned to safe location

y(l,i) the number of teams transferred from supply location l to safe location i

gamma(k) available supply for each commoditiy

z(i,j,o) the number of teams assigned from location i to demand region j in scenario w

h(i,j,k,o) the number of commodities of type k transferred from location i to affected area j in scenario w

u(i,j,v,o) Unrepaired ATONs of type v in region j in scenario w by teams from location i

r(i,j,v,o) Repaired atons of type v region j in scenario w by teams from location i;

positive variable s,u,r,gamma;

integer variable z,x,y,h;

free variable q;

Equations

repaireditems objective function

con1 Flow balance pre-position constraint

con2 Flow balance pre-position constraint

con3 flow balance supply constraint

con4 number of supplies stored at safe location i cannot exceed more thatn what teams can carry

con5 Total items prepositioned cannot exceed budget constraint con6 The number of teams dispatched per location per scenario cannot exceed available team supply per location

con7 Time to repair items at demand region per scenario cannot exceed daily operating time of teams allocated to affected area j

con8 Inventory balance contraint

con9 Relationship between repaired ATONs and pre-positioned supplies

con10 Amount of supplies sent into affected areas cannot exceed available supply

con11 Commodities can only be allocated to an affected area if there are teams allocated to that area;

```
repaireditems..  q =e= sum(v,sum(j,sum(o,(p(o)*alpha(v)*sum(i,r(i,j,v,o))))));

con1(i).. sum(l,y(l,i)) =e= x(i);

con2(l).. sum(i,y(l,i)) =l= N(l);

con3(k).. sum(i,s(i,k)) =l= gamma(k);

con4(i)..sum(k,w(k)*s(i,k)) =l= M*x(i);

con5.. sum(k,sum(i,c(k)*s(i,k))) =l= B;

con6(i,o).. sum(j,z(i,j,o)) =l= x(i);

con7(i,j,o).. sum(v,t(v,o)*r(i,j,v,o)) =l= z(i,j,o)*(120-e(i,j));

con8(j,v,o).. sum(i,r(i,j,v,o)+ u(i,j,v,o)) =e= D(j,v,o);

con9(i,j,k,o).. sum(v,a(v,k)*r(i,j,v,o)) =l= h(i,j,k,o);

con10(i,k,o).. sum(j,h(i,j,k,o)) =l= s(i,k);

con11(i,j,o).. sum(k,w(k)*h(i,j,k,o)) =l= z(i,j,o)*M;


Model ThesisModel1 /all/;

Solve ThesisModel1 using mip maximizing q;

Display x.l, s.l, y.l, z.l, h.l, r.l, u.l, gamma.l;
```

**Model without pre-positioning**

Sets

l set of supply locations /l1*l4/

i set of safe locations /i1*i4/

k set of commodities used in repair activity /k1*k3/

v set of possible Aids to Navigation repair types /v1*v3/

j set of demand areas affected by the storm path /j1*j5/

o set of scenarios /o1*o5/;

Parameters

w(k) weight associated with commodity k (lbs)

/k1 190

k2 1

k3 6/

N(l) number of teams based at location l

/l1 50

l2 20

l3 30

l4 25/

alpha(v) criticality weight associted with aton repair of type v

/v1 3

v2 2

v3 1/

```
        c(k) per unit cost associated with pre-positioning commodity k
               /k1 350
                k2 179
                k3 139/
        p(o) scenario specific probabilties
               /o1 0.05
                o2 0.15
                o3 0.25
                o4 0.25
                o5 0.30/;

Scalar
*M is the weight associated with commodities
*B is the maximum allowable cost associated with prepositioned commodities
         M /1500/
         B/1002000/;

Table
a(v,k) amount of commodity k used in repair of type v
    k1   k2   k3
v1   1    0    0
v2   0    1    0
v3   0    0    1 ;
```

Table

D(j,v,o) amount of ATONs in need of repair of type v in region j under scenario w

| | v1.o1 | v1.o2 | v1.o3 | v1.o4 | v1.o5 | v2.o1 | v2.o2 | v2.o3 | v2.o4 | v2.o5 | v3.o1 | v3.o2 | v3.o3 | v3.o4 | v3.o5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| j1 | 0 | 109 | 127 | 147 | 156 | 0 | 3 | 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| j2 | 0 | 5 | 8 | 8 | 9 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| j3 | 0 | 177 | 208 | 259 | 290 | 0 | 6 | 5 | 4 | 1 | 0 | 0 | 0 | 0 | 0 |
| j4 | 0 | 15 | 171 | 182 | 189 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| j5 | 0 | 90 | 11 | 15 | 16 | 0 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0; |

Table

t(v,o) Repair time for ATONs

| | o1 | o2 | o3 | o4 | o5 |
|---|---|---|---|---|---|
| v1 | 0 | 1 | 1 | 2 | 2 |
| v2 | 0 | 1 | 1 | 2 | 2 |
| v3 | 0 | 1 | 1 | 2 | 2 ; |

Table

e(i,j) travel time

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i1 | 3 | 5 | 2 | 2 | 2 |
| i2 | 2 | 4 | 3 | 2 | 2 |
| i3 | 3 | 5 | 5 | 2 | 2 |
| i4 | 4 | 2 | 6 | 4 | 4; |

Variables

x(i) the number of teams assigned to safe location

y(l,i) the number of teams transferred from supply location l to safe location i

z(i,j,o) the number of teams assigned from location i to demand region j in scenario w

h(i,j,k,o) the number of commodities of type k transferred from location i to affected area j in scenario w

u(i,j,v,o) Unrepaired ATONs of type v in region j in scenario w by teams from location i

r(i,j,v,o) Repaired atons of type v region j in scenario w by teams from location i;

positive variable u,r;

integer variable z,x,y,h;

free variable q;

Equations

repaireditems objective function

con1 Flow balance pre-position constraint

con2 Flow balance pre-position constraint

con5 Total items prepositioned cannot exceed budget constraint

con6 The number of teams dispatched per location per scenario cannot exceed available team supply per location

con7 Time to repair items at demand region per scenario cannot exceed daily operating time of teams allocated to affected area j

con8 Inventory balance contraint

con9 Relationship between repaired ATONs and pre-positioned supplies con11 Commodities can only be allocated to an affected area if there are teams allocated to that area;

```
repaireditems..  q =e= sum(v,sum(j,sum(o,(p(o)*alpha(v)*sum(i,r(i,j,v,o))))));

con1(i).. sum(l,y(l,i)) =e= x(i);

con2(l).. sum(i,y(l,i)) =l= N(l);

con5(o).. sum(k,sum(i,sum(j,c(k)*h(i,j,k,o)))) =l= B;

con6(i,o).. sum(j,z(i,j,o)) =l= x(i);

con7(i,j,o).. sum(v,t(v,o)*r(i,j,v,o)) =l= z(i,j,o)*(120-e(i,j));

con8(j,v,o).. sum(i,r(i,j,v,o)+ u(i,j,v,o)) =e= D(j,v,o);

con9(i,j,k,o).. sum(v,a(v,k)*r(i,j,v,o)) =l= h(i,j,k,o);

con11(i,j,o).. sum(k,w(k)*h(i,j,k,o)) =l= z(i,j,o)*M;

Model ThesisModel1 /all/;

Solve ThesisModel1 using mip maximizing q;

Display x.l, y.l, z.l, h.l, r.l, u.l;
```

**Supply Constrained Model**

Sets

l set of supply locations /l1*l4/

i set of safe locations /i1*i4/

k set of commodities used in repair activity /k1*k3/

v set of possible Aids to Navigation repair types /v1*v3/

j set of demand areas affected by the storm path /j1*j5/

o set of scenarios /o1*o5/;

Parameters

w(k) weight associated with commodity k (lbs)

/k1 190

k2 1

k3 6/

N(l) number of teams based at location l

/l1 50

l2 20

l3 30

l4 25/

gamma(k) available supply

/ k1 533

k2 12

k3 0/

```
alpha(v) criticality weight associted with aton repair of type v
       /v1 3
        v2 2
        v3 1/
c(k) per unit cost associated with pre-positioning commodity k
        /k1 350
         k2 179
         k3 139/
p(o) scenario specific probabilities
        /o1 0.05
         o2 0.15
         o3 0.25
         o4 0.25
         o5 0.30/;


Scalar
*M is the weight associated with commodities
*B is the maximum allowable cost associated with prepositioned commodities
          M /1500/
          B/609937/;
```

Table

a(v,k) amount of commodity k used in repair of type v

| | k1 | k2 | k3 |
|---|---|---|---|
| v1 | 1 | 0 | 0 |
| v2 | 0 | 1 | 0 |
| v3 | 0 | 0 | 1 ; |

Table

D(j,v,o) amount of ATONs in need of repair of type v in region j under scenario w

| | v1.o1 | v1.o2 | v1.o3 | v1.o4 | v1.o5 | v2.o1 | v2.o2 | v2.o3 | v2.o4 | v2.o5 | v3.o1 | v3.o2 | v3.o3 | v3.o4 | v3.o5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| j1 | 0 | 109 | 127 | 147 | 156 | 0 | 3 | 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| j2 | 0 | 5 | 8 | 8 | 9 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| j3 | 0 | 177 | 208 | 259 | 290 | 0 | 6 | 5 | 4 | 1 | 0 | 0 | 0 | 0 | 0 |
| j4 | 0 | 15 | 171 | 182 | 189 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| j5 | 0 | 90 | 11 | 15 | 16 | 0 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0; |

Table

t(v,o) Repair time for ATONs

| | o1 | o2 | o3 | o4 | o5 |
|---|---|---|---|---|---|
| v1 | 0 | 1 | 1 | 2 | 2 |
| v2 | 0 | 1 | 1 | 2 | 2 |
| v3 | 0 | 1 | 1 | 2 | 2 ; |

Table

e(i,j) travel time

| | j1 | j2 | j3 | j4 | j5 |
|---|---|---|---|---|---|
| i1 | 2 | 3 | 1 | 1 | 1 |
| i2 | 1 | 3 | 2 | 1 | 1 |
| i3 | 2 | 3 | 2 | 1 | 1 |
| i4 | 3 | 1 | 3 | 3 | 3; |

Variables

x(i) the number of teams assigned to safe location

s(i,k) the number of supplies of commodity type k assigned to safe location

y(l,i) the number of teams transferred from supply location l to safe location i

z(i,j,o) the number of teams assigned from location i to demand region j in scenario w

h(i,j,k,o) the number of commodities of type k transferred from location i to affected area j in scenario w

u(i,j,v,o) Unrepaired ATONs of type v in region j in scenario w by teams from location i

r(i,j,v,o) Repaired atons of type v region j in scenario w by teams from location i;

positive variable s,u,r;

integer variable z,x,y,h;

free variable q;

Equations

repaireditems  objective function

con1 Flow balance pre-position constraint

con2 Flow balance pre-position constraint

con3 flow balance supply constraint

con4 number of supplies stored at safe location i cannot exceed more than what teams can carry

con5 Total items prepositioned cannot exceed budget constraint

con6 The number of teams dispatched per location per scenario cannot exceed available team supply per location

con7 Time to repair items at demand region per scenario cannot exceed daily operating time of teams allocated to affected area j

con8 Inventory balance constraint

con9 Relationship between repaired ATONs and pre-positioned supplies

con10 Amount of supplies sent into affected areas cannot exceed available supply

con11 Commodities can only be allocated to an affected area if there are teams allocated to that area;

```
repaireditems..  q =e= sum(v,sum(j,sum(o,(p(o)*alpha(v)*sum(i,r(i,j,v,o))))));

con1(i).. sum(l,y(l,i)) =e= x(i);

con2(l).. sum(i,y(l,i)) =l= N(l);

con3(k).. sum(i,s(i,k)) =l= gamma(k);

con4(i)..sum(k,w(k)*s(i,k)) =l= M*x(i);

con5.. sum(k,sum(i,c(k)*s(i,k))) =l= B;

con6(i,o).. sum(j,z(i,j,o)) =l= x(i);

con7(i,j,o).. sum(v,t(v,o)*r(i,j,v,o)) =l= z(i,j,o)*(72-e(i,j));
```

```
con8(j,v,o).. sum(i,r(i,j,v,o)+ u(i,j,v,o)) =e= D(j,v,o);

con9(i,j,k,o).. sum(v,a(v,k)*r(i,j,v,o)) =l= h(i,j,k,o);

con10(i,k,o).. sum(j,h(i,j,k,o)) =l= s(i,k);

con11(i,j,o).. sum(k,w(k)*h(i,j,k,o)) =l= z(i,j,o)*M;

Model ThesisModel1 /all/;

Solve ThesisModel1 using mip maximizing q;

Display x.l, s.l, y.l, z.l, h.l, r.l, u.l;
```