Development of a methodology to delineate hurricane evacuation zones

Nandagopal Meduri
Louisiana State University and Agricultural and Mechanical College, nmedur1@lsu.edu

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DEVELOPMENT OF A METHODOLOGY TO DELINEATE HURRICANE EVACUATION ZONES

A Thesis

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

in

The Department of Civil and Environmental Engineering

by
Nandagopal Meduri
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May 2004
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Abstract

The main focus of this study is to exhibit a simple and easily implemented process to identify hurricane evacuation zones. The proposed study presents a new methodology to delineate hurricane evacuation zones. The new methodology helps in easier identification of zones, thereby making the task of evacuation officials easier.

Hurricane evacuation zones were identified based on the elevation of the points comprising the study area. An area layer was created based on the storm surge models run, and were overlaid with zip code boundary layer and land use data available. Elevation point file data was superimposed on the study area layer to find out the mean elevation and standard deviation values of elevation, which help in identifying the adjacent zones which are similar in elevation. These zones are grouped together and the process of joining zones is continued until the zones are sufficiently reduced. The entire process was carried out in TransCAD, a Transportation/GIS software package. This task involves an iterative process which would be extremely tedious to perform manually. Hence, the process was automated by writing a customized add-in program to TransCAD.

The study also included the application of this methodology to the New Orleans metropolitan area, it being an ideal test case for implementing the methodology that was developed. The results portray New Orleans area being ideally and conveniently divided into hurricane evacuation zones based on their elevations, zip code and storm surge data. The GIS program developed during this study provides a framework, which may be built upon and shared with other researchers in the future.
1. Introduction

1.1. General

Evacuation zones are those areas that need to be evacuated for a particular hurricane scenario to protect residents at risk from flooding or high winds (Central Coastal Conglomerate Annex, 2001). The delineation information about hurricane evacuation zones is generally included in the hurricane evacuation studies conducted by Federal Emergency Management Agency (FEMA), the U.S. Army Corps of Engineers, National Oceanic and Atmospheric Administration (NOAA), and the respective state emergency management agencies.

The purpose of delineating zones is threefold. First, it is to distinguish the portion of the population at risk from that which is not. Second, they provide the basis on which emergency managers can direct portions of the population to evacuate while others remain. Last, they allow estimation of population and other socioeconomic data, which is subsequently used in evacuation modeling and in estimating sheltering requirements. Evacuation zones are often presented in map format for the benefit of the population and evacuation officials. These maps serve two purposes. First, they communicate to each community the land areas (evacuation zones) vulnerable to hurricane surge, which should be considered for evacuation prior to a hurricane’s landfall. Second, the map shows locations of public shelters, medical facilities and other amenities of importance that may require special provisions during evacuation proceedings (USACE, 1995).

The current research focuses on developing a methodology to delineate hurricane evacuation zones and to apply that method to northern part of New Orleans metropolitan area in a practical demonstration of the process.
1.2 Problem Statement

Hurricanes can cause severe damage to the community in terms of its population, property and facilities. The storm surge that accompanies the hurricane causes the major damage. The areas that will be subject to flooding from various categories of hurricanes are determined based on these storm surges and elevation data. Because of this flooding, there is a need to evacuate the vulnerable population to the safer places.

The area that potentially could be flooded is divided into evacuation zones so that the officials can issue the evacuation orders in an efficient manner minimizing the damage. Some hurricane evacuation studies in the past have included a map containing hurricane evacuation zones for their particular area, but they have not described the method they followed in establishing the zones. Generally, the principles used in identifying hurricane evacuation zones have not been well documented in the literature. We suspect this is because professional judgement has been the main means of establishing the zones. However, evacuation zones are required for each hurricane evacuation study. Thus, the activity of establishing evacuation zones is one that is often conducted and yet few guidelines exist on how to do it. The research performed in the present study is aimed at addressing that need.

1.3 Purpose of Study

The primary objective of this study is to develop a systematic, repeatable and criteria-based methodology to delineate the hurricane evacuation zones. The overall goal is to postulate a clearly defined procedure that can be the subject of public review, to enumerate the factors that feature in the process, and to explain how these factors are
combined into a procedure that can be replicated. The specific objectives of this study are to:

a) Examine the previous methodologies used for delineating hurricane evacuation zones by reviewing different hurricane evacuation studies.

b) Identify criteria that should be used to distinguish hurricane evacuation zones.

c) Establish a procedure which uses the criteria identified in (b) to identify hurricane evacuation zones.

d) Demonstrate the process by establishing hurricane evacuation zones in the northern part of the New Orleans metropolitan area.
2. Literature Review

2.1 Introduction

A literature review was conducted to identify current practice with respect to the establishment of hurricane evacuation zones and to gain background information on the subject. This involved reviewing published literature and reports from agencies that have conducted hurricane evacuation studies in the past. It also included personal communication with experts.

2.2 The Hurricane

Hurricanes may be defined as large, ocean-born tropical cyclones with wind speeds in excess of 73 miles per hour (117 km/hr). In the northern half of the western hemisphere, these storms are born over warm oceans in the summer months, usually from June until November. Hurricanes form from tropical depressions, or concentrated areas of low pressure over warm oceans where surface temperature exceeds 26° - 27° C (Simpson and Riehl, 1981). They rotate counterclockwise and a tropical cyclone that has winds of 38 mph or less is called a tropical depression. When the tropical cyclone's winds reach 39-73 mph, it is called a tropical storm. When the winds exceed 74 mph, the storm is considered to be a hurricane. The Saffir-Simpson scale classifies hurricanes into 5 separate categories based on maximum sustained wind speeds as shown in table 1.

Tropical storms and hurricanes of all categories can pose serious threats to lives and property along the coast, both from storm surge and wind. Storm surge is defined as the superelevation of the still-water surface that results from the transport and circulation of water induced by wind stresses and pressure gradients in an atmospheric storm (Simpson and Riehl, 1981).
As air is drawn inward toward the eye of the storm in the lower atmosphere, it moves surface water as waves inward as well. Since the storm is rotating, this water transport results in a gradual buildup of excess water beneath the eye. In addition, the lower air pressure beneath the eye causes the hydrostatic water level to rise in compensation (Simpson and Riehl, 1981). As windspeed increases and pressure decreases in a growing storm, the water level continues to rise. As the hurricane approaches land, shallowing bathymetric conditions act to superelevate the mound of water (Simpson and Riehl, 1981). Although historically most deaths from hurricanes result from storm surge, improved forecasting and evacuation has drastically reduced the threat.

### 2.3 SLOSH Model

SLOSH (Sea, Lake and Overland Surges from Hurricanes) is a computerized model run by the National Hurricane Center (NHC) to estimate storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes by taking pressure, size, forward speed, track and winds into account. This model was designed to predict

<table>
<thead>
<tr>
<th>Category</th>
<th>Wind Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>74-95 mph</td>
</tr>
<tr>
<td>II</td>
<td>96-110 mph</td>
</tr>
<tr>
<td>III</td>
<td>111-130 mph</td>
</tr>
<tr>
<td>IV</td>
<td>131-155 mph</td>
</tr>
<tr>
<td>V</td>
<td>&gt; 155 mph</td>
</tr>
</tbody>
</table>

Table 1: Saffir-Simpson Scale

(Simpson and Riehl, 1981).
storm surge penetration in real-time as a hurricane approaches. SLOSH is especially effective when comparing two hurricanes of equal strengths, which can produce very different surge conditions depending on a variety of factors, including forward speed of the storm, path, point of landfall, as well as the bathymetry of the offshore basin (Blakely, 1997). The point of a hurricane's landfall is crucial to determining which areas will be inundated by the storm surge. Where the hurricane forecast track is inaccurate, SLOSH model results will be inaccurate. The SLOSH model, therefore, is best used for defining the potential maximum surge for a location.

2.4 Maximum Envelopes of Water (MEOWs)

For a SLOSH model simulation of a discrete hurricane event, one of the model’s products is the plot of maximum water surface elevation at all grid cells affected by the storm, irrespective of when during the storm that maximum water level is attained. The imaginary surface defined by the maximum water level in each cell is termed the “envelope” of maximum water surface elevations for that storm.

Because of the inability to predict exactly where a hurricane will make landfall, and because it may be necessary to begin evacuations of areas susceptible to hurricane evacuation surges as much as 18 hours before landfall, it is necessary to predict potential surge elevations for a given hurricane over a range of potential landfall points (USACE, 1990). In order to meet this need, the SLOSH model is used to develop a “MEOW” map; the maximum envelope of water from a number of individual hurricane simulations which differ only in point of landfall of the storm center. In this manner, the maximum water surface elevations for each grid cell are calculated for a particular class of
hurricane, defined by direction, forward speed, and intensity, independent of where the
storm actually crosses the coastline.

2.5 Maximum of Maximums (MOMs)

MEOWs represent maximum surge heights plotted by storm track and hurricane
category. These maps are further modified into Maximums of the Maximums (MOMs),
to display the surge inundation limits. The MOMs represent the maximum surge expected
to occur at any given location, regardless of the storm track or direction of the hurricane.
The only variable is the intensity of the hurricane represented by category strength (1-5).
The MOM surge heights include an upward adjustment to reflect surges occurring during
an astronomical high tide. In order to find out the ultimate depth of surge flooding at a
particular location, for a given hurricane, the ground elevation at that location must be
deducted from the respective hurricane category surge elevation. However, the accuracy
of these elevation data will be limited to the precision and tolerance associated with that
map.

2.6 ADCIRC – Storm Surge Model

ADCIRC, (A Parallel ADvanced CIRCulation Model For Oceanic, Coastal And
Estuarine Waters) is a newly developed storm surge model that promises to produce more
accurate results than the SLOSH model. It is currently being used at LSU to obtain the
water levels that result from alternative hurricane scenarios. Inputs to the model include the
coastline bathymetry, water depths, the hurricane storm track and the hurricane central
pressure. Results are shown as color contour plots of water level. ADCIRC is a highly
developed computer program for solving the equations of motion for a moving fluid on a
rotating earth. These equations have been formulated using the conventional hydrostatic
pressure and Boussinesq approximations and have been discretized in space using the finite element (FE) method and in time using the finite difference (FD) method. (Luettich, R.A., Jr. and J.J. Westerink, 2000).

ADCIRC can be applied to computational domains encompassing the deep ocean, coastal seas, and small-scale estuarine systems. In a single simulation, ADCIRC can provide tide and storm surge elevations and velocities corresponding to each node over a very large domain encompassing regional domains such as the western North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico (USACE, 2001).

The ADCIRC model is an ongoing interactive collaboration involving researchers around the United States. A number of different runs are being implemented, results of which were scheduled to be imported into the research reported in this thesis to indicate water levels for different storm scenarios. The storm surge estimates for different hurricane scenarios for New Orleans area can be estimated from the model runs and these estimates form a vital factor in deciding the areas to be evacuated in a prioritized order.

An external boundary of the analysis area and the maximum flood limits for the problem area are established from the ADCIRC model runs. The establishment of an external boundary is important in that data acquisition need only be performed for that particular area. Since the model takes a wide range of hurricane intensities and categories into consideration, the application potentially becomes a generic model.

2.7 Current Practice in Establishing Hurricane Evacuation Zones

Hurricane evacuation zones include all areas that have a risk of flooding. Evacuation zones sometimes comprise non-flood areas if they are cut off or completely surrounded by flooded areas (USACE, 2001). The rate at which the evacuation area
grows is a function of the nature of the emergency source and the speed of its movement. In the case of a natural source such as a hurricane, the rate is a function of the storm’s strength and the speed and direction of its movement (Barrett et al, 2000).

In general, the evacuation zone boundaries have been delineated using census block boundaries in the past and they are generally made to conform to identifiable geographic features such as streets, railways, and other man-made land features (USACE, 1995). Census boundaries are used for evacuation zone delineations because they help in estimation of the total number of people potentially at risk from hurricane surge flooding. In most cases, evacuation zones have been delineated using major natural or man-made features as much as possible. They have also been chosen to conform to existing political boundaries (e.g. parish boundaries) because evacuation orders are issued at parish level. Evacuation zones are usually categorized so that a parish contains several evacuation zones. PBS&J (2000) conducted studies on hurricane evacuation travel demand modeling for Southwest Louisiana and they provide some guidelines for the delineation of hurricane evacuation zones:

a) Zones should relate to maximum potential surge flooding limits for each storm scenario.

b) Zones should relate well to census data base units.

c) Zonal boundaries should include identifiable natural features, roadways, landmarks, etc.

d) Small “pocket” zones that would be isolated by surrounding surge should be avoided.

e) Zones should be able to be served by major evacuation routes.
In an effort to assist state and local governments with the needed technical information, the Federal Emergency Management Agency (FEMA), the U.S. Army Corps of Engineers, and the National Oceanic and Atmospheric Administration (NOAA) joined Delaware state and local emergency management agencies in conducting the Delaware hurricane evacuation study (USACE, 1990). Evacuation zones were developed for each of the Delaware hurricane evacuation study area counties. Each of the evacuation zones was delineated as much as possible using major natural or man-made features and they conform to parish boundaries. Through a flood analysis, those areas which would receive hurricane storm surge were identified and graphically shown on MEOW maps. Those residents who would need to evacuate were defined. Having established those persons who should evacuate during a particular storm situation, it was then necessary to develop a series of zones to geographically locate and quantify the vulnerable population. The fact that evacuation zones must also provide a base to model traffic movements from one geographic area to another was also taken into account. A series of zones was established for each county based on the following factors (USACE, 1990):

a. Zones should relate to expected surge flooding limits (based on MEOWs) for each storm scenario.

b. Zones should relate well to census, traffic analysis zones, or other data base units.

c. Zonal boundaries should include identifiable natural features, roadways, landmarks etc.

d. Rural counties should have no more than 20 zones and counties with major urban areas should have no more than 35 zones.
e. Zones should be set up where possible for use in emergency management operations.

The *South Carolina Hurricane Evacuation Study* also provides similar guidelines for hurricane evacuation zone delineation. The factors include ensuring that zones can be served by major evacuation routes and that zones must have relatively balanced population levels (USACE, 1986). In the study conducted for Southeast Louisiana, the SLOSH storm surge prediction model was used as the basis of the hazards analysis. In order to identify the areas to evacuate in case of hurricane, all the parishes in southeast Louisiana study area were divided into smaller evacuation zones. These zones were divided on the basis of SLOSH data as well as zones that had been developed early in the transportation analysis. Based on the hurricane experience and study maps previously developed, a recommendation was also made to revise surge maps with a more definitive color scheme, which is easier to read and understand (PBS&J, 1993).

The *Southwest Florida Regional Hurricane Evacuation Study* provided updates for the Regional Hurricane Evacuation Plan for Collier, Lee and Sarasota counties. This study was conducted in 2001 as an update to the studies in 1991 and 1995. Prior to 1991, the officials in Collier County had a difficult time assessing the timing and shelter needs of the population as there was no clear understanding of the location of the borders of hurricane flood zones. After 1991, new hurricane evacuation zone boundaries were created based on locally known communities or geographic areas which have commonly understood names. Similarly, in Lee County new evacuation zones were created consistent with the existing evacuation routes, natural and manmade barriers and neighborhood or community boundaries where possible. Sarasota County also created
new evacuation zones very similar to Lee County, creating the boundaries based on geographic areas, existing evacuation routes or natural or manmade barriers which have commonly understood names (Southwest Florida Regional Planning Council, 2001). These evacuation zones were overlaid on the existing storm surge zones to create a map, which was then used by the officials to determine the appropriate changes to create new hurricane evacuation zones. GIS was used to perform this overlay operation.

Cedar Key Region located in Florida is frequently struck by hurricanes. It has some of the highest expected storm surge in the country. The Cedar Key Basin Hurricane Evacuation Study conducted by the Jacksonville District of the U.S. Army Corps of Engineers identified a series of zones to geographically locate and quantify vulnerable population in the area. These zones were established for each coastal county based on certain factors, the primary factor being that zones must relate well to expected surge flooding limits based on Maximum of Maximums (MOMs) for each category of storm. Other factors included the need for zones to relate well to traffic analysis zones and evacuation routes (USACE, 1996).

One of the most hurricane-vulnerable areas of the United States is the southeastern region of Florida. The Treasure Coast Region Hurricane Evacuation Study provides a framework within which each county can revise and implement their hurricane evacuation plan. Identification of the vulnerable areas and population is part of this plan and this study provides some guidelines to establish evacuation zones for each county. The factors included the need for zones to relate well to maximum surge flooding limits based on MEOWs, for zones to have relatively balanced population levels, ease with
which the area associated with an evacuation order can be understood, and zones which
are not isolated by surrounding surge (USACE, 1994).

The parishes in southwest Louisiana also represent extremely vulnerable areas to the
threat of an intense hurricane strike. The *Southwest Louisiana Hurricane Evacuation
Study* provides information about evacuation zones that are displayed in public
information brochures developed by each parish. The parishes, in conjunction with the
Corps of Engineers and PBS&J, developed the boundaries of each zone in relation to
well-known man-made or natural features, census boundaries, roadways and SLOSH
storm surge areas. The primary purpose of developing evacuation zones was to identify
the areas that will be asked to evacuate by local emergency management for different
storm scenarios (PBS&J, 2000).

In the study conducted for Southeast Louisiana by PBS&J, the factors to be
considered for evacuation zone delineation were listed and they were similar to those
listed in Delaware Hurricane Evacuation Study, with an additional factor being that zones
must allow for appropriate transportation modeling. This information is one of the key
inputs to the transportation analysis. Evacuation zones also provide a base to model
traffic movements from one geographic area to another. Developing these zones was
necessary to geographically locate and quantify the vulnerable population. The number of
zones ranged from 5 zones in St. Bernard Parish to 35 zones in Orleans parish (PBS&J,

In the study conducted for the State of Connecticut, the Corps of Engineers, New
England Division, developed an inundation map of hurricane storm surge for the entire
State of Connecticut, using the SLOSH model. The inundated portions of the state were
divided into smaller evacuation zones. The various evacuation zones were expanded utilizing traffic analysis zones and census tracts. Final delineations conformed as much as possible to easily recognizable geographic features (USACE, 1988).

On the whole, the literature reviewed regarding identification of hurricane evacuation zones clearly depict that the factors or the criteria used by agencies in the past have been quite similar. The factors used to identify zonal boundaries in the past have been:

   a. Flood limits
   b. Census tracts
   c. Well-known physical factors such as roads and landmarks.
   d. Areas that the public can identify through a verbal message.
3. Development of Procedure

3.1 Introduction

A method to delineate hurricane evacuation zones has been identified based on past practice, from discussions with experts in hurricane evacuation modeling (Baker 2002, Lewis 2003), and from experimentation of what is achievable with available data. A GIS platform has been used to implement the procedure. The proposed procedure is explained in a detailed step-by-step process in the following sections.

3.2 Establishing the Criteria

In transportation studies, transportation planners divide the urban area into analysis units called traffic zones. These zones form the basis for analysis of travel movements within, into, and out of the urban area (Meyer et al, 1984). The delineation of these zones is generally based on the following criteria (Baass, 1981):

1. Socioeconomic characteristics for each zone’s population must be homogeneous.

2. Intrazonal trips must be minimized.

3. The zones that are completely contained within another zone must be avoided and only those zones that are connected are considered.

4. The number of households, population, area, or trips generated and attracted should be nearly equal in each zone.

5. The physical, political and historical boundaries should be recognizable.

6. The zonal boundaries should be based on census zones.

The traffic analysis zones (TAZ’s) identified above are different from evacuation zones in several aspects. In the case of hurricanes, the primary source of damage is storm surge. Therefore, areas that have high risk of flooding must be grouped together.
Elevation of the zones is the key element in deciding the areas at risk, unlike traffic analysis zones where socio-economic homogeneity is the key element in determining TAZ boundaries. Similarly, intrazonal travel is a factor among TAZs but is generally negligible among evacuation zones due to the length of the evacuation trip.

The previous hurricane evacuation studies and the procedures they used to delineate hurricane evacuation zones have been studied as reported in the previous section. These practices have been taken into consideration in developing the following proposed criteria for delineating hurricane evacuation zones in this study:

1) The zones should be areas of similar elevation.
2) Zones should include elevations that extend up to maximum potential surge flooding limits.
3) Zones should be easily identifiable by the common man.
4) Zones should be as homogeneous as possible in their population, employment and land use.
5) Zones should not straddle parish boundaries.
6) Zonal boundaries should include features such as major roads and landmarks.

3.3 Formulation of Overall Procedure

3.3.1 Overall Outline

Values of the criteria proposed in the previous section to identify evacuation zones are obtainable from a variety of sources such as USGS digital elevation models (DEMs), Census data, and data provided with various GIS software. These data are dealt with in much more detail in the next chapter. In this section, the manner in which the above information is used to identify evacuation zones is described. The overall
procedure is explained in terms of a flow diagram in figure 1. Each activity is described in the sections that follow.

Figure 1: Flow Diagram of Process to Identify Evacuation Zones

3.3.2 Establishment of the Total Analysis Area

It is important that the area on which the analysis is to be performed is decided beforehand. The areas at risk are identified by finding out the maximum flood limits for the problem area. This involves identifying MEOWs for the most severe storms that are likely to strike the area. The envelope of the MEOWs will describe the landside limit of
the area to be subdivided into evacuation zones. Models such as SLOSH or ADCIRC may be used to identify this external boundary of the analysis area.

### 3.3.3 Identification of Uninhabited Areas

The next step in the process is to use land use information to identify areas that are uninhabited and therefore should be excluded from the analysis. This includes areas such as lakes, swamps, parks, nature reserves, cemeteries, sports fields, and any other area where humans do not reside or work. While evacuation from approaching hurricanes is an activity that usually takes place from home because of the relatively long warning time associated with hurricanes, work places are included within evacuation zones because it is also important for employers to know when their work locations are threatened.

### 3.3.4 Identification of Inhabited Areas within Zip code Areas

The Zip code areas should be used to form the basis of the evacuation zone delineation because it is an areal identification with which the public is familiar. These should be the 5-digit Zip code areas only and should not include the additional 4-digit extensions that serve to further subdivide a Zip code area. The 4-digit extension should be omitted because everyone is not necessarily familiar with the Zip code extension in his or her area. Zip code areas minus the uninhabited areas identified in section 3.3.3 were considered in the remainder of the analysis.

Several different areal systems identifiable by the common man were considered. These included residential subdivisions, telephone exchange areas, and Zip code areas. It was found to be difficult to obtain electronic files of subdivision boundaries and while GIS-readable files of telephone exchange areas could be found, they were only
commercially available and were expensive ($2000 for the New Orleans area). In contrast, Zip code boundaries were readily available at no cost. The Zip code boundary data was provided along with the software ArcGIS. This data also has population and area of each Zip code associated with it. This data makes the task of officials much easier when quantifying the impact of an evacuation order.

3.3.5 Division of Zip Code areas into Sub Areas

The next step in the process of establishing the evacuation zones is to identify the main roads in the area and specifically any evacuation routes serving the area. The roads are used to subdivide the Zip code areas into sub areas so that smaller areas form the basis of the analysis. Using roads to divide ZIP code areas allows the establishment of more zones while still retaining the ability to easily communicate the extent of each zone to the public. Thus, the resulting sub areas are identified by a Zip code and an orientation to one or more roads subdividing the Zip code area.

3.3.6 Identifying the Elevation of the Sub Areas

The elevation of an area describes its risk of flooding. Since risk of flooding is one of the major factors motivating evacuation, it was considered appropriate in this study to establish evacuation zones of similar uniform elevation. If the sub areas identified in the previous step are used as the basic building blocks in establishing evacuation zones, adjacent sub areas can be merged in their formation of an evacuation zone if their mean elevation is similar and the standard deviation of the elevation in each sub area is small. Standard deviation is a good method to measure the variation in elevation. Even though there are many methods in statistics that measure the variation in
an efficient manner, standard deviation can still be used to serve the purpose. Merged sub areas of similar uniform elevation reflect similar flooding potential.

3.3.7 Merging Sub Areas into Evacuation Zones

The merging of the sub areas is necessary, as it makes the process of evacuation management easier with only few zones to handle. The process of merging sub areas into evacuation zones needs to be formulated so that it can be conducted in a systematic and repetitive manner. Formulating the process forms the basis of an algorithm that can be programmed for automated application. The suggested procedure is:

1) Establish the mean and the standard deviation of the elevation points within each sub area.

2) Identify all sub areas that are contiguous or adjacent (i.e., have at least one point on their perimeter in common).

3) If $S_i$ is the standard deviation of the elevation of points in sub area $i$, estimate $\sqrt{(S_i^2 + S_j^2)/2}$ for all adjacent zones $i$ and $j$.

4) Determine the $10^{th}$ percentile of $\sqrt{(S_i^2 + S_j^2)/2}$.

5) Retain all adjacent sub area pairs $(i, j)$ which have value of $\sqrt{(S_i^2 + S_j^2)/2}$ less than or equal to $10^{th}$ percentile.

6) Among the sub area pairs retained in (5), identify the pair with the smallest difference in mean elevation value.

7) Merge the sub areas identified in step (6).

8) Estimate the mean elevation value of the sub areas merged in step (7).

9) Estimate the standard deviation of the sub areas merged in step (7).
10) Return to Step (2) and repeat the process until a closure criterion on the similarity of sub areas is satisfied or number of zones has decreased sufficiently.

When combining sub areas, merging of sub areas that cross the parish boundaries should not be permitted because parishes retain the authority to issue their own evacuation orders.

3.3.8 Estimating the Population in Evacuation Zones

Generally speaking, population data for the polygons that emerge from the previous step would not be available. However, data at the census tract level is freely available. If this procedure is implemented on a GIS platform, the overlay feature common to all GIS systems can be used to estimate the population in the sub areas and merged sub areas from the census tract data.
4. Building the Procedure on a GIS Platform

4.1 Introduction

Geographic Information Systems (GISs) are a system of computer software, hardware, data, and personnel that manipulate, analyze and present spatial information. In other words, GISs combine layers of spatial information about a place to give us a better understanding of that place. TransCAD, a transportation/GIS software package is the only package that fully integrates GISs with planning modeling and logistics applications.

TransCAD has a built-in programming language called GISDK (GIS Developer’s Kit), which lets the users customize and extend the capabilities of TransCAD in almost any way they like. GISDK lets the users automate the task they perform on a regular basis, so that one can accomplish it by clicking a single button or choosing a single menu item. GISDK was used to automate the above process to establish hurricane evacuation zones. To incorporate the procedure described in the previous chapter into a GIS, the manner in which the input to the process is prepared, and the procedure is executed, must be explained. The following sections deals with how the procedure is implemented on a GIS platform.

4.2 Obtaining & Presenting the Data

4.2.1 Elevation Data

Digital Elevation Model (DEM) data files are digital representations of cartographic information in a raster form. DEMs consist of a sampled array of elevations for a number of ground positions at regularly spaced intervals. These digital cartographic/geographic data files are produced by the U.S. Geological Survey (USGS) as part of the National Mapping Program. DEM data for 7.5-minute units correspond to
the USGS 7.5-minute topographic quadrangle map series for all of the United States and its territories except Alaska. Each 7.5-minute DEM is based on a 30- by 30-meter data spacing with the Universal Transverse Mercator (UTM) projection. Each 7.5- by 7.5-minute block provides the same coverage as the standard USGS 7.5-minute map series (U. S. Army Corps of Engineers, 2001).

DEM data are stored as profiles in which the spacing of the elevations along and between each profile is 30 meters. The number of elevations between each profile will differ because of the variable angle between the quadrangle's true north and the grid north of the UTM coordinate system. DEM data of low-relief terrain, or those generated from contour maps with intervals of 10 feet or less, are recorded in feet while DEM data of moderate to high-relief terrain, or those generated from maps with terrain contour intervals greater than 10 feet, are generally recorded in meters.

An alternative source of elevation information is LIDAR data. Light Detection and Ranging (LIDAR) is becoming more widely accepted as a source of remotely sensed data for GIS applications. In many cases, it represents a cost-effective method for acquiring digital elevation data and has a significant advantage over conventional aerial photography in that it can be acquired at night and in cloudy or hazy weather conditions. In a GIS, LIDAR data can be displayed in grid format or as contour lines. Once LIDAR data is in grid format, additional products such as digital elevation models (DEMs) can be generated (ArcUser, 2003, p.31).

LIDAR elevation data is available for the major portion of Louisiana in the form of DEMs. These can be imported into TransCAD and exported as a shapefile to other GIS systems such as ArcView. This feature was used to translate individual DEM files that
cover the study area into individual shapefiles covering the entire area. These shapefiles are merged into a single large shapefile in ArcView. This large shapefile was then opened in TransCAD as a compact geographic file in which the individual elevations were presented as a point file. This process of working between TransCAD and ArcView was necessary because TransCAD did not have the means to merge the DEM files. The merged shapefile consists of a point at every 30 meters throughout the study area, which, with the study area selected, resulted in a file with approximately 1.5 million points.

4.2.2 Data from SLOSH Model

A maximum possible number of hypothetical hurricanes are modeled for the study area SLOSH model. These hurricanes are specified to travel in each of the five possible directions, and at various forward speeds. A range of track locations is used for each direction in order to evaluate the surge heights resulting from different storm landfall points. Storms are modeled at categories 1 through 5 of the Saffir-Simpson scale of intensity. For each SLOSH model simulation of a particular hurricane scenario, the maximum water surface elevations or MEOW is determined. The MEOWs for each hurricane event are determined in this manner and the combination of all the MEOWs produces a total analysis area.

4.2.3 Identifiable Areal Information

The Zip code data were available in the format of layer files which TransCAD cannot read. Therefore, these files were converted into shapefiles in ArcGIS and then imported into TransCAD. The projection system used was UTM (Universal Transverse Mercator), zone 15 and NAD83 (North American Datum). Figure 3 shows the zip code boundary layer of the study area with their zip code numbers displayed.
4.2.4 Land Use Data

Land use data showing vegetated urban, non-vegetated urban, wetland barren, water, fresh marsh etc. are available from the web site http://www.epa.gov. The data was provided in the form of an ArcInfo interchange file. This file was converted into an ArcView shapefile. Each record in the data describes a land use in terms of its area, perimeter and land use code. The land use codes use a hierarchical system of classification where the first digit represents the main distinction and the second digit represents a subdivision of the level 1, and so on. For example, Land use code 1 refers to Urban land, and 11 is Residential, 12 is Commercial and Services, and 13 is Industrial. More detailed land use codes are provided in the Appendix A.
Figure 3: The Inhabited Land Use data for the study area

Using Lucode as the classification field, a map is created which distinguishes inhabited from uninhabited areas. Only the inhabited areas in the study area are extracted as shown in the map in figure 3.

4.2.5 Parish Boundaries

Parish boundaries are important in the delineation of evacuation zones because each parish issues their own evacuation orders and, therefore, evacuation zones should not straddle parish boundaries. Parish boundaries are obtained from the data that is provided along with the ArcView software. Their function in the evacuation zone delineation process is only to ensure that evacuation zones do not cross parish boundaries.
4.2.6 Highway and Landmark Data

Highways are used to subdivide ZIP code areas into smaller and yet still recognizable areas. That is, while people generally know the ZIP code of their home location well, they are also generally well capable of identifying that location with respect to a major highway or landmark. For example, if an announcement is made that persons in ZIP code area xxxxx, south of highway Y or north of the church (or any other well-known landmark) must evacuate, then most people would have no difficulty in determining whether they were being called upon to evacuate or not. Highway and landmark data is available from the data provided with TransCAD software. The highway data has other information such as length of the road, type of the road (multilane divided, paved undivided etc.), and class of the road (Inter state, Highway etc).

4.2.7 Census Tract Data

The United States Census Bureau provides digital census maps (TIGER files) as well as population data. This data is available at the website of Environmental Systems and Research Institute Inc. (www.esri.com). The other source of the census tract data is TransCAD, which has the population data associated with it. This population data is useful for identifying the number of people to be evacuated after establishing the hurricane evacuation zones. Since the data provided with TransCAD is readily available, it was used. The census tracts for the study area are shown in figure 6.
Figure 4: Census Tracts for the study area

4.2.8 Combining the Data

As explained in the previous chapter, all the individual data collected, should be combined to form a final sub area layer. The total analysis area that was established from the storm surge model runs was considered and only the data pertaining to that area was obtained. The process of combining the data and dividing the zip code layer into sub areas was performed in another GIS software called GeoMedia Professional. This software was chosen ahead of other GIS programs because it was comparatively easy to perform the above said operation in GeoMedia Professional.

The process is initiated by opening the Zip code area boundary layer and the land use layer for the study area in GeoMedia. The uninhabited areas are identified using LUCODE and are excluded from the zip code areas.
After subtracting the uninhabited areas from the zip code layer, the roads are used to subdivide them into sub areas. Again using the Spatial Intersection feature of GeoMedia, the zip code attributes are attached to each of the sub area. Then a final cleaning is performed to avoid minute areas, which cause trouble in final merging. The figure shown below provides an example of zip code areas being cut by roads and also excluding the uninhabited areas.

Figure 5: Sub area layer

A final sub area layer was created. Each of the resulting sub areas was identified by an identification number and an orientation to one or more roads, subdividing the Zip code area. The program developed to combine the sub areas is described in the following section.
4.3 Calculation of the Mean and Standard Deviation of Elevation

In order to arrive at mean and standard deviation values of elevation, DEMs are overlaid on the sub area layer identified in the previous section. These DEMs were made into a single shape file to allow use of the Overlay process and to handle the large volume of elevation data efficiently. The conversion of DEMs to shape files was performed in TransCAD while the merging of all the shapefiles used ArcView.

The overlay procedure is a procedure that estimates the attributes of one or more features by superimposing them over other features (Caliper Corporation, 2000). We use overlays to estimate the attributes of features in a layer based on data in another map layer. Using the zip code areas subdivided by the highways as the base layer, the elevation point shape file was placed over it in TransCAD. Using the Overlay procedure, the average elevation in each subdivided Zip code area was estimated and added to the dataview of the Zip code layer. To allow estimation of the standard deviation of the elevations in each subdivided ZIP code area, it was necessary to transfer the mean elevation of each area to the layer containing the individual point elevation data. This was accomplished using the ‘tagging’ feature in a GIS, which fills a column in the dataview of the elevation point layer with the corresponding average elevation. The values for the square of the difference between the elevation and average elevation were calculated and filled in the dataview. Using the Overlay procedure again and following the same procedure followed for finding out the mean elevation, the average of the square of the difference between elevation and average elevation column was estimated. This value is the square of standard deviation or variance. Thus, a new column was created in the data view of the zip code layer which is the squared value of the standard deviation.
The above procedure was used to obtain mean and standard deviation of the elevation of the sub areas.

4.4 Adjacency Matrix

An adjacency matrix file has one row and one column for each sub area, and there are three alternative matrices that can be used. The first matrix contains the value one in a cell if the two areas have a common linear border and a missing value otherwise. The second matrix contains a value between zero and one indicating the level of adjacency. This measure is computed as the length of the common border divided by the average of the perimeter of the two areas involved. The third matrix contains the length of the common boundary.

The adjacency matrix that is used in the current methodology is the matrix obtained in the first manner i.e., using common linear border. The table below is the adjacency matrix of a map, which contains five areas, some of which are adjacent to each other. A value of 1.00 indicates that the areas have a common border.

Table 2: Sample Adjacency Matrix

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>--</td>
<td>1.00</td>
<td>--</td>
<td>1.00</td>
<td>--</td>
</tr>
<tr>
<td>B</td>
<td>1.00</td>
<td>--</td>
<td>1.00</td>
<td>1.00</td>
<td>--</td>
</tr>
<tr>
<td>C</td>
<td>--</td>
<td>1.00</td>
<td>--</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>D</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>--</td>
<td>1.00</td>
</tr>
<tr>
<td>E</td>
<td>--</td>
<td>--</td>
<td>1.00</td>
<td>1.00</td>
<td>--</td>
</tr>
</tbody>
</table>
4.5 Program Execution in GIS

4.5.1 Execution Platform

The Geographic Information System Developer’s Kit (GISDK) provides a tool kit that one can use to customize TransCAD in anyway they desire. GISDK is a collection of software tools that come with TransCAD which make automation of repetitive tasks in TransCAD possible. It also helps in creating user-designed add-ins, integrating other programs, or building custom applications. GISDK also makes it possible to call a TransCAD functionality from other software applications (GISDK programmer’s Guide for TransCAD, 2001).

The primary component of the GISDK is a programming language called Caliper Script. This is an easy-to-learn programming language that provides a way to interact with the TransCAD program and data. The code written in other languages such as C or FORTRAN can be mixed with GISDK programs written in Caliper Script, allowing for compatibility with existing software. There are over one thousand GISDK functions in TransCAD, all of which can be called using Caliper Script. These functions facilitate in managing and analyzing maps efficiently.

Caliper Script has three components: a compiler, a debugger and a toolbox for interacting with the compiler and debugger. The GISDK compiler takes the caliper script code and creates a User Interface database that can be run with the TransCAD platform. The compiler reports any errors in the code including the details about the type and location of the error. The GISDK debugger runs the Caliper Script code in testing mode to make sure that there are no errors, such as errors in logic or variable handling. If the code does not behave as expected, the debugger allows the user to set breakpoints or to
step through the code one line at a time, to make sure that the code is executing as
expected. The GISDK Toolbox not only has buttons to run the compiler and the debugger
but also has tools to make interacting with the program faster and easier (GISDK

The hardware requirements for GISDK are minimal, if TransCAD can be run,
then GISDK can be run. GISDK does not have its own editor. Therefore, the GISDK
source code can be created, edited and displayed in any text editor such as notepad. The
source code files have an .rsc extension.

4.5.2 Implementation of Program

The elevation point file is overlaid on the final sub area layer to further proceed
with the implementation of the methodology identified in the previous chapter.

In the first step, the mean elevation of each sub area is calculated and is added in
the data view of sub area layer, corresponding to each sub area. GISDK has a function
called Column Aggregate (), which performs a geographic overlay between two layers
and aggregates tabular data. This function calculates the average elevation of each sub
area based on the elevation points overlaid on it. Then each elevation point is associated
with a corresponding average elevation using the tagging function. GISDK has a separate
set of code which performs this operation. The entire GISDK program written in Caliper
Script is shown in Appendix B. The standard deviation values are then filled in the data
view of the sub area layer using the average elevation values.

In the second step, an adjacency matrix is created for the sub area layer. GISDK
has a function called CreateAdjacencyMatrix (), which produces an adjacency matrix
consisting of values 0 and 1 depending on whether the zones are adjacent or not. This
adjacency matrix is used as input and corresponding adjacent zones are identified to calculate \( \sqrt{(S_i^2 + S_j^2)/2} \) values for adjacent zones i and j. The 10\(^{th}\) percentile values of \( \sqrt{(S_i^2 + S_j^2)/2} \) were also determined and the values less than 10\(^{th}\) percentile were retained. The functions GetMatrixValue(), Percentile() etc. perform the above said calculations. The use of these functions are demonstrated in the program listed in Appendix B.

The smallest value of \( \overline{X}_i - \overline{X}_j \) among the \((i, j)\) pairs retained was determined and the corresponding zones i and j were combined, where \(X_i = \text{Mean Elevation of sub area ‘i’} \) and \(X_j = \text{Mean Elevation of sub area ‘j’} \). This merging is performed by a function called MergeByValue(), which creates districts by merging areas from a geographic file, based on the value of a field. The values have to be similar to get the areas merged. Again the process has to be repeated to get the next pair of zones merged. This is an iterative process and entire program is conducted in a loop, with the program terminating when a relevant closing criterion is attained.

4.5.3 Determination of Closing Criterion

A relevant closing criterion is very important for any iterative process since it needs to identify a meaningful stage for the process to stop. In the present scenario of merging the sub areas to form a series of evacuation zones, one possible closing criterion is the reduction of the number of zones to a specified number. However, this kind of closing criterion does not indicate whether the number chosen is a good number at which to terminate the process or not. Several other criteria were considered to end the iterations such as the difference of mean elevations between the merged zones at the end of each iteration, the average standard deviation of the merged zones \(\sqrt{(S_i^2 + S_j^2)/2}\) at the end of each iteration and the product of these two values.
A graph plotted for difference of the mean elevations against the number of iterations is shown in figure 6. The curve is observed to be irregular and, while a general increase in its values can be observed with the progression of iterations, it was not considered an appropriate closing criterion.

![Difference of Mean Elevations Vs No. of Iterations](image)

Figure 6: Difference of Mean Elevations Vs No. of Iterations

Another criterion which was considered was the $\sqrt{(S_i^2 + S_j^2)/2}$ value of the zones being merged. The value of this statistic at the end of each iteration is shown in the figure 7. The graph shows that there is reasonably well-behaved trend in this statistic with the exception of a few points. This statistic was selected as a candidate closing criterion in this study.
Figure 7: Variation in Standard Deviation by No. of Iterations
5. Application in Northern New Orleans Metropolitan Area

5.1 Introduction

The New Orleans metropolitan area is for the most part, protected by levees. Even though New Orleans itself could have been considered, the land on which New Orleans is situated, is below sea level. These levees have been built to protect life and property from storm surge. They reduce the need for evacuation but sophisticated computer modeling of storm surge effects indicates most levees in Southeast Louisiana would be overtopped during a direct strike of a major hurricane resulting in widespread flooding. In such a case, the entire New Orleans area would be flooded and the entire population would have to evacuate. Therefore, the current methodology, which is designed to identify which sub areas within an urban must be evacuated, is not applicable in such an application. In contrast, the northern portion of the metropolitan area does not have levees. Therefore it would be an ideal test case for implementing the proposed methodology. The study area considered for this application consists of certain portions of Tangipahoa and St. Tammany’s parish, below Interstate-12.

The data that was used for this particular application was the census tract data, land use data, the elevation data from the DEMs, and the parish boundary data. All the above data was used and the methodology discussed in previous sections was implemented to arrive at the hurricane evacuation zones. Further, the SLOSH storm surge model was used to obtain the water levels that result from hurricanes. This identified which zones would be flooded based on the scenarios considered. These scenarios include

I. Storm categories 2 and 5.

II. Hurricanes approaching from the southeast, south and southwest directions.
III. Forward speeds of 5 mph and 15 mph.

Finally, overlaying the flood projections on the evacuation zones was performed to identify the zones that need to be evacuated with each storm scenario.

LIDAR data has recently been collected for the entire state of Louisiana. However, it is still being processed and the data was not available for the entire area of study at the time this research was done. Hence, the USGS DEMs were used in this study.

5.2 Data Sources

The data used in this application was obtained from a variety of sources. The census tract data, which is helpful in estimating the population to be evacuated, was obtained from TransCAD. Land use data was obtained from the web site http://www.epa.gov and the data was downloaded and converted to a recognizable format as explained in the section 4.2.4. The elevation data was obtained from www.atlas.lsu.edu. The parish boundary data was obtained from the ArcView software package. This data was also available with other software such as TransCAD and ArcGIS.

5.3 Results

The GISDK program was run on the sub area layer created for the northern New Orleans Metropolitan area. This iterative process was repeated until the specified closing criterion was attained. In each iteration, the number of zones is reduced by one. In the present situation, the sub area layer initially had 53 individual sub area zones as shown in figure 8. These were reduced to the 43 zones as shown in figure 9, and finally to the 33 zones shown in figure 10. For this analysis, we terminated the process after 20 iterations.
Figure 8: Sub Areas Layer Before Application of the GISDK Program
Figure 9: Evacuation Zone Layer After 10 Iterations
Figure 10: Evacuation Zone Layer After 20 Iterations
5.3.1 Hurricane Scenarios

Based on different storm categories, forward speeds and direction, different flood projection maps were produced showing the storm surges for the study area. The scenarios considered in section 5.1 amounted to a total of 12 scenarios with all the combinations. Table 3 shows the scenarios considered.

<table>
<thead>
<tr>
<th>Scenario Number</th>
<th>Storm Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Category 2; South; 5 mph</td>
</tr>
<tr>
<td>2</td>
<td>Category 2; Southeast; 5 mph</td>
</tr>
<tr>
<td>3</td>
<td>Category 2; Southwest; 5 mph</td>
</tr>
<tr>
<td>4</td>
<td>Category 2; South; 15 mph</td>
</tr>
<tr>
<td>5</td>
<td>Category 2; Southeast; 15 mph</td>
</tr>
<tr>
<td>6</td>
<td>Category 2; Southwest; 15 mph</td>
</tr>
<tr>
<td>7</td>
<td>Category 5; South; 5 mph</td>
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<tr>
<td>8</td>
<td>Category 5; Southeast; 5 mph</td>
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<td>9</td>
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</tr>
<tr>
<td>10</td>
<td>Category 5; South; 15 mph</td>
</tr>
<tr>
<td>11</td>
<td>Category 5; Southeast; 15 mph</td>
</tr>
<tr>
<td>12</td>
<td>Category 5; Southwest; 15 mph</td>
</tr>
</tbody>
</table>
Of all the scenarios mentioned only three were chosen for discussion. These are scenarios 1, 6 and 11. The idea was to choose the three scenarios that give the most different results. Each of the above three scenarios has the storm approaching from a different direction. Scenario 1 and Scenario 11 are storms which are extreme opposites. Scenario 1 is a category 2 storm moving at a speed of 5 mph while scenario 11 is a category 5 storm moving at 15 mph respectively. Scenario 6 is a storm approaching from a different direction from the other two storms which causes different flooding patterns. Therefore, these three storm scenarios were used to yield a range of results that may be expected from all of the scenarios. The flood maps of the remaining 9 scenarios are included in the appendix.

The evacuation zone layer was overlaid on the flood projection map to identify the zones that needed to be evacuated. Figure 11 shows the storm surge map for the entire coastal region for a category 2 storm, moving in from the south with forward speed of 5 mph i.e., scenario 1. Figure 12 shows the storm surge map of scenario 1 for the study area overlaid with the evacuation zone layer. Figure 13 shows the hurricane evacuation zone layer overlaid on the storm surge map of the study area for scenario 6. Figure 14 displays the hurricane evacuation zone layer displayed on the storm surge map of the study area for scenario 11.
Figure 11: Storm Surge Map of Scenario 1
Figure 12: Evacuation Zone layer Overlaid on Storm Surge Map of Scenario 1
Figure 13: Evacuation Zone layer Overlaid on Storm Surge Map of Scenario 6
Figure 14: Evacuation Zone layer Overlaid on Storm Surge Map of Scenario 11
5.3.2 Discussion of the Results

Figure 12 shows the storm surge map of a category 2 storm, coming from the south with a forward speed of 15 mph, overlaid with the final evacuation zone layer. Table 4 lists shows the evacuation zones which are identified from the storm surge map as being vulnerable to the storm scenario 1. The average elevation of the zones and the estimated storm surge are expressed in height above mean sea level in feet. The difference between maximum storm surge and average elevation should be calculated to estimate the depth of inundation. In those zones where the average elevation was greater than the estimated storm surge, the population residing in those zones would not need to evacuate.

Overlaying the census tract layer on the final hurricane evacuation zone layer, the population vulnerable to the hurricane is estimated. The sub areas that make up the zip code areas of 70471, 70433, 70447, 70454, 70460, 70445, 70448, 70403 are affected by the storm and are vulnerable to the storm surge. Therefore, they should be issued an evacuation order. Population estimates of these areas allow estimation of evacuation volumes.

Figure 13 shows the storm surge map of a category 2 storm approaching from the southwest with a forward speed of 15 mph, overlaid with the final evacuation zone layer. Table 5 shows the zones that are vulnerable to the storm surge caused by the scenario 6. The hurricane evacuation zones, whose estimated inundation was less than the mean elevation, need not evacuate as they are in the safe zone. Overlaying the census tract layer on the hurricane evacuation zone layer, the population vulnerable to the hurricane is estimated.
Table 4: Evacuation Zones affected by Storm Scenario 1

<table>
<thead>
<tr>
<th>Zone ID</th>
<th>Average Elevation (ft) (X)</th>
<th>Storm Surge (ft) (Y)</th>
<th>Estimated Inundation (ft) Y-X</th>
<th>Zonal Population</th>
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<td>6.82</td>
<td>2 - 3</td>
<td>-3.82</td>
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<td>-</td>
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<td>-</td>
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Table 5: Evacuation Zones affected by Storm Scenario 6

<table>
<thead>
<tr>
<th>Zone ID</th>
<th>Average Elevation (ft) (X)</th>
<th>Storm Surge (Y) (ft)</th>
<th>Estimated Inundation (Y-X) (ft)</th>
<th>Zonal Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.82</td>
<td>2 - 3</td>
<td>-3.82</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>4.31</td>
<td>3</td>
<td>-1.31</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>5.29</td>
<td>6</td>
<td>0.71</td>
<td>2700</td>
</tr>
<tr>
<td>5</td>
<td>3.84</td>
<td>4 - 5</td>
<td>1.16</td>
<td>3400</td>
</tr>
<tr>
<td>9</td>
<td>2.10</td>
<td>3</td>
<td>0.9</td>
<td>30800</td>
</tr>
<tr>
<td>12</td>
<td>4.85</td>
<td>2</td>
<td>-2.85</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>9.22</td>
<td>2</td>
<td>-7.22</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>1.48</td>
<td>5 - 6</td>
<td>4.52</td>
<td>13</td>
</tr>
<tr>
<td>17</td>
<td>2.38</td>
<td>4 - 5</td>
<td>3.62</td>
<td>5030</td>
</tr>
<tr>
<td>19</td>
<td>3.27</td>
<td>4 - 5</td>
<td>1.73</td>
<td>3190</td>
</tr>
<tr>
<td>20</td>
<td>2.74</td>
<td>5 - 6</td>
<td>3.26</td>
<td>1170</td>
</tr>
<tr>
<td>21</td>
<td>6.41</td>
<td>1 - 2</td>
<td>-4.41</td>
<td>-</td>
</tr>
<tr>
<td>22</td>
<td>3.59</td>
<td>4</td>
<td>0.41</td>
<td>750</td>
</tr>
<tr>
<td>23</td>
<td>7.15</td>
<td>1 - 2</td>
<td>-5.15</td>
<td>-</td>
</tr>
<tr>
<td>24</td>
<td>4.16</td>
<td>5 - 6</td>
<td>1.84</td>
<td>750</td>
</tr>
<tr>
<td>25</td>
<td>7.15</td>
<td>3</td>
<td>-4.15</td>
<td>-</td>
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<td>29</td>
<td>5.93</td>
<td>2</td>
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</tr>
<tr>
<td>31</td>
<td>6.83</td>
<td>0 - 1</td>
<td>-5.83</td>
<td>-</td>
</tr>
<tr>
<td>32</td>
<td>8.88</td>
<td>0 - 1</td>
<td>-7.88</td>
<td>-</td>
</tr>
</tbody>
</table>
For the storm scenario 6, the people from the sub areas making up the zip code areas 70471, 70433, 70447, 70454, 70460, 70445, 70448, 70403 and 70471 are affected by the storm and are vulnerable to the storm surge. The entire population from each zone is evacuated even for a small amount of inundation. The inundation is calculated according to average elevation and for a given area the true elevation may be lesser than the average elevation. These areas can have greater risk of flooding. Moreover, the flood estimates are not highly accurate. Therefore, on a point that it is advisable to be safe rather than be sorry, the evacuation of entire population is justified. Evacuation officials would order the people from these zones to evacuate as soon as possible to a safer zone.

Figure 14 shows the storm surge map of category 5 storm, coming from southeast direction and with a forward speed of 15 mph, overlaid with the final evacuation zone layer. Table 6 shows the zones that are vulnerable to the storm surge caused by the storm scenario 11.

For the storm scenario 11, the people from the zip code areas 70455, 70461, 70458, 70471, 70433, 70447, 70454, 70460, 70445, 70448, 70403 and 70471 are severely affected by the storm and are vulnerable to the storm surge. A Category 5 storm is the highest intensity hurricane and, as shown, it causes extremely high storm surges. Therefore, the people residing in the above-mentioned Zip code areas would be ordered to evacuate at the earliest possible time.
Table 6: Evacuation Zones affected by Storm Scenario 11

<table>
<thead>
<tr>
<th>Zone ID</th>
<th>Average Elevation (X) (ft)</th>
<th>Storm Surge (Y) (ft)</th>
<th>Estimated Inundation (Y-X) (ft)</th>
<th>Zonal Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.82</td>
<td>18-20</td>
<td>13.18</td>
<td>14200</td>
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<td>2</td>
<td>4.31</td>
<td>18-20</td>
<td>15.69</td>
<td>5400</td>
</tr>
<tr>
<td>3</td>
<td>6.20</td>
<td>18-20</td>
<td>13.80</td>
<td>520</td>
</tr>
<tr>
<td>4</td>
<td>5.29</td>
<td>20</td>
<td>14.71</td>
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<td>5</td>
<td>3.84</td>
<td>18-20</td>
<td>14.16</td>
<td>3400</td>
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<tr>
<td>6</td>
<td>4.09</td>
<td>18-20</td>
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<td>7</td>
<td>4.76</td>
<td>18-20</td>
<td>15.24</td>
<td>3750</td>
</tr>
<tr>
<td>8</td>
<td>4.06</td>
<td>22-24</td>
<td>19.94</td>
<td>5400</td>
</tr>
<tr>
<td>9</td>
<td>2.10</td>
<td>21</td>
<td>18.9</td>
<td>30800</td>
</tr>
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<td>10</td>
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<td>13.19</td>
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<tr>
<td>11</td>
<td>4.32</td>
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<tr>
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<td>17</td>
<td>2.38</td>
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<td>20</td>
<td>2.74</td>
<td>20-22</td>
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<td>21</td>
<td>6.41</td>
<td>24-26</td>
<td>19.59</td>
<td>980</td>
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<tr>
<td>22</td>
<td>3.59</td>
<td>18-20</td>
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<td>32</td>
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<td>33</td>
<td>90.23</td>
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<td>-70.23</td>
<td>-</td>
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</tbody>
</table>

In the three cases that were tested, the Category 5 storm approaching from the southeast with a forward speed of 15 mph was found to be the hurricane that caused the most damage. It forced the people from all the zip code areas in the study area to evacuate, whereas in the case of the other two storm scenarios, the affect was considerably less with only seven zip code areas being affected. Storm Scenarios 1 and 6
are both category 2 storms but moving in different directions and with different forward speeds. The storm surge caused by the scenario1 is greater than scenario 6, which can be attributed to the direction from which it is approaching. This is because the forward speed of scenario1 is less than scenario 6 and yet it still produces a higher surge. Therefore, it can be deduced that direction in which the storm is approaching is a more important factor in storm surges than forward speed. Moreover hurricanes approaching from the southeast (i.e., scenario 11) cause higher storm surge than those from the south and southwest. Part of this is because scenario 11 is a category 5 storm but when compared to the other category 5 scenarios (in the appendix) it is evident that storms moving in from the southeast cause more damage. Similarly all the other hurricane scenarios can be analyzed to estimate the population at risk. The storm surge maps for the remaining scenarios are displayed in the Appendix C.
6. Summary and Conclusions

6.1 Study Summary

The study presented a methodology to identify hurricane evacuation zones. The approach focused on elevation of the area as the primary factor in delineating the zones. However, other factors such as zones being identifiable by people, zones being homogeneous in land use and zones not crossing parish boundaries were also incorporated. An area layer was created based on the total analysis area that comes from the MEOWs of storm surge models, and was then overlaid with the zip code boundaries and land use data available. The inhabited areas of the zip code area layer were retained for analysis. Then highways were used to sub divide ZIP code areas into sub areas. Elevation point file data were overlaid on the sub areas to deduce the mean elevation and standard deviation values of elevation for each sub area. These values were further used to combine adjacent sub areas which are similar in elevation. Similarity of elevation was judged both on the mean elevation and the variance of elevations within a sub area. The variance was considered because sub areas with large variances in elevation do not represent areas of uniform elevation even if their means are similar. Only sub-area pairs with small relative variance in both sub areas were considered for combination. Within this subgroup of sub area pairs, the pair with the smallest difference in mean value was combined and a new combined zone was formed. These zones were grouped together in an iterative process until the zones were sufficiently reduced. The entire process was automated in TransCAD, to provide a quick, graphic display of results that may be set to any level of aggregation chosen by the user.
The study also included an application of the methodology to the northern portion of New Orleans metropolitan area, to demonstrate operation of the process. The application demonstrated how initial sub areas are established and then combined through the automated process to arrive at a reduced number of evacuation zones. The application also demonstrated how different storm scenarios are combined with the evacuation zone information to identify those zones that must be evacuated and the number of people affected.

6.2 Conclusions

The primary objective of this study was to develop a criteria-based methodology to delineate hurricane evacuation zones. The specific objectives of this study were to examine the previous methodologies used for delineating hurricane evacuation zones by reviewing different hurricane evacuation studies, identify criteria that should be used to distinguish hurricane evacuation zones, establish a procedure which uses the criteria identified before to identify hurricane evacuation zones and to demonstrate the process by establishing hurricane evacuation zones in the northern part of the New Orleans metropolitan area.

Using knowledge gained from past studies, a systematic, repeatable and criteria-based methodology has been developed to delineate hurricane evacuation zones. It is based on a GIS platform which facilitates certain data operations and allows a convenient means of graphically displaying the results. The process provides an automated means of identifying evacuation zones that are as homogeneous as possible with respect to elevation while also being readily identifiable to the residents of an area.
The data collection for the application involved lot of time and effort as some of the data were not that easily available. Applying the methodology manually would have been very tedious. Therefore, the process was automated in TransCAD using the custom software GISDK. The running time of the application in northern New Orleans iterations was approximately 7 hours for the 20 iterations tested.

The methodology developed can be applied to any area where levees are not built. Construction of levees nullifies the need for identification of hurricane evacuation zones. Hence, any area where hurricanes are predominant and levees are not built would be an appropriate area for application of the process.

Out of the three cases tested, the Category 5 storm approaching from southeast with a forward speed of 15 mph was found to be the hurricane that caused the most damage. It caused the people from all the zip code areas in the study area to evacuate whereas in the case of the other two storm scenarios, the affect was less. Moreover, hurricanes approaching from the southeast generally cause higher storm surge compared to the other directions (i.e., south and southwest). This is evident when comparing the storm surge maps for the different scenarios.

In the past, hurricane evacuation zones have been established manually using professional judgement. The resulting zones have typically been classified into categories 1 to 5 to correspond to the category storm that would be needed to flood the zone. However, as demonstrated in this study, the track of a storm is also important in terms of the direction from which the storm is approaching and, while not shown, the location of the eye of the storm. Thus, flood levels change due to a variety of factors that are, perhaps, best described in terms of a scenario rather than only in terms of the category of
a storm. Using a system of zones of homogeneous elevation that are overlaid on a surge map to identify those that will be flooded in each scenario is, in our opinion, a more appropriate way to identify which evacuation zones need to be evacuated. Thus, in the system developed in this study, evacuation zones are not identified by risk level a priori, they are identified by average elevation and spatial location only and the position and magnitude of the storm surge determines whether inhabitants are at risk or not.

The proposed methodology developed for delineating the evacuation zones is the primary step in developing the evacuation zones relative to the transportation network. The zones were delineated along some of the major roads, which can as well serve as evacuation routes. As and when new transportation facilities such as new evacuation routes become available, they can be incorporated in the present zone system so as to serve the evacuation traffic better.

The methodology developed can be transferred to the any other location, where hurricanes are predominant. The proposed methodology is responsive to any changes made to serve real time decisions made, based on the changing conditions.

6.3 Future Research

The GIS procedure that was created during this study provides a framework, which may be followed and shared with other researchers in the future. The storm surge model used in the present study does not incorporate accurate elevation values. Therefore one has to subtract the elevation of the land from the maximum potential surge at that particular location to arrive at accurate potential surge values. SLOSH model also does not consider any physical obstructions or any levees, while calculating the maximum potential surge limits. On the other hand, ADCIRC takes these into account and also
incorporate higher accuracy elevation data. Therefore, future research should concentrate on incorporating the ADCIRC model into the methodology. Moreover, LIDAR data is the highly accurate elevation data that is becoming widely available. This data can be used instead of USGS DEMs in delineating the hurricane evacuation zones in the future. Rainfall can be taken into account in future while calculating the inundation, as rain fall at a certain place also contributes to the flooding. The option of using hydrologic boundaries as one of the criteria can also be considered.
References


# Appendix A: Land Use Codes

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>Urban or built-up land</td>
</tr>
<tr>
<td>12</td>
<td>Residential</td>
</tr>
<tr>
<td>13</td>
<td>Commercial and services</td>
</tr>
<tr>
<td>14</td>
<td>Industrial</td>
</tr>
<tr>
<td>15</td>
<td>Transportation, communication, utilities</td>
</tr>
<tr>
<td>16</td>
<td>Industrial and commercial complexes</td>
</tr>
<tr>
<td>17</td>
<td>Mixed urban or built-up land</td>
</tr>
<tr>
<td>18</td>
<td>Other urban or built-up land</td>
</tr>
<tr>
<td>2</td>
<td>Agricultural land</td>
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<tr>
<td>21</td>
<td>Cropland and pasture</td>
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<tr>
<td>22</td>
<td>Orchards, groves, vineyards, nurseries, and ornamental horticultural</td>
</tr>
<tr>
<td>23</td>
<td>Confined feeding operations</td>
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<td>Other agricultural land</td>
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<td>3</td>
<td>Rangeland</td>
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<tr>
<td>31</td>
<td>Herbaceous Rangeland</td>
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<tr>
<td>32</td>
<td>Shrub and brush rangeland</td>
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<tr>
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<td>Mixed rangeland</td>
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<td>Streams and canals</td>
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<td>Lakes</td>
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<td>Reservoirs</td>
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<td>54</td>
<td>Bays and Estuaries</td>
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<td>Nonforested wetland</td>
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<td>71</td>
<td>Dry salt flats</td>
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<tr>
<td>72</td>
<td>Beaches</td>
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<td>Sandy areas not beaches</td>
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<td>Strip mines, quarries, gravel pits</td>
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<td>Transitional areas</td>
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<td>Tundra</td>
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<td>Mixed tundra</td>
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<td>Perennial snow or ice</td>
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<td>91</td>
<td>Perennial snowfields</td>
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<td>92</td>
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</table>
Appendix B: GISDK Program

Macro"Script"
RunMacro("TCB Init")

zipfile = "C:\Nanda_Thesis\Application\nov14\nov14\Sub_Area.DBD"
layers = GetDBLayers(zipfile)
ziplayer = layers[1]

pointfile = "C:\Nanda_Thesis\Application\DEM\Final_Data.CDF"
layers = GetDBLayers(pointfile)
pointlayer = layers[1]

maps = OpenMap("C:\Nanda_Thesis\Application\Sub_Area.map")//this statement opens the map
totalitrations = 25
dim stats[totalitrations]

for totalitr= 1 to totalitrations step 1 do
filename = "C:\Nanda_Thesis\Application\testing_map.dbd"

n = "Merged"+"_"+ IntToString(totalitr-1)
k= "Merged"+"_"+ IntToString(totalitr)

if totalitr=1 then do
   SetLayer("landuse_hwys_zip")
   ColumnAggregate("landuse_hwys_zip",0,"final",{{"[Average Elevation]","AVG","DATA_NEW",}},null)//This statement performs a geographic overlay between two layers and aggregates tabular data
end
else do
   lyr = GetDBLayers(s)

   new_lyr = AddLayer("Sub_Area", n, s, lyr[1])//Adds a layer from a geographic file to a map
   SetLayer(n)//Sets the current layer (and the current view)
   ColumnAggregate(n+","0,"final",{{"[AVERAGE_EL]","AVG","DATA_NEW",}},null)//Performs a geographic overlay between two layers and aggregates tabular data
end
// STEP 1: Fill Dataview for Average Elevation using Tagging

Opts = null

if totalitr= 1 then do
    Opts.Input.[Dataview Set] = {pointfile + "|" + pointlayer,pointlayer}
    Opts.Input.[Tag View Set] = {zipfile + "|" + ziplayer, ziplayer}
    Opts.Global.Fields = {pointlayer + ".Mean"}
    Opts.Global.Method = "Tag"
    Opts.Global.Parameter = {"Value", ziplayer, ziplayer + ".[Average Elevation]"}
end
else do
    Opts.Input.[Dataview Set] = {pointfile + "|" + pointlayer,pointlayer}
    Opts.Input.[Tag View Set] = {s + "|" + n, n}
    Opts.Global.Fields = {pointlayer + ".Mean"}
    Opts.Global.Method = "Tag"
    Opts.Global.Parameter = {"Value", n, n + ".[AVERAGE_EL]"}
end

ret_value = RunMacro("TCB Run Operation", 1, "Fill Dataview", Opts)

// Step 2: Fill Dataview for Square of the difference using formula
Opts = null
Opts.Input.[Dataview Set] =
    {"C:\\Nanda_Thesis\\Application\\DEM\\Final_Data.CDF|final", "final"}
Opts.Global.Fields = {"[(Elevation-Average Elevation)^2]"}
Opts.Global.Method = "Formula"
Opts.Global.Parameter = "pow((DATA_NEW-Mean),2)"
ret_value = RunMacro("TCB Run Operation",1, "Fill Dataview", Opts)

if totalitr= 1 then do
    SetLayer("landuse_hwys_zip")
    ColumnAggregate("landuse_hwys_zip|",0,"final|",{"[Variance]","AVG","[(Elevation-Average Elevation)^2]"},null)
end
else do
    SetLayer(n)
    ColumnAggregate(n + "|",0,"final|",{"[Variance]","AVG","[(Elevation-Average Elevation)^2]"},null)
end
Step 3: Fill Dataview for Standard Deviation using formula

opts = null
if totalitr= 1 then do
    opts.input.[dataview set] = 
        {"C:\Nanda_Thesis\Application\nov14\nov14\Sub_Area.DBD\landuse_hwys_zip", 
         "landuse_hwys_zip"}
    opts.global.fields = {"standard deviation"}
    opts.global.method = "formula"
    opts.global.parameter = "sqrt(variance)"
end
else do
    opts.input.[dataview set] = {s + "|" + n, n}
    opts.global.fields = {"standard_d"
    opts.global.method = "formula"
    opts.global.parameter = "sqrt(variance)"
end

ret_value = runmacro("TCB Run Operation", 1, "Fill Dataview", opts)

if totalitr= 1 then do
    m1 = createadjacencymatrix("landuse_hwys_zip", "zip_adj", 
        {"filename","adj_1.mtx"},"edge",double,"C:\\Program 
        Files\\TransCAD\\","adjacency") //This statement creates an adjacency matrix for an area layer
    current_core = getmatrixcore(m1) //Gets the name of the current core of a matrix
    mc1 = creatematrixcurrency(m1, current_core, null, null.) //Creates a matrix
    currency
    shared d_matrix_options1 //default options used for creating matrix editors
    editor_name1 = creatematrixeditor("New Editor1", m1, 
    d_matrix_options1) //Creates a new matrix editor window
    col_labels1 = getmatrixcolumnlabels(mc1) //Gets an array containing the column labels of a matrix
    row_labels1 = getmatrixrowlabels(mc1) //Gets an array containing the row labels of a matrix
    dim id1[arrraylength(row_labels1)]
    len1 = arraylength(row_labels1) //Computes the number of elements in an array
    for i1=1 to len1 step 1 do
        id1[i1]=stringtoint(row_labels1[i1]) //Converts a string to an integer value
    end
    max1 = realtoint(arraymax(id1)) //Converts a real number to an integer
    dim stdev[max1]
len1 = ArrayLength(row_labels1)

dim countArray[max1]
for i= 1 to max1 step 1 do
    countArray[i]=i
end
for i= 1 to max1 step 1 do
    rh1 = LocateRecord("landuse_hwys_zip", "ID", {countArray[i]}, )
    vals1 = GetRecordValues("landuse_hwys_zip", rh1, {"ID", "Standard Deviation"})
    stdev[i] = vals1[2][2]
end

m1 = CreateAdjacencyMatrix("landuse_hwys_zip", "zip_Adj", {"File Name", "adj_1.mtx"}, "Edge", double, "C:\Program Files\TransCAD\", "Adjacency")
current_core = GetMatrixCore(m1)
mc1 = CreateMatrixCurrency(m1, current_core, null, null,)
shared d_matrix_options1 // default options used for creating matrix editors
editor_name1 = CreateMatrixEditor("New Editor1", m1, d_matrix_options1)
col_labels1 = GetMatrixColumnLabels(mc1)
row_labels1 = GetMatrixRowLabels(mc1)
dim id1[ArrayLength(row_labels1)]
len1 = ArrayLength(row_labels1)
for i=1 to len1 step 1 do
    id1[i]=StringToInt(row_labels1[i])
end
max1 = RealToInt(ArrayMax(id1))
dim avgelv[max1]
len1 = ArrayLength(row_labels1)

dim countArray[max1]
for i= 1 to max1 step 1 do
    countArray[i]=i
end
for i= 1 to max1 step 1 do
    rh1 = LocateRecord("landuse_hwys_zip", "ID", {countArray[i]}, )
    vals1 = GetRecordValues("landuse_hwys_zip", rh1, {"ID", "Average Elevation"})
    avgelv[i] = vals1[2][2]
end
end
else do

    m1 = CreateAdjacencyMatrix(n, "Adj_zip", {"FileName","adj_"+IntToString(totalitr)+".mtx"},"Edge",double,"C:\Program Files\TransCAD\","Adjacency")
    current_core = GetMatrixCore(m1)
    mc1 = CreateMatrixCurrency(m1, current_core, null, null)
    shared d_matrix_options1 // default options used for creating matrix editors
    editor_name1 = CreateMatrixEditor("New Editor1", m1, d_matrix_options1)
    col_labels1 = GetMatrixColumnLabels(mc1)
    row_labels1 = GetMatrixRowLabels(mc1)
    dim id1[ArrayLength(row_labels1)]
    len1 = ArrayLength(row_labels1)
    for i=1 to len1 step 1 do
        id1[i]=StringToInt(row_labels1[i])
    end
    max1 = RealToInt(ArrayMax(id1))
    dim stdev[max1]
    len1 = ArrayLength(row_labels1)
    for i=1 to max1 step 1 do
        countArray[i]=i
    end
    for i=1 to max1 step 1 do
        rh1 = LocateRecord("landuse_hwys_zip", "ID", {countArray[i]}, )
        vals1 = GetRecordValues(n, rh1, {"ID", "STANDARD_D"})
        stdev[i] = vals1[2][2]
    end

end
max1 = RealToInt(ArrayMax(id1))
dim avgelv[max1]
len1 = ArrayLength(row_labels1)

dim countArray[max1]
for i= 1 to max1 step 1 do
countArray[i]=i
end
for i= 1 to max1 step 1 do
   rh1 = LocateRecord("landuse_hwys_zip", "ID", {countArray[i]}, )
   vals1 = GetRecordValues(n, rh1, {"ID", "AVERAGE_EL"})
   avgelv[i] = vals1[2][2]
end

if totalitr=1 then do
   m = OpenMatrix("C:\Program Files\TransCAD\Adj_1.mtx", "False")
   mc = CreateMatrixCurrency(m, "Adjacency", null, null,)
else do
   v= "C:\Program Files\TransCAD\adj_"+IntToString(totalitr)+".mtx"
   m = OpenMatrix(v, "False")
   mc = CreateMatrixCurrency(m, "Adjacency", null, null,)
end

shared d_matrix_options // default options used for creating matrix editors
editor_name = CreateMatrixEditor("New Editor", m, d_matrix_options)
row_labels = GetMatrixRowLabels(mc)
col_labels = GetMatrixColumnLabels(mc)
dim id[ArrayLength(row_labels)]//Declaring an array
len = ArrayLength(row_labels)
for i=1 to len step 1 do
    id[i]=StringToInt(row_labels[i])
end

max = RealToInt(ArrayMax(id))//Converts a real number to an integer value, the integer being the largest value in an array of numbers
dim intersect[max]
dim getintersect_percentile[max*max]
dim getpercentile[max*max]
percentile=0
for row_ID=1 to max step 1 do
    count = 0
dim subintersect[max]
    for column_ID= row_ID to max step 1 do
        dim subsubintersect[4]
        cell_value = GetMatrixValue(mc, IntToString(row_ID),
IntToString(column_ID))
        value = RealToInt(cell_value)
        if value = 1 then do
            count = count + 1
            subsubintersect[1] = row_ID
            subsubintersect[2] = column_ID
            subsubintersect[3] = sqrt(pow(stdev[row_ID],2)+pow(stdev[column_ID],2))/2
            subintersect[count] = subsubintersect
            if subsubintersect[3] != null then do
                percentile = percentile +1
                getintersect_percentile[percentile] = subsubintersect
                getpercentile[percentile] = subsubintersect[3]
            end
        end
        subsubintersect=null
    end
    intersect[row_ID]=subintersect
    subintersect=null
end

sub_array = Subarray(getpercentile, 1, percentile)//Extracts a number of elements from an array
pct_value = Percentile(sub_array, 10)//Returns the value at which a given percentile is reached

dim minperarr[percentile]
minpernum = 0
for i= 1 to percentile step 1 do
    if getintersect_percentile[i][3] < pct_value then do
        minpernum = minpernum + 1
        minperarr[minpernum] = getintersect_percentile[i]
    end
end

dim minelevarr[minpernum]
for i= 1 to minpermun step 1 do
    minelevarr[i] = minperarr[i][4]
end

minelev = ArrayMin(minelevarr)
pos = ArrayPosition(minelevarr, {minelev}, )//Finds the position of a sub-array in an array

if totalitr=1 then do
    rh1 = LocateRecord("landuse_hwys_zip", "ID", 
{IntToString(minperarr[pos][1])}, )
    vals1 = GetRecordValues("landuse_hwys_zip", rh1, {"ID", "County"})
    rh2 = LocateRecord("landuse_hwys_zip", "ID", 
{IntToString(minperarr[pos][2])}, )
    vals2 = GetRecordValues("landuse_hwys_zip", rh2, {"ID", "County"})

    while((vals1[2][2] != vals2[2][2]) & count <= ArrayLength(minelevarr)) do
        minelevarr[pos] = 999.99
        minelev = ArrayMin(minelevarr)
pos = ArrayPosition(minelevarr, {minelev}, )
count=count+1
    end
else do
    rh1 = LocateRecord(n +"|", "ID", 
{IntToString(minperarr[pos][1])}, )
    vals1 = GetRecordValues(n, rh1, {"ID", "County"})
    rh2 = LocateRecord(n +"|", "ID", 
{IntToString(minperarr[pos][2])}, )
    vals2 = GetRecordValues(n, rh2, {"ID", "County"})

    while((vals1[2][2] != vals2[2][2]) & count <= ArrayLength(minelevarr)) do
        minelevarr[pos] = 999.99
        minelev = ArrayMin(minelevarr)
pos = ArrayPosition(minelevarr, {minelev}, )
count=count+1
    end
end

Opts = null
s = Substitute(filename, "map", IntToString(totalitr), 1)
s = Substitute(s, ".dbd", ".dbd\landuse_hwys_zip", 1)

// Fills the dataview for values in 'Merge_To' with values from 'ID' column
if totalitr = 1 then
    Opts = {{"Input", {{"Dataview Set", "C:\Nanda_Thesis\Application\nov14\nov14\Sub_Area.DBD|landuse_hwys_zip", "landuse_hwys_zip"}}}},
    {{"Global", {{"Fields", "Merge_To"}},
        {{"Method", "Formula"}},
        {{"Parameter", "ID"}}}}
else do
    s = Substitute(filename, "map", IntToString(totalitr-1), 1)
s = Substitute(s, ".dbd", "+n", 1)
    Opts = {{"Input", {{"Dataview Set", s+n}}}},
    {{"Global", {{"Fields", "MERGE_TO"}},
        {{"Method", "Formula"}},
        {{"Parameter", "ID"}}}}
end

ret_value = RunMacro("TCB Run Operation", 1, "Fill Dataview", Opts)

if totalitr=1 then do
    SetLayer("landuse_hwys_zip")
    SetView("landuse_hwys_zip")
    rh = ID2RH(minperarr[pos][1])//Converts a map feature ID to a record handle
    SetRecordValues("landuse_hwys_zip", rh, {{"Merge_To", minperarr[pos][1]}})\//Updates the data for a record in a view
    rh1 = ID2RH(minperarr[pos][2])
    SetRecordValues("landuse_hwys_zip", rh1, {{"Merge_To", minperarr[pos][1]}})
end
else do
    SetLayer(n)
    SetView(n)
    rh = ID2RH(minperarr[pos][1])
    SetRecordValues(n, rh, {{"MERGE_TO", minperarr[pos][1]}})
end
rh1 = ID2RH(minperarr[pos][2])
    SetRecordValues(n, rh1, {{"MERGE_TO", minperarr[pos][1]}})
end

s = Substitute(filename, "map", IntToString(totalitr), 1)

// Statements below: creates districts by merging areas from a geographic file, based on
// the value of a field
if totalitr=1 then
    MergeByValue(s,k,"landuse_hwys_zip","Merge_To","DBASE",{{"Area","sum"},
        {"Average Elevation","sum"},{"Variance","sum"},{"Standard Deviation","sum"},
        {"County","dominant"}}, null)
else do
    MergeByValue(s,k,n +"","MERGE_TO","DBASE",{{"Area","sum"},{"AVERAGE_EL","sum"},{"Variance","sum"},
        {"STANDARD_D","sum"},{"County","dominant"}}, null)
end

stats[totalitr] = minperarr[pos]
stats[totalitr][3] = minperarr[pos][3]* minperarr[pos][4]
stats[totalitr][4] = null

end
ShowArray(stats)
endMacro
Appendix C: SLOSH maps for Different Hurricane Scenarios

Storm Surge Map for Scenario 2
Storm Surge Map for Scenario 3
Storm Surge Map for Scenario 4
Storm Surge Map for Scenario 8
Storm Surge Map for Scenario 10
Storm Surge Map for Scenario 11
Vita

Nandagopal Meduri was born in a village near Tanuku, India, in 1977. He received his Bachelor of Engineering for Civil Engineering from Osmania University, India, in 2001. He joined the Louisiana State University in August 2000. He received a degree of Master of Science in Engineering Science in May 2003. He expects to receive the degree of Master of Science in Civil Engineering in May 2004.