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16. Abstract

Road flooding is a serious operational hazard in the low-lying areas of southern Louisiana. This hazard is especially acute for the region's emergency evacuation routes, which must be accessible by coastal residents who plan evacuations ahead of an approaching hurricane. Numerous factors contribute to road flooding during a hurricane. These include road elevations, tidal ranges, winds, storm surge, and storm speed and direction. To enhance the situational awareness and mitigation of these inundation hazards for emergency and operational managers, a decision support tool was developed as a proof-of-concept for identifying the flood hazards of specific road segments vulnerable to hurricane flooding. Additional research was performed to analyze the risks of these hazards to civilian and military vehicles.

Geographic information systems (GIS) software is used to estimate and display storm surge inundation over road surfaces that have flooded in the past. The data utilized for this project included road surface elevations (in feet, NAVD88) of previously flooded, state-maintained highways provided by the Louisiana Department of Transportation & Development (LADOTD), storm surge estimates (in feet, NAVD88) published by the National Weather Service (NWS), and the locations of tide and water gauges maintained by the U.S. Geological Survey (USGS) and the NWS. Attributes depicting worse case hurricane storm surge scenarios were subtracted from road elevations to estimate the water depth over a road surface. Inundation estimates and nearby gauge data were synthesized and accessible using a map interface.

Finally, this report includes a summary of research that analyzed the flood risk associated with vehicle type. The analysis addresses the relationship between flood characteristics (e.g., flowing versus standing water and wind driven water) and the configuration of both civilian and military vehicles (e.g., size, weight, and ground clearance).

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Quantifying the Key Factors that Create Road Flooding

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January 2013

ABSTRACT

Road flooding is a serious operational hazard in the low-lying areas of southern Louisiana. This hazard is especially acute for the region's emergency evacuation routes, which must be accessible by coastal residents who need to evacuate ahead of an approaching hurricane. Numerous factors contribute to road flooding during a hurricane. These include road elevations, tidal ranges, winds, storm speed and direction, and storm surge. In an effort to enhance the situational awareness and improve response and mitigation of these inundation hazards, a decision support tool was developed to identify the flood hazards of specific road segments vulnerable to hurricane flooding. This tool was developed as a proof-of-concept for emergency management and operations managers requiring easy access to these resources during an event.

Geographic information systems (GIS) software is used to estimate and display storm surge inundation over road surfaces that have flooded in the past. Data used for this project include:

- Road surface elevations (in feet, NAVD88) of previously flooded, state-maintained highways provided by the LA Dept. of Transportation & Development (LADOTD)
- Storm surge estimates (in feet, NAVD88) published by the National Weather Service (NWS)
- Tide and water level information obtained from gauges maintained by the U.S. Geological Survey (USGS) and the NWS.

Attributes depicting worse-case hurricane storm surge scenarios were subtracted from road elevation data to estimate the water depth over a road surface. Inundation estimates were made accessible using a common map interface.

To augment the situational awareness provided by the tool, this study concluded with a report summarizing research that analyzed the flood risk relative to civilian and military vehicle types. The analysis addresses the relationship between flood characteristics (e.g., flowing versus standing water and wind driven water) and the configurations of both civilian and military vehicle (e.g., size, weight, and ground clearance).

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IMPLEMENTATION STATEMENT

The decision support mapping tool presented with this report has been developed as a proof of concept for revealing the flooding hazards associated with hurricane storm surge on flood vulnerable, state maintained routes located across southern Louisiana. The provided data and documentation will support decision makers with a simple device for quantifying the key factors that create flood-vulnerable road segments during a hurricane.

Project deliverables are digital and include an ArcGIS version 10.0 (Service Pack 4) map document (*.mxd) for each LADOTD district: 02, 03, 07, 61, and 62. Each map document depicts the selected road segments attributed with *road surface elevations*, *storm surge estimates organized by hurricane scenario*, and *links to tidal and water gauge stations*. The MXD As per the data management recommendations of the LADOTD IT-GIS, this data has been provided in an ESRI file geodatabase (version 10) format. All GIS related deliverables will be maintained according to the standards and practices of the LADOTD IT-GIS.

To ensure a successful utilization of these map documents, the MXDs and related geodatabases should be implemented and maintained relative to the provided directory structure. The directory structure recommended for this project should be maintained accordingly:

root:\\ vector\dotd\ LADOTD_FLOODED_ROUTES_AGL.gdb
root:\\ vector\dotd\ LADOTD_FLOODED_ROUTES_DATUM.gdb
root:\\ vector\dotd\ LDOTD_PMS_2011.gdb
root:\\vector\noaa\ SLOSH_LOUISIANA.gdb
root:\\vector\noaa\eb3meow_AGL.zip
root:\\vector\noaa\eb3meow_datum.zip
root:\\vector\noaa\eb3mom_agl.zip
root:\\vector\noaa\eb3mom_datum.zip
root:\\vector\noaa\lf2meow_AGL.zip
root:\\vector\noaa\lf2meow_datum.zip
root:\\vector\noaa\lf2mom_agl.zip
root:\\vector\noaa\lf2mom_datum.zip
root:\\vector\noaa\ms6meow_AGL.zip
root:\\vector\noaa\ms6meow_datum.zip
root:\\vector\noaa\ms6mom_agl.zip
root:\\vector\noaa\ ms6mom_datum.zip
root:\\District 02 – AGL.mxd
root:\\District 02 – Datum.mxd
root:\\District 03 – AGL.mxd
root:\\District 03 – Datum.mxd
root:\\District 07 – AGL.mxd
root:\\District 07 – Datum.mxd
root:\\District 61 – AGL.mxd
root:\\District 61 – Datum.mxd
root:\\District 62 – AGL.mxd
root:\\District 62 – Datum.mxd

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INTRODUCTION

Road flooding is a serious operational hazard for the many low-lying areas across southern Louisiana. The consequences are especially acute during hurricane season when emergency evacuation routes must be clear to allow for the safe evacuation of coastal residents ahead of an incoming storm. To mitigate the risk of flooding during hurricanes, emergency managers and decision-makers use situational awareness to acquire a synoptic understanding of the key factors and conditions that contribute to inundated roads [*1*].

Several hazards are associated with road flooding. The first identifies the flood risk relative to a vehicle type. This requires an assessment of the conditions in which flooding becomes a travel hazard. Such conditions include the relationship between the flood depth and velocity and the vehicle's weight, shape, and ground clearance. Additional hazards include the conditions that contribute to the flooding of land surfaces from hurricanes. Factors include tidal ranges, wave effects, wind speed, storm surge, and storm speed and direction. Many of these factors are deterministic and can be derived from available coastal weather services. Hurricane storm characteristics such as forward velocity, direction, intensity, and surge are deterministically modeled by the National Hurricane Center (NHC) and provided as a geospatial data product distributed for approaching storms at specified intervals.

Accordingly, a near real-time, data-driven decision support tool was developed as a proof of concept to evaluate the parameters and workflows that support mitigation and response strategies for state maintained routes vulnerable during hurricane induced flooding. This document details the scope, methodologies, and implementation requirements for deploying this tool at the LADOTD. It concludes with a summary of research and analysis for determining flood risk to vehicles relative to flood scenarios.

OBJECTIVE

The fundamental objective for this study was to perform the research and develop techniques for quantifying the key factors that contribute to road flooding and a vehicle's flood risk. As a proof-of-concept, this study first developed a comprehensive, data-driven operational instrument capable of synthesizing the key factors and conditions that contribute to the flood risks on state maintained roads across south Louisiana. To provide effective situational awareness for such events, hurricane storm surge hazards on flood-vulnerable, state maintained routes were quantified and compiled using geographic information systems software. The tool will support decision-makers with a simple device for identifying and assessing the flood potential over vulnerable road segments during a hurricane. This study assessed the relationship between flood characteristics (e.g., flowing versus standing water and wind driven water) and vehicle class (e.g., size, weight, clearance, etc.).

SCOPE

The project will be executed in three phases. First, the potential inundation hazards will be compiled and computed for flood-vulnerable, state-maintained routes in five LADOTD districts in southern Louisiana. Second, a decision support tool that synthesizes these flood hazards will be developed as a proof-of-concept to validate the techniques for calculating and representing inundated road surfaces. Finally, research will assess vulnerabilities and risks associated with vehicle type and flooded roads.

Inundation Estimates: The potential inundation hazard for state-maintained routes in southern Louisiana will be computed by subtracting road elevation from modeled estimates of hurricane-induced storm surge. Elevations will be based on the LADOTD ARAN data.

Decision Support Tool: The operational instrument designed for this project will parameterize multiple factors contributing to road flooding during a hurricane: (1) road surface elevations, (2) storm surge inundation estimates, and (3) real-time water level observations obtained from near-by water and/or tide gauge facilities. A geographic information systems (GIS) software platform will be used to quantify, qualify, and display the estimated inundation over roads identified by the LADOTD as being vulnerable to hurricane induced storm surge.

Vehicle Flood Risk Analysis: The research will conclude with a risk analysis of flood hazards associated with vehicle type. The analysis will address the relationship between flood characteristics (e.g., flowing versus standing water) and vehicle type (civilian and military class vehicles) to determine the vehicle’s flood risk.

To establish and ensure a foundation for reproducible decision support instrument, the data used for this study will originate from appropriates sources that correspond to the following criteria:

- Data must originate from authoritative sources;
- Data must be available in near-real-time;
- Data must be available 24/7/365;
- Data should be easily accessible via the Internet; and
- Data should have redundant (i.e., backup) sources whenever possible.

The data and tools will be provided digitally (e.g., hard drive and DVD-ROM) as ArcGIS Desktop version 10.0 map document (*.mxd) files and file geodatabases (*.gdb). Deliverables will include:

- Compilation of various NWS storm surge modeled products for coastal Louisiana.
- Road surface elevations for each flooded road segment identified by the LADOTD.
- Decision support model, formatted in a map interface, which incorporates all combinations of storm scenarios, as defined in accordance with the project objectives and NWS storm surge data.
- Each flooded road segment will be attributed with the sources of corresponding data (e.g., road surface elevations, surge estimates, and nearest water gauge resource).

METHODOLOGY

In accordance with the scope and objectives established above, the techniques employed for this project have been organized into four primary development phases: (1) data collection and processing; (2) inundation modeling; (3) decision support tool implementation; and (4) assessment of vehicle vulnerability relative to flood risk.

Data Collection & Processing

The data requirements for computing and quantifying hurricane induced flood hazards over road segments are summarized accordingly:

- elevations of select LADOTD routes that are vulnerable to storm surge;
- hurricane induced storm surge estimates relative to storm intensity, forward velocity, direction, and tide stage;
- and links to real-time water level observations from water/tide gauges;

Road Data

Inundation from hurricane induced storm surge was computed and quantified for select LADOTD roads, which were chosen due to their vulnerability to flooding.

Pavement Management System (PMS). State-maintained road survey data were provided by the LADOTD Pavement Management Systems (PMS), Section 21.

The road data was comprised of 4.42 million records stored within 13 Microsoft® Access databases. The data indicated publication during the first half of State fiscal year 2011. The databases represented the five LADOTD districts corresponding to the southern parishes of the state: Districts 02, 03, 07, 61, and 62. With the exception of District 61, three databases were provided for each district: *frontage routes*, *off-system national highway system routes*, and *state maintained routes* (e.g., Interstate, US, and LA). Only the *state maintained routes* database was provided for District 61. Table 5 in the appendix lists the attribute field names and descriptions that were provided with the PMS databases. Point features representing the PMS data were saved in an ArcGIS version 10.0 file geodatabase labeled, "LDOTD_PMS_2011."

Routes Subject to Inundation by Storm Surge. A list of 88 routes identified as vulnerable to storm surge was provided by the LADOTD Office of Operations.

The list was provided as a Microsoft® Excel worksheet, which had a publication date of August 23, 2010. The vulnerable routes were arranged by *District*, *Parish*, *Route name* and *number*, and *Description of location* (e.g., control section, log mile, and other pertinent attributes). Table 6 in the appendix lists the vulnerable routes used in this study.

The select PMS road observation data that are vulnerable to flooding was compiled and saved as point feature GIS data types.

Of the 88 surge-vulnerable routes listed in the Excel worksheet, 86 (~98%) were successfully identified from the PMS data. Routes that could not be identified or located included portions of US 11 in Orleans and portions of US 61 in St. Charles parishes. As depicted in Figure 1, vulnerable routes were extracted, arranged by district, and converted into point features using ArcGIS™ Desktop software published by ESRI®. A total of 316, 907 point features were saved within two ArcGIS file geodatabases labeled using the prefix, "LDOTD_FLOODED_ROUTES_".

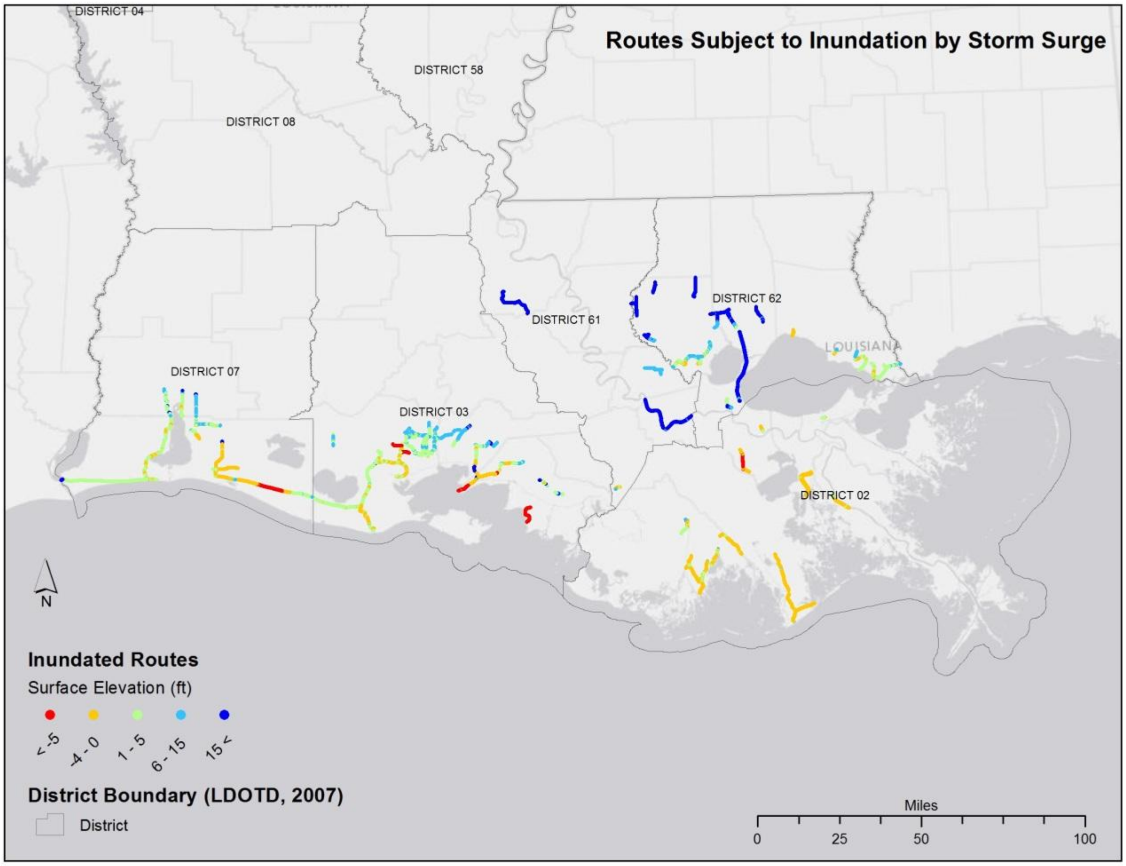


Figure 1
Routes subject to inundation by storm surge

Storm Surge Data

The potential flood heights from hurricane induced storm surge was acquired and used to estimate inundation over flood-vulnerable, state-maintained routes.

SLOSH Storm Surge Models. Storm surge estimates were extracted from the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) modeled data products published by the National Weather Service (NWS) and maintained by the National Hurricane Center (NHC).

The SLOSH storm surge models provide hazards analysis and operational guidance by simulating storm surge flooding based on historical, hypothetical, and forecast hurricane scenarios. Surge height estimates were derived using an ensemble of statistical and deterministic models designed to relate surge inundation with empirical and theoretical characteristics of meteorological and physical phenomena [*2*], [3]. Such estimates represent the relative surge potential for a given geographical region, referred to as a basin (Figure 2).

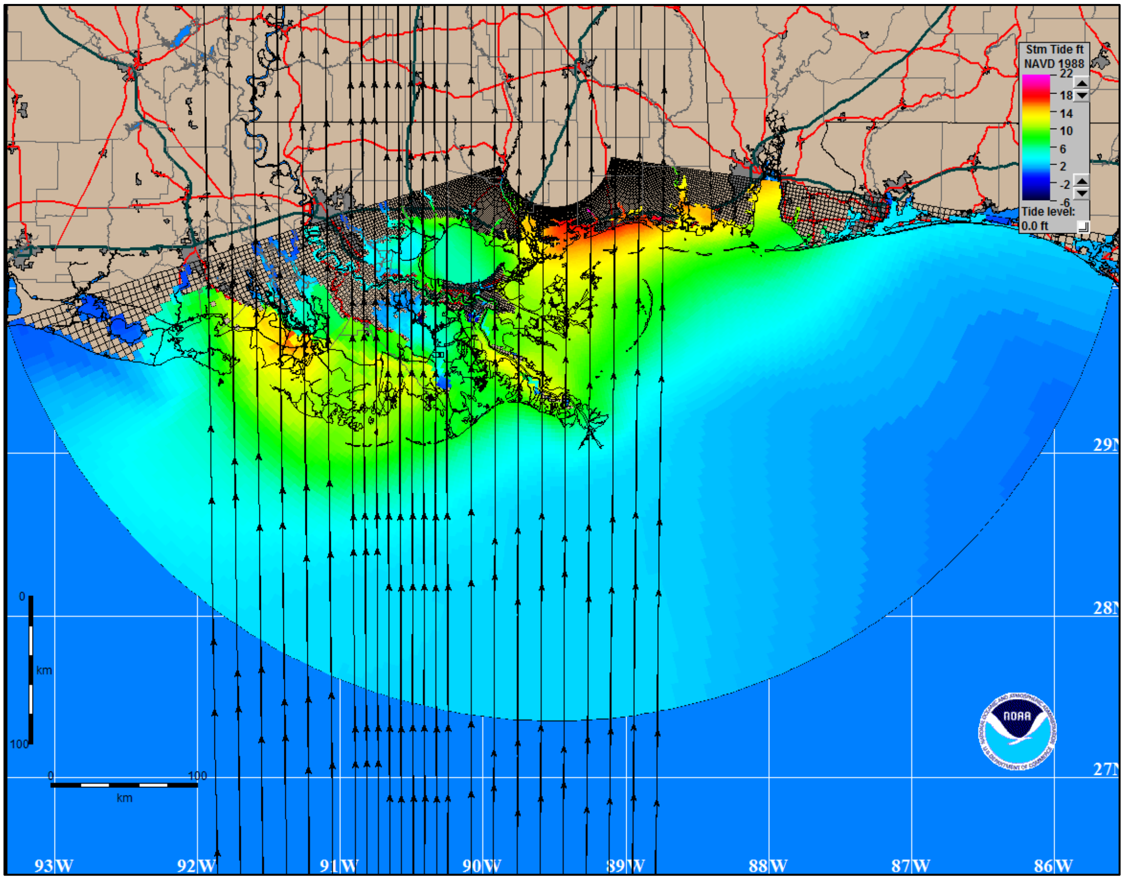


Figure 2
SLOSH storm surge model for the New Orleans, LA, basin

All SLOSH data products included with this project were provided as polygon feature classes. Features, organized by SLOSH basin, were saved in an ArcGIS file geodatabase labeled, "SLOSH_LOUISIANA."

SLOSH Basins. Three SLOSH basins are available for Louisiana: *New Orleans*, *Vermilion Bay*, and *Sabine Lake* (Figure 3).

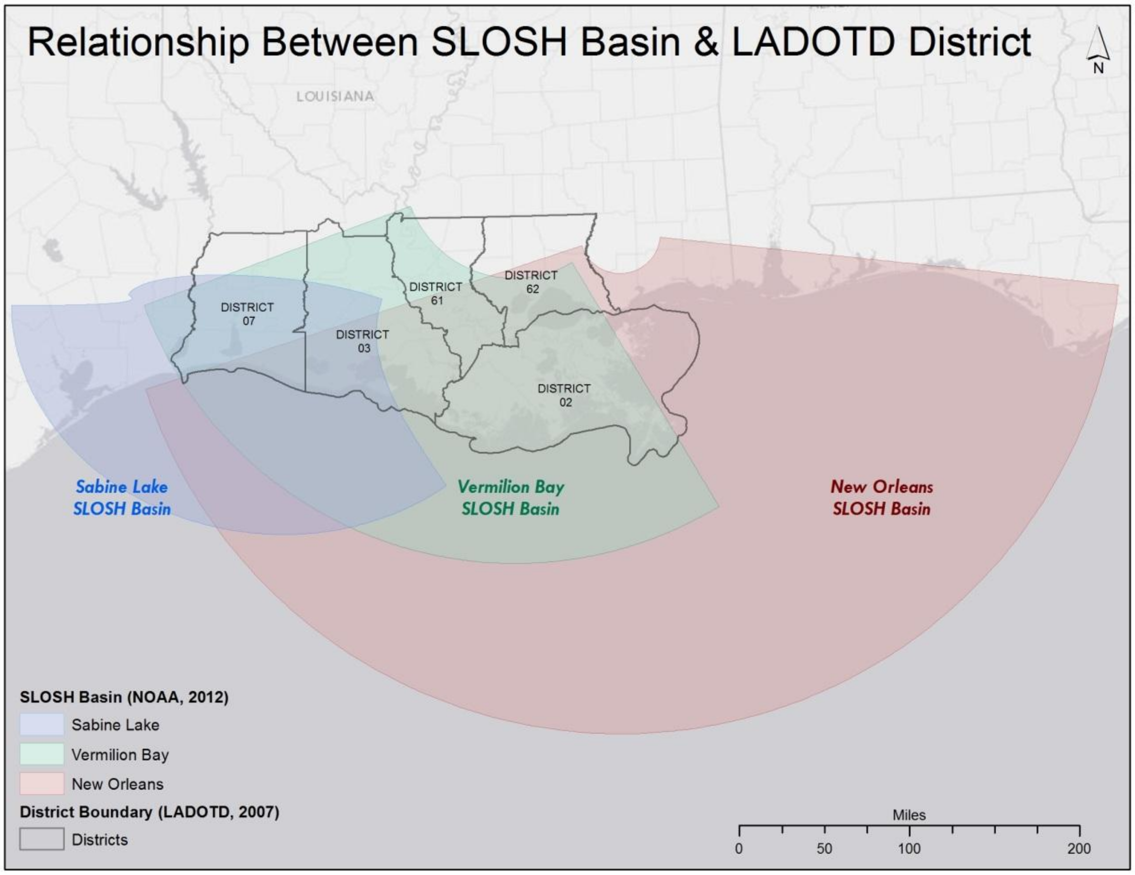


Figure 3
Distribution of SLOSH basins and districts

SLOSH surge basins are typically represented as either polar or hyperbolic grids centered over select coastal areas [*3*]. Surge heights are computed for each grid cell in a given basin and relative to various hurricane scenarios. Grid cells vary in size, thus providing higher resolution estimates, which are computed for areas of greater significance (e.g., communities, coastlines, and bays) when compared to areas of less significance (e.g., open water). In order to account for the physical and hydrographic features that influence surge (e.g., hurricane protection levees and water bodies); basin grids are assigned relative elevation values using contemporary topographic and bathymetric data available for the region. To ensure constancy across all modeled output, SLOSH basins reference elevations.

SLOSH MEOW and MOM Data Products. The SLOSH surge products were selected to compute inundation levels for the surge-vulnerable routes used in this study. The SLOSH storm surge model provides two composite data products: the Maximum Envelope of Water (MEOW) and Maximum of MEOWs (MOM). The MEOW provides surge estimates over a given basin relative to simulated storm conditions. Simulation parameters include storm category, forward velocity, direction, and tide level. As many as 360 surge estimates may be derived for a single SLOSH MEOW basin, each depicting various combinations of the simulated parameters. The MOM surge product represents a composite of maximum inundation estimates simulated by a MEOWs for a given storm category. Accordingly, there are only five MOMs per SLOSH basin, one for each storm category. Because the MOM forecasts the maximum inundation as an aggregate of MEOW simulations, it effectively overestimates the surge within a given grid cell.

For both the MEOW and MOM surge products, surge height values can range from 0.0 – 90.0 feet, and are represented as real data types measured to one decimal place. Whenever surge is not predicted for a given cell (i.e., dry land), a 99.9 real-type value is assigned. All surge height estimates are provided in US Feet, and are referenced to either surge above ground level (AGL) or surge above the reference datum (e.g., NAVD-88). Both reference measurements have favorable and unfavorable characteristics. As such, readers are encouraged to research the differences at the SLOSH Web site *[4]*. Because of the implicit uncertainties associated with such estimates, SLOSH products for both AGL and NAVD-88 datum references have been included as deliverables for this project.

Given the sheer quantity of MEOW products available, the data and analysis provided for this project was limited to the following modeled parameterizations:

- Tide Stage (e.g., Mean or High Tide)
- Storm Direction (e.g., North West, North, or North East)
- Storm Velocity (e.g., 5 mph, 15 mph, or 25 mph)
- Storm Intensity (e.g., Categories 1- 5, as defined by the Saffir-Simpson hurricane wind scale)
- Basin geometry (e.g., New Orleans, Vermilion Bay, and Sabine Lake).

Real-time Water Gauge Data

Gauge data for tide stations and monitored water bodies were compiled and georeferenced for use in this project.

Real-time Water Level Observations. Real-time water level data are acquired for gauges maintained by the U.S. Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA).

Gauge data and station information published by the USGS National Water Information System (http://waterdata.usgs.gov/la/nwis/rt) and the NOAA Center for Operational Oceanographic Products and Services (CO-OPS; http://tidesandcurrents.noaa.gov/) for southern Louisiana were geocoded using ArcGIS version 10 (service pack 4) desktop software and referenced to decimal degree geographic coordinate system, NAD83. Water level gauge data includes the following attributes:

- Gauge name and ID
- Description
- Management agency (e.g., NOAA or USGS)
- Web address (i.e., URL) to real-time measurements
- Distance in miles to the nearest tide and/or water gauge.

Note: Internet access is required when connecting to the real-time gauge data via the Web address.

Data Management

The PMS data used for this project were sorted by district and road type (e.g., frontage roads, off-system National Highway System, and state maintained routes) and saved as point features in the ArcGIS version 10.0 (service pack 4) file geodatabase, labeled, "LDOTD_PMS_2011." Horizontal positions for the point features are stored as decimal degrees in the geographic coordinate system (GCS), NAD-88. Vertical measurements (i.e., elevations and surge heights) were calculated and are maintained in US Feet, relative to NAVD-88.

The file ArcGIS geodatabase, "SLOSH_LOUISIANA" stores the MEOW and MOM feature classes used to compile storm surge and inundation. Both the AGL and datum referenced surge models have been included. All MEOW data products are referenced to geographic coordinates, NAD-83, in decimal degree units. With the exception of the Sabine Lake, all MOM surge products use the same GCS NAD-83 coordinate system as the MEOW features. However, the Sabine Lake MOM is referenced to NAD-27.

Finally, a single feature data set containing the geocoded locations of real-time water gauge facilities was saved with the inundation model output, which will be discussed in the next section. Horizontal coordinates used for this dataset were fixed to the Universal Transverse Mercator (UTM) coordinate system, zone 15-north, NAD-83.

Inundation Modeling

Inundation values were calculated using the maximum SLOSH MEOW surge heights estimates above the surge-vulnerable routes. Real-time water level observations from near-by gauge facilities were assigned to the road points using a proximity analysis tool. The modeled outputs derived are compiled and maintained within a file geodatabase.

Inundation Calculations

A road will become inundated once its elevation is exceeded by flood waters. Simplistically, inundation over a road surface, F_r, can be estimated as the sum of three contributing factors to flooding:

$$F_r = Z_r - (Z_w + T_z + S_z) \tag{1}$$

Where, Z_r is the road surface elevation, Z_w is the vertical wave height increment, T_z is the tide stage, and S_z is the maximum estimated surge height.

Of these variables, the estimated effects resulting from wave action was excluded from this model, with prejudice. The initial rationale for using wave action was to account for waves breaking over and covering the road surface during surge event. However, the ability to accurately and consistently detect the wave heights was problematic. First, few sensors capable of providing this information exist in the region. Second, the spatial resolution for most mathematical wave-action models were too coarse (e.g., 250,000 km^2) for utilization in the region. Accordingly, only the LADOTD road surface elevations and SLOSH MEOW storm surge (which implicitly incorporates tide stage) were parameterized for this proof-of-concept.

As per guidance from the NWS, the maximum forecasted storm surge estimated from the three SLOSH MEOW basins had to be computed and assigned to the surge-vulnerable road features. In order to more effectively perform the computations, the surge-vulnerable road observations were subset into LADOTD districts.

Calculating and Assigning Inundation. Values were computed and assigned to each road feature in three steps: (1) determining the maximum surge over the vulnerable routes, (2) computing the inundation, and (3) re-combining the estimates with point feature data set. For each road point feature in a given district, the maximum surge height estimated of the three SLOSH MEOWs was conditionally determined and used to compute the road surface inundation as follows:

1) MEOW surge heights for each SLOSH basin were assigned to spatially coincident road point features using the *Spatial Join* tool provided with ArcGIS software. Because a SLOSH basin covered one or many LADOTD districts (see Figure 3), a total of twelve unique point feature data sets were created:
    a. two each for Districts 02, 61 and 62 (total of six)

    b. three each for District 03 and 07 (total of six)

2) The attribute tables for each of the twelve road point feature data sets were imported into a Microsoft Access database. For each district, a custom query was created to synthesize the attributes of the multiple data sets into a single table depicting the maximum inundation for a point feature.
    a. The maximum surge estimate for a particular basin was conditionally determined using a customized Visual Basic scripted module.
    b. Surge inundation was estimated by subtracting the point feature elevation from the maximum surge estimate.
3) The synthesized attribute table was exported from Microsoft Access and re-combined with the point feature data sets. A total of five surge-vulnerable road point feature classes were generated, one for each LADOTD district in this study:
    a. District_02_Inundated_Routes
    b. District_03_Inundated_Routes
    c. District_07_Inundated_Routes
    d. District_61_Inundated_Routes
    e. District_62_Inundated_Routes

Assigning Gauges to Point Features

The distances from each road point feature to the nearest real-time water level facilities were computed using the *Near* analysis tool available within ArcGIS. This step associated the facility name, ID, management agency, web address, and proximity (in miles) of each gauge to each road point feature.

Determining and Assigning the Near-by Gauge Facilities. For each road point feature, the nearest water or tide gauge facility was assigned using a proximity analysis tool. Gauge attributes, including the URL (i.e., Web link) to the real-time content, are added the road features.

Modeled Output and Data Management

For each of the five point feature class generated, a total of 110 attributes representing surge-vulnerable routes, maximum inundation estimates, and water gauge elements were compiled. In addition to the two default attributes added by ArcGIS software (OBJECTID and Shape), these attributes included:

1) **Surge-Vulnerable Route Information** (13 field attributes):
    a. File Name (FILENAME)
    b. Control Section (CSECT)
    c. Route Name and Number (ROUTE)

    d. Direction (DIRECTION)
    e. Original Direct (ORIG_DIRECTION)
    f. Latitude (V_LATITUDE)
    g. Longitude (V_LONGITUDE)
    h. Road Elevation (V_ELEV)
    i. Control Section Log Mile of Subsection (FOFFSETFR)
    j. ARAN Begin Chain (FBEGCHAIN)
    k. Video Image File (ROWPATH)
    l. Lead in and out code(LEAD)

2) **Storm Surge Inundation Estimates** (90 field attributes):
    a. Inundation estimate (feet, NAVD-88). Field name constructed relative to the hurricane scenario, which is based on:
        - Storm Direction : North (N), North East (NE), and North West(NW)
        - Saffir-Simpson Storm Category: 1,2,3,4, or 5
        - Storm Forward Velocity (mph): 05, 15, or 25
        - Tide Stage: average-tide (i0) or high-tide (i2)
    b. For Example: a north-bound, Category-1 storm traveling at 15mph at high-tide would be labeled: *N115i2*

3) **Nearest Water or Tide Gauge Facility Content** (5 field attributes):
    a. Gauge Name (GAUGE_NAME)
    b. Gauge Description (GAUGE_DESC)
    c. Gauge Agency (GAUGE_AGENCY)
    d. Web Address to Real-time Gauge Data (GAUGE_URL)
    e. Gauge Distance (miles) from Current Point Feature (GAUGE_DIST)

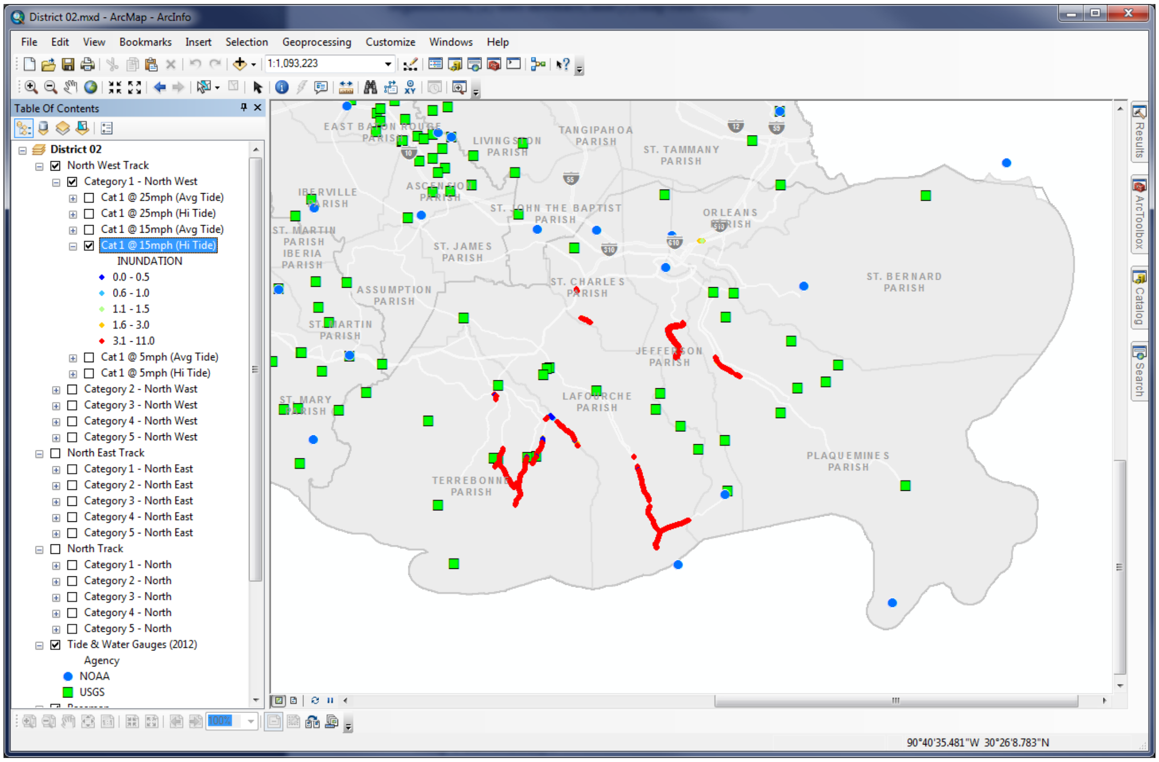
These five feature classes have been stored within an ArcGIS version 10.0 (service pack 4) file geo-database labeled with the prefix, "LDOTD_FLOODED_ROUTES_". Two versions were compiled to represent the AGL and DATUM vertical references (see SLOSH discussion). Horizontal units stored in meters and referenced to the UTM coordinate system, zone 15-north, NAD-83.

Decision Support Tool Implementation

In accordance with the scope and objectives defined for this project, the operational requirements for this instrument were designed and implemented according to (1) map organization and (2) user interface and functionality.

Map Organization

The decision support tool developed for this project is powered by the ArcGIS Desktop version 10.0 (service pack 4) platform. The data collected and compiled for this project have been organized and assembled by district and stored as ArcGIS map documents (Figure 4).



- District 02
  - ☑ North West Track
    - ☑ Category 1 - North West
      - ☐ Cat 1 @ 25mph (Avg Tide)
      - ☐ Cat 1 @ 25mph (Hi Tide)
      - ☐ Cat 1 @ 15mph (Avg Tide)
      - ☑ Cat 1 @ 15mph (Hi Tide)
        - INUNDATION
        - ◆ 0.0 - 0.5
        - ◆ 0.6 - 1.0
        - ◆ 1.1 - 1.5
        - ◆ 1.6 - 3.0
        - ◆ 3.1 - 11.0
      - ☐ Cat 1 @ 5mph (Avg Tide)
      - ☐ Cat 1 @ 5mph (Hi Tide)
    - ☐ Category 2 - North Wast
    - ☐ Category 3 - North West
    - ☐ Category 4 - North West
    - ☐ Category 5 - North West
  - ☐ North East Track
    - ☐ Category 1 - North East
    - ☐ Category 2 - North East
    - ☐ Category 3 - North East
    - ☐ Category 4 - North East
    - ☐ Category 5 - North East
  - ☐ North Track
    - ☐ Category 1 - North
    - ☐ Category 2 - North
    - ☐ Category 3 - North
    - ☐ Category 4 - North
    - ☐ Category 5 - North
  - ☑ Tide & Water Gauges (2012)
    - Agency
    - ● NOAA
    - 🟩 USGS

Figure 4
An ArcGIS map document depicting the estimated inundation risk for roads in District-02

Five map documents (i.e., MXD) were created for each LADOTD District in southern Louisiana: 02, 03, 07, 61, and 62. Each MXD contains two categories of data that are defined according to function: *actionable* and *basemap* layer types.

- Actionable data include the (a) surge-vulnerable road features and (b) tide and water gauge locations.
- Basemap layers include (a) major highways and interstates, (b) the five southern LADOTD districts, and (c) the twenty-six parishes that comprise south Louisiana. No additional data is required to utilize the map document.

Actionable Data Layers. Actionable data layers include surge-vulnerable road features and water/tide gauge locations.

<u>Surge-vulnerable road features</u> were hierarchically organized into three principal groups defined relative to the hurricane storm scenario:

- Storm track (north, north east, or north west)
  - Saffir-Simpson hurricane category (1-5)
    - Forward speed (5, 15, or 25 mph) and Tide stage (average or high tide).

Surge-vulnerable roads were represented as point features. Each point was labeled relative to storm category, speed, and tide stage. Features were thematically symbolized according to inundation (feet) above the road surface. In order to support comparisons across hurricane surge scenario, all point features were symbolized and categorized identically.

For each hurricane scenario, road features were symbolized according to inundation (feet) above the road surface. Five symbol levels were applied:

- < 0.5 ft. (blue)
- 0.5 – 1.0 ft.
- 1.0 – 1.5 ft.
-
- 1.5 – 3.0 ft.
- > 3.0 ft. (red)

Note: only those roads with predicted surge heights are visible.

The real-time water level gauge data were geocoded and represented as point features symbolized according to agency name (e.g., NOAA or USGS).

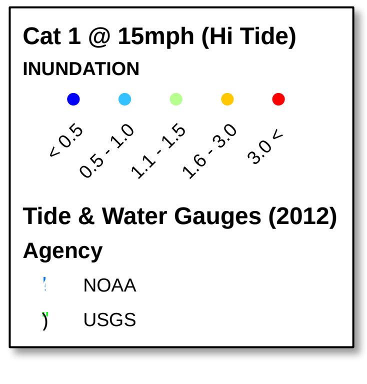


Figure 5
Example symbology

Basemap Data Layers. To provide geographic context, reference information including roads, parishes, and district boundaries were included with each MXD:

- major highways and interstates line features,
- LADOTD district boundary polygons, and
- Twenty-six southern Louisiana parish boundary polygon features

No additional data is required to utilize the map document. However, end-users may discretionarily add additional reference data as needed.

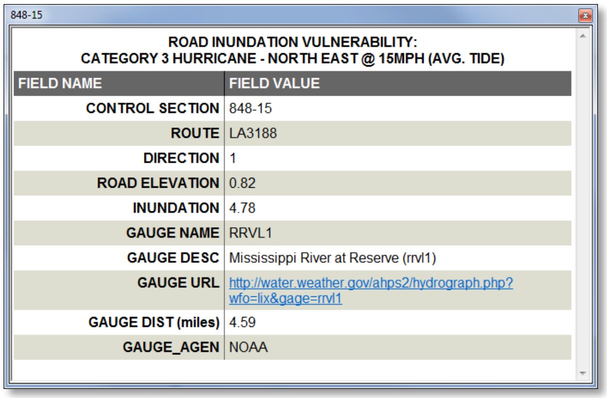
User Interface & Functionality

As noted earlier, the user interface (UI) for this decision support tool is ArcGIS desktop. ArcGIS serves as the management platform for presenting the various combinations of inundation over surge-vulnerable routes (see Figure 4).

Available Map Tools. Users can interact and manipulate the map content using the default pan, zoom, and identify tools. Additionally, the "HTML Popup" has been enabled within a custom interface for convenient assessment of the inundation conditions (right). Tool tips are also enabled for convenience.

Map Functions are summarized accordingly:

- Map Manipulation: Users interact with the map according to the default capabilities of ArcMap
    - pan, zoom-in, zoom-out, etc.
- Information Retrieval: Conditions at each point feature will be accessible via the HTML Pop-Up Identify Tool that is provided with the ArcGIS software:
    - Identify and display the attributes for any point using the Identify and HTML Pop-Up tools. Information returned to the user will include (Figure 5):
        - Route Name/Number
        - District Location
        - Road Elevation (feet).
        - Estimated Surge Height (feet).
        - Direct Link to Nearest NOAA Tide Gauge
        - Direct Link to Nearest USGS Tide Gauge
- Map Bookmarks: Bookmarks are provided to zoom-to the full extents of the district, the parishes with vulnerable roads, or the individual routes.



ROAD INUNDATION VULNERABILITY:
CATEGORY 3 HURRICANE - NORTH EAST @ 15MPH (AVG. TIDE)

FIELD NAME	FIELD VALUE
CONTROL SECTION	848-15
ROUTE	LA3188
DIRECTION	1
ROAD ELEVATION	0.82
INUNDATION	4.78
GAUGE NAME	RRVL1
GAUGE DESC	Mississippi River at Reserve (rrvl1)
GAUGE URL	http://water.weather.gov/ahps2/hydrograph.php?wfo=lix&gage=rrvl1
GAUGE DIST (miles)	4.59
GAUGE_AGEN	NOAA

Figure 6
Example of "HTML Popup"

Vehicle Vulnerability to Flood Risk

According to data published by the Federal Emergency Management Agency (FEMA) and the NWS, nearly half of all flood fatalities in the United States are vehicle related [5], [6]. To mitigate the consequences and ensure a consistent message for the general public, research has been performed analyzing the flood risks for specific vehicle classes. However, a basic approach for measuring the impact of floodwaters on a vehicle requires the parameterization of key factors:

- *buoyancy* of an object in water,
- *lateral forces* of water exerted on objects, and
- *friction* of wet road surfaces.

As per Archimedes' principle, the buoyant force exerted by a fluid on an object is equal to the weight of the fluid displaced by that object. Water weighs approximately 62.4 lbs./ft^3.

For each foot of rise, the average car may displace approximately 1,500 lbs. of water (NOAA, 2008). A vehicle will begin to 'float' when the weight of the water it displaces exceeds the weight of the vehicle, or neutral buoyancy.

A second hazard associated with floodwaters is the lateral forces exerted by the flow. Estimates published by FEMA and NWS indicate that floodwaters will typically flow between 6 to 12 miles per hour (mph). The water's momentum is easily transferred to any vehicle stalled in the water. For each foot of rise, up to 500 lbs. of lateral force may be applied to the vehicle *[7]*.

A vehicle's vulnerability is proportional to the amount of water and ground clearance above that water. As water levels increase, the friction of road surfaces decreases. Vehicle instability increases as surface friction decreases, effectively making automobiles more susceptible to the lateral forces of the water acting against them. The constant coefficient of friction for automobile tires in wet conditions has been estimated to be 0.4 *[8]*.

Computing Vehicle Risk to Flooding

A simplistic, yet comprehensive, approach for computing vehicle risk follows a three-stage conditional function in which the buoyancy, friction forces, and lateral forces are combined *[9]*. First, the net weight of a vehicle is reduced according to the weight displaced by the rising water (i.e., buoyancy). Second, the lateral forces of the water on the vehicle are computed. Third, the friction force of the vehicle is estimated. Ultimately, the vehicle is considered to be destabilized and at risk when lateral forces of the water exceed the friction force.

Computing Vehicle Buoyancy. The apparent weight of an immersed vehicle, W_B, is computed according to the difference between the weight of the vehicle, W_v, and the product of the vehicle area (length x width), A_v, the net depth of water impacting the vehicle, Z_w (i.e., the difference between actual flood height and the vehicle's ground clearance), and water's weight per volume (i.e., density), ρ_w.

$$W_B = W_v - (A_v \cdot Z_w \cdot \rho_w) \tag{2}$$

Computing Lateral Force of Water. To compute the added effects of moving water, calculations must account for the force of the water moving against the vehicle, the weight of the vehicle, and the drag forces of the vehicle within the water.

As per Blasé Pascal's Second Law, the force of water, F_w, exerted on an object is computed using the dynamic hydrostatic pressure of water, P_{dw}, moving horizontally against (i.e., perpendicular to) the submerged surface area of the object, A_z [equation (2)]:

$$F_w = (P_{dw} \cdot A_z) \tag{3}$$

where the dynamic hydrostatic pressure of water, P_{dw}, is the product of a constant density value of water on a square object, k, and the squared velocity of the water, V, on the object. Equation (4) estimates the dynamic hydrostatic pressure is:

$$P_{dw} = k \cdot V_w^2 \tag{4}$$

where the constant value, k, has been determined by the American Association of State Highway and Transportation Officials (AASHTO) to be 1.4 lbs./ft^3 [*10*].

Computing Friction Force. The force applied to a vehicle necessary to overcome its static inertia is dependent on both the friction forces keeping the vehicle still and the lateral forces of the water incident to the vehicle's surface area. The friction force of a vehicle, F_f, is the product of the coefficient of friction for a wet road surface, C_f, and the apparent weight of an immersed vehicle, W_B [equation (1)]:

$$F_f = C_f \cdot W_B \tag{5}$$

where, the value for the coefficient for friction of a wet surface has been determined to be 0.4.

Assessing Vehicle Risk. Finally, the risk assessed for a stalled vehicle in moving flood waters can be assessed by combining equations (1) through (4):

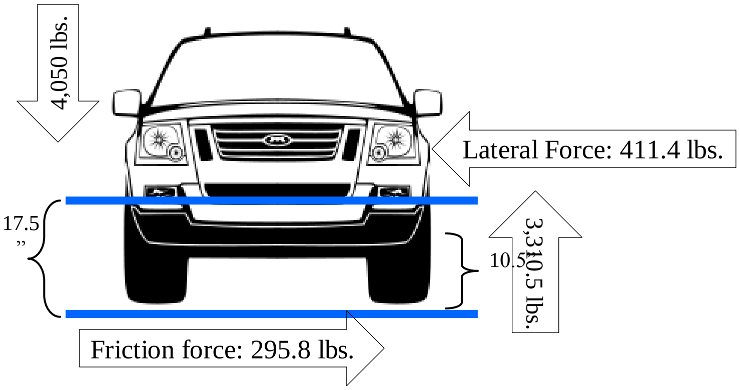
$$\text{Lateral Force of Water } (F_w) \geq \text{Friction Force } (F_f) \tag{6}$$

from which vehicle risk is assessed if the lateral force, F_w, of the floodwaters exceeds the friction forces, F_f, keeping the vehicle immobile.

<u>**Note**</u>: For more information on these equations, readers are encouraged to see the presentation, "Flood Physics" by Steve Waters (2004), senior hydrologist of the flood warning/water quality branch of the Maricopa County flood control district in Arizona.

Example Risk Assessment

Consider a scenario in which a Sport Utility Vehicle (SUV) weighing 4,050 lbs. is stalled in 17.5 inches of flood waters moving laterally at 6 feet-per-second. Vehicle risk can be calculated following equations (1) through (5).



- Width = 6.5 ft.
- Length = 14 ft.
- Clearance = 10.5 in.
- Weight = 4,050 lbs.
- Flood Depth = 17.5 in.
- Submerged Depth = 0.583 ft.
- Water Velocity = 6 ft. sec.^{-1}

Figure 7
Vehicle stalled in flood waters moving at 6 feet per second

Vehicle Buoyancy: (equation 1)	$W_B = W_v - (A_v \cdot Z_w \cdot \rho_w)$ $W_B = 4050\text{lbs} - [(6.5\text{ft} \cdot 14\text{ft}) \cdot (0.583\text{ft}) \cdot (62.4 \text{ lbs./ft}^3)]$ $B = 4{,}050\text{lbs} - 3{,}310.5\text{lbs}$ $W_B = 739.5$ lbs.
Lateral Force of Water: (equations 2 & 3)	$F_w = (P_w \cdot A_z)$ where $P_w = k \cdot V_w^2$ $F_w = [1.4 \cdot (6 \text{ ft./sec})^2] \cdot (14\text{ft} \cdot 0.583\text{ft})$ $F_w = 411.4 \text{ lbs. ft. sec}^{-2}$
Friction Force: (equation 4)	$F_f = C_f \cdot W_B$ $F_f = 0.4 \cdot 739.5\text{lbs}$ $F_f = 295.8$ lbs.
Assessing Vehicle Risk: (equation 5)	$F_w > F_f$ 411.4 lbs. > 295.8 lbs. *the vehicle is at risk*

Vehicle Classification Data

Knowledge of the potential vulnerabilities and consequences to vehicles during flood conditions is instrumental for emergency responders and decision makers. In order to compute the relative flood risk to a vehicle, the unique characteristics for both civilian and military vehicles were parameterized and applied to the formulae defined above. Vehicle specifications published by the American National Standards Institute (ANSI), the Environmental Protection Agency (EPA), the National Highway Traffic Safety Administration (NHSTA), and field manuals published by the U.S. Army were compiled and classified relative to designated categories.

Civilian Vehicle Classifications. Table 1 lists the average weight, length, width, and ground clearance of civilian automobiles by vehicle classes and body style. The automobile classification schema in Table 1 represents a hybrid of classifications standards proposed by the ANSI (D16.1 2007§3.10), the EPA, and the NHSTA *[11], [12],[13]*.

Table 1
Civilian vehicle specifications

CLASS	BODY	MEAN CURB WEIGHT in lbs.	MEAN LENGTH in feet	MEAN WIDTH in feet	MEAN GROUND CLEARANCE in inches
PASSENGER	MINI (PC/Mi)	1,750	12.50	5.50	5.50
	SUBCOMPACT (PC/L)	2,250	13.00	5.50	6.00
	COMPACT (PC/C)	2,750	14.75	5.75	6.75
	MIDSIZE (PC/Me)	3,250	15.75	6.00	7.00
	FULL-SIZE (PC/H)	3,750	16.00	6.25	7.50
MULTI-PURPOSE VEHICLE (MPV)	MINIVAN	2,250	15.00	6.50	7.00
	FULL	2,750	16.50	6.50	10.00
SPORT UTILITY VEHICLE	MID-SIZED	3,250	15.75	6.25	11.00
	FULL	5,250	17.25	6.50	15.50
PICKUP/TRUCK	MID-SIZED	3,750	15.50	6.25	11.75
	FULL-SIZE	5,250	17.25	6.50	15.50

Note: Curb weight represents the total weight of the vehicle with standard equipment and full capacity of fuel.

Military Vehicle Classifications. Table 2 presents the average weight, length, width, and ground clearance of military ground vehicles by class and body style. These vehicle types are those expected to be those utilized by the Louisiana National Guard during emergency/disaster scenarios *[14]*.

Table 2
Military vehicle specifications

CLASS	BODY	AVG. CURB WEIGHT (lbs.)	AVG. LENGTH (feet)	AVG. WIDTH (feet)	AVG. GROUND CLEARANCE (inches)
High Mobility Multipurpose Wheeled Vehicle (HMMWV) "humvee"	M-998	5,500	15.00	7.10	16.00
	M-1114/6	7,800	15.00	7.10	16.00
2½ Ton Cargo "deuce and a-half"	M-35/G-742	18,000	23.00	8.00	20.00 (30" w/fording kit)
Family of Medium Tactical Vehicles (FMTV)	M-1078-81 LMTV (2.5 ton)	17,000	21.00	8.00	22.00
	M-1083-84 FMTV (5-ton)	20,000	23.00	8.00	22.00

DISCUSSION OF RESULTS

Flooding represents a serious operational hazard for evacuation routes located across southern Louisiana. There are numerous factors that contribute to flooded roads during a hurricane, which include vehicle type, road elevations, storm speed and direction, and storm surge heights. In an effort to enhance the situational awareness and mitigation of these inundation hazards, a decision support tool was developed as a proof-of-concept for identifying the flood hazards of specific road segments vulnerable to hurricane flooding. This tool was augmented with research analyzing the flood risk associated with vehicle type. The analysis addresses the relationship between flood characteristics (e.g., flowing versus standing water and wind driven water) and vehicle class.

Quantifying Surge Inundation

Inundation from hurricane induced storm surge was computed for the surfaces of 86 LADOTD routes distributed across the five management districts comprising south Louisiana, which were selected because of their historic vulnerability to flooding. Inundation was derived from the maximum surge heights, in feet, estimated using the SLOSH surge models. The MEOW surge product was chosen because it simulated storm surge for various hurricane scenarios (e.g., category, direction, speed, and tide stage).

ArcGIS version 10.0 software was used to compile and display surge inundation over the select vulnerable road surfaces. For each LADOTD district, a single point feature class was produced for the corresponding vulnerable routes. Data compiled for each point feature included:

- road surface elevations (in feet, NAVD88) of previously flooded, state-maintained highways provided by the LADOTD;
- estimated SLOSH storm surge inundation (in feet, NAVD88); and
- nearest tide or water gauge maintained by either the USGS and the NOAA.

Utilizing the Decision Support Tool

Five ArcGIS map documents were constructed for each LADOTD district (e.g., 02, 03, 07, 61, and 62) to provide an operational platform for depicting the inundation risks over surge-vulnerable, state maintained routes located in south Louisiana. Map documents were composed of GIS feature data classes depicting vulnerable routes, water gauge stations, and reference features. Features were symbolized to depict the worst-case hurricane storm surge scenarios assigned to the road elevation data. Inundation estimates and road characteristics were accessed using a map tools provided by the ArcGIS desktop interface.

Data Organization

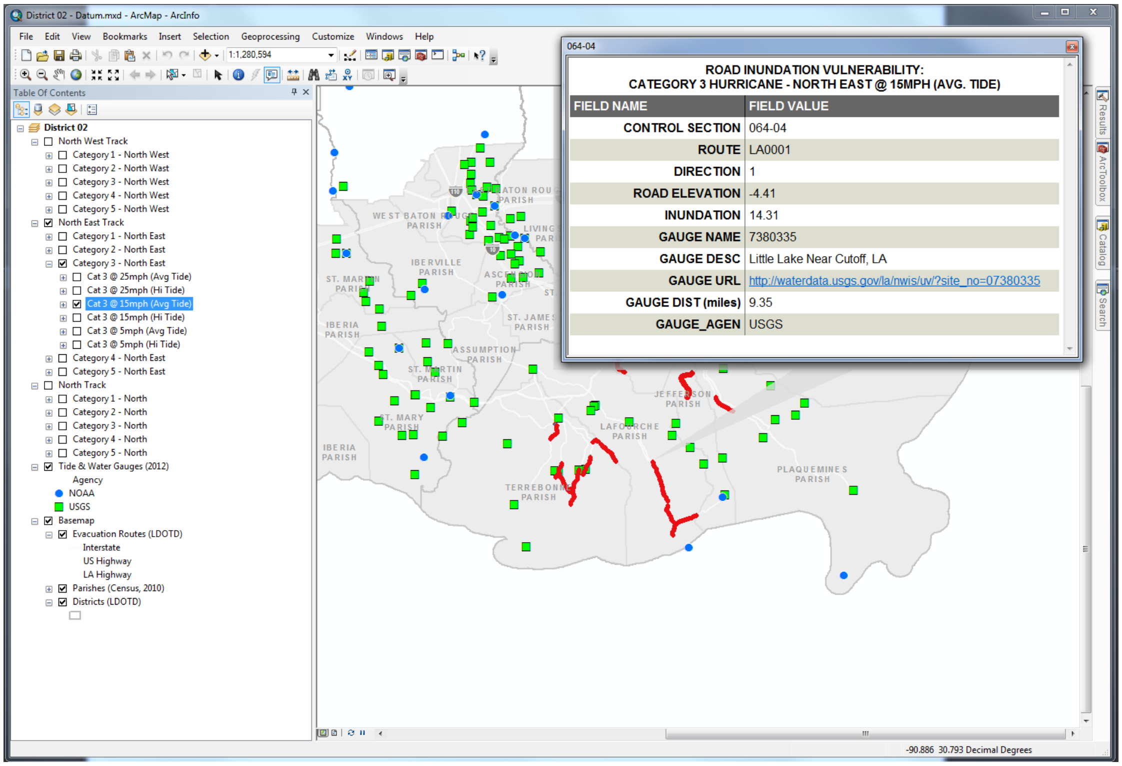
Data organization was a significant challenge for this decision support tool. Each MXD presented no fewer 90 different representations of inundation over the surge-vulnerable routes. To be effective, the information presented in an MXD had to be clearly structured and presented in such a way that navigating the content was intuitive and obvious. Accordingly, vulnerable route features were hierarchically organized relative to storm track, storm category, forward speed, and tide stage.

User Interface

End-users can interact and manipulate the map content using the pan, zoom, and identify tools provided by the ArcGIS software (see below). An “HTML Popup” tool can be used to present a customized interface of the inundation conditions for any given road point feature. Tool tips are also enabled for convenience.

Figure 8
Example of ArcGIS toolbar

The decision support tool and user interface was demonstrated to Project Review Committee members for feedback. While numerous constructive suggestions were offered regarding the utility of this proof-of-concept, the consensus was that the user interface fulfilled the expectations for the situational awareness necessary to assess the flood risks to surge-vulnerable, state maintained roads. Figures 9 – 12 illustrate the map documents produced for this tool.

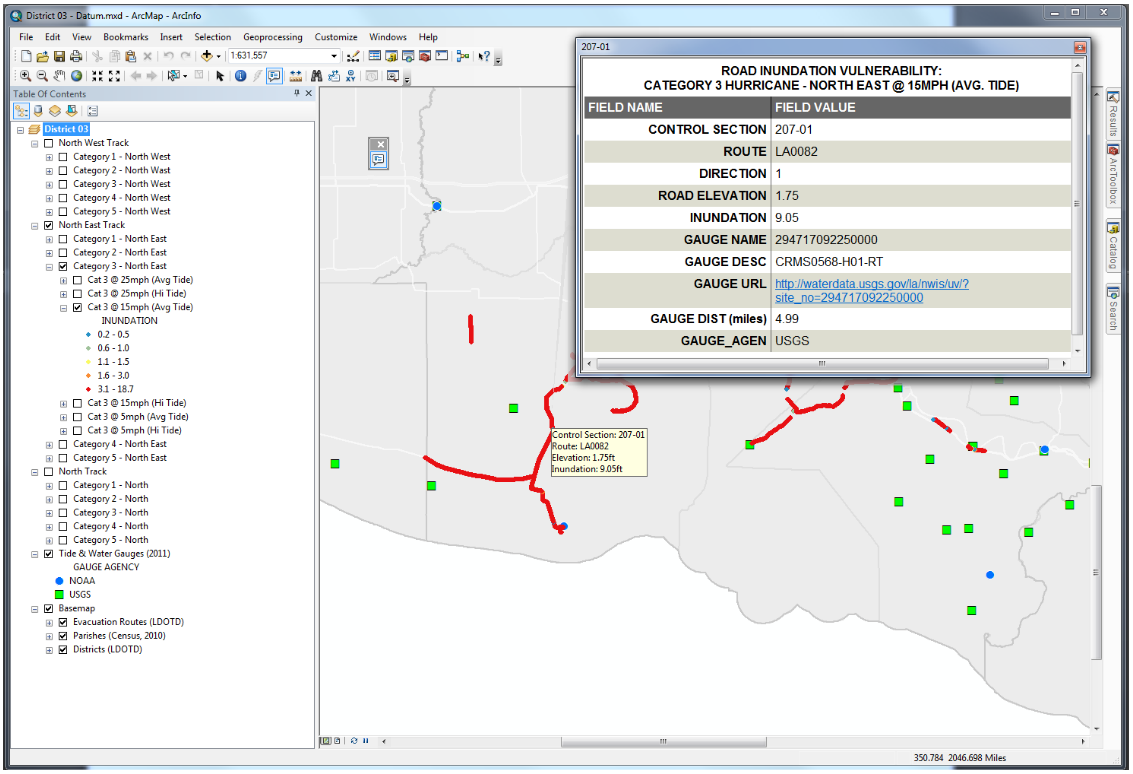


064-04

ROAD INUNDATION VULNERABILITY:
CATEGORY 3 HURRICANE - NORTH EAST @ 15MPH (AVG. TIDE)

FIELD NAME	FIELD VALUE
CONTROL SECTION	064-04
ROUTE	LA0001
DIRECTION	1
ROAD ELEVATION	-4.41
INUNDATION	14.31
GAUGE NAME	7380335
GAUGE DESC	Little Lake Near Cutoff, LA
GAUGE URL	http://waterdata.usgs.gov/la/nwis/uv/?site_no=07380335
GAUGE DIST (miles)	9.35
GAUGE_AGEN	USGS

Figure 9
ArcGIS map document depicting road inundation in District 02



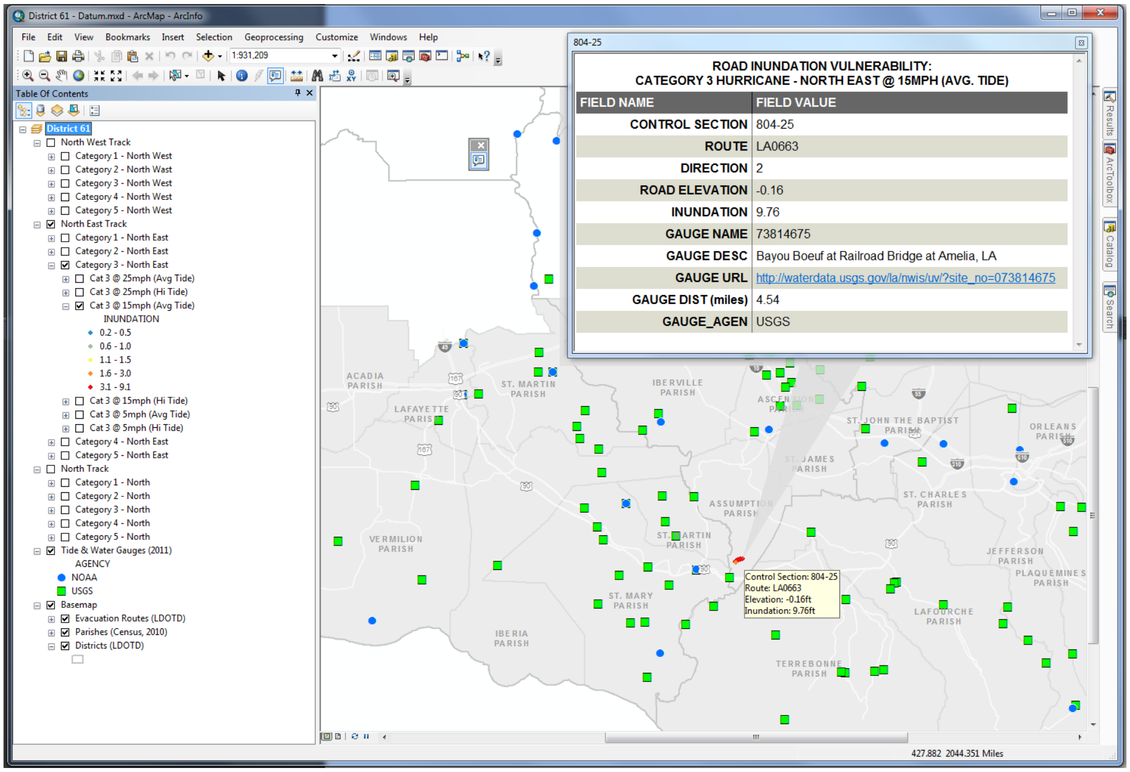
207-01

ROAD INUNDATION VULNERABILITY:
CATEGORY 3 HURRICANE - NORTH EAST @ 15MPH (AVG. TIDE)

FIELD NAME	FIELD VALUE
CONTROL SECTION	207-01
ROUTE	LA0082
DIRECTION	1
ROAD ELEVATION	1.75
INUNDATION	9.05
GAUGE NAME	294717092250000
GAUGE DESC	CRMS0568-H01-RT
GAUGE URL	http://waterdata.usgs.gov/la/nwis/uv/?site_no=294717092250000
GAUGE DIST (miles)	4.99
GAUGE_AGEN	USGS

Control Section: 207-01
Route: LA0082
Elevation: 1.75ft
Inundation: 9.05ft

Figure 10
ArcGIS map document depicting road inundation in District 03

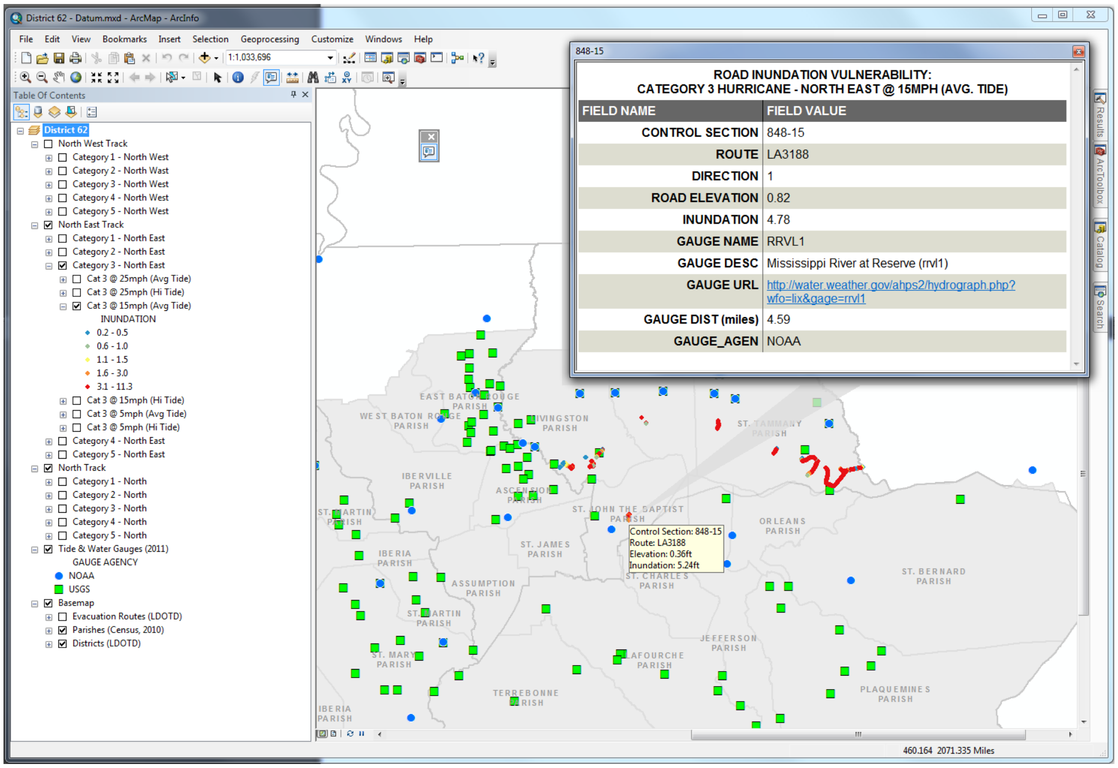


804-25

ROAD INUNDATION VULNERABILITY:
CATEGORY 3 HURRICANE - NORTH EAST @ 15MPH (AVG. TIDE)

FIELD NAME	FIELD VALUE
CONTROL SECTION	804-25
ROUTE	LA0663
DIRECTION	2
ROAD ELEVATION	-0.16
INUNDATION	9.76
GAUGE NAME	73814675
GAUGE DESC	Bayou Boeuf at Railroad Bridge at Amelia, LA
GAUGE URL	http://waterdata.usgs.gov/la/nwis/uv/?site_no=073814675
GAUGE DIST (miles)	4.54
GAUGE_AGEN	USGS

Figure 11
ArcGIS map document depicting road inundation in District 61



848-15

ROAD INUNDATION VULNERABILITY:
CATEGORY 3 HURRICANE - NORTH EAST @ 15MPH (AVG. TIDE)

FIELD NAME	FIELD VALUE
CONTROL SECTION	848-15
ROUTE	LA3188
DIRECTION	1
ROAD ELEVATION	0.82
INUNDATION	4.78
GAUGE NAME	RRVL1
GAUGE DESC	Mississippi River at Reserve (rrvl1)
GAUGE URL	http://water.weather.gov/ahps2/hydrograph.php?wfo=lix&gage=rrvl1
GAUGE DIST (miles)	4.59
GAUGE_AGEN	NOAA

Figure 12
ArcGIS map document depicting road inundation in District 62

Results for Vehicle Vulnerability to Flood Risk

This report includes research on flood risk associated with vehicle type. The analysis addresses the relationship between flood characteristics (e.g., flowing versus standing and wind driven water) and vehicle class (e.g., weight, size, and ground clearance). A comprehensive approach for computing vehicle risk followed a simplistic, three-staged conditional function in which the buoyancy, frictional forces, and lateral forces are combined to assess flood risk [equations (2) – (6)]. For each class of vehicle (see Tables 1 and 2) the net weight is reduced according to the weight displaced by the rising water. Second, the lateral forces of the water on the vehicle are computed. Finally, the friction force of the vehicle is estimated. The vehicle is considered to be at risk when lateral forces of the water exceed the unique frictional force of the vehicle (i.e., threshold value).

Vehicle Vulnerability by Class

As inundation depths increase, a vehicle becomes more buoyant. Vehicle stability becomes compromised when its static inertial becomes overwhelmed by the forces from the water. Instability becomes a product of buoyancy and the lateral forces imposed on the vehicle by moving water.

Civilian Vehicle Flood Risks. The following charts illustrate the flood risks for given water depths for each vehicle listed in Table 1. For a given water depth, the charts illustrates the increase in lateral forces relative to the velocity of the flood waters. The stability threshold, represented as a dashed line, illustrates the point at which the friction force, F_f, which is based on the product of the coefficient of friction in water and the vehicle's buoyant weight, W_b, is overwhelmed by the forces exerted by the moving flood waters. In each instance, estimates were based on idealized assumptions of debris-less water on evenly submerged vehicles. Variations in the vehicle construction, design, and frame were not accounted-for in the computations.

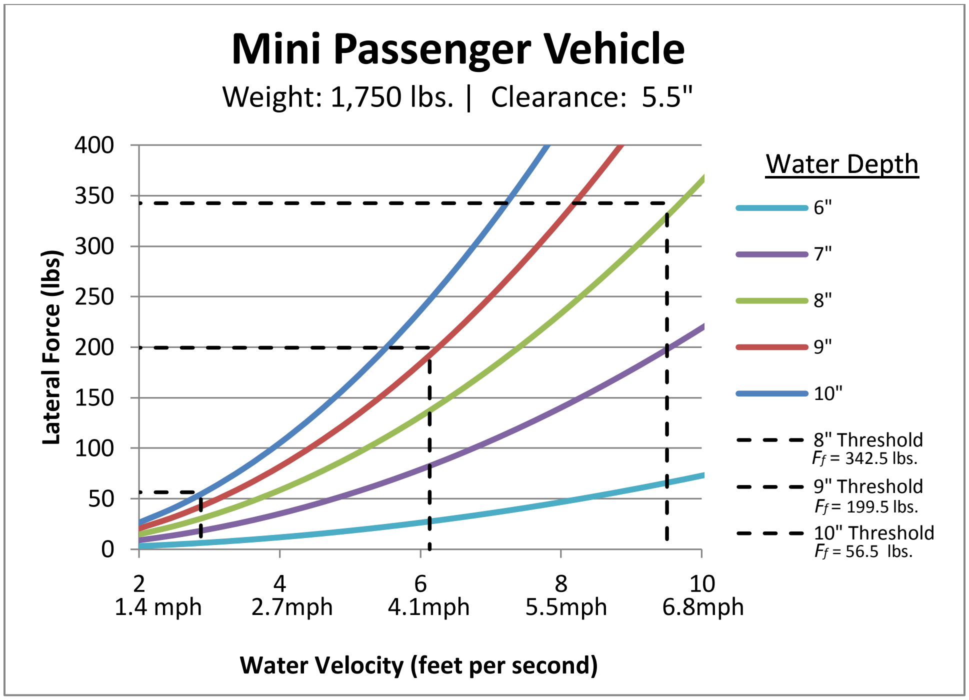


Figure 13
Mini passenger vehicle flood risk

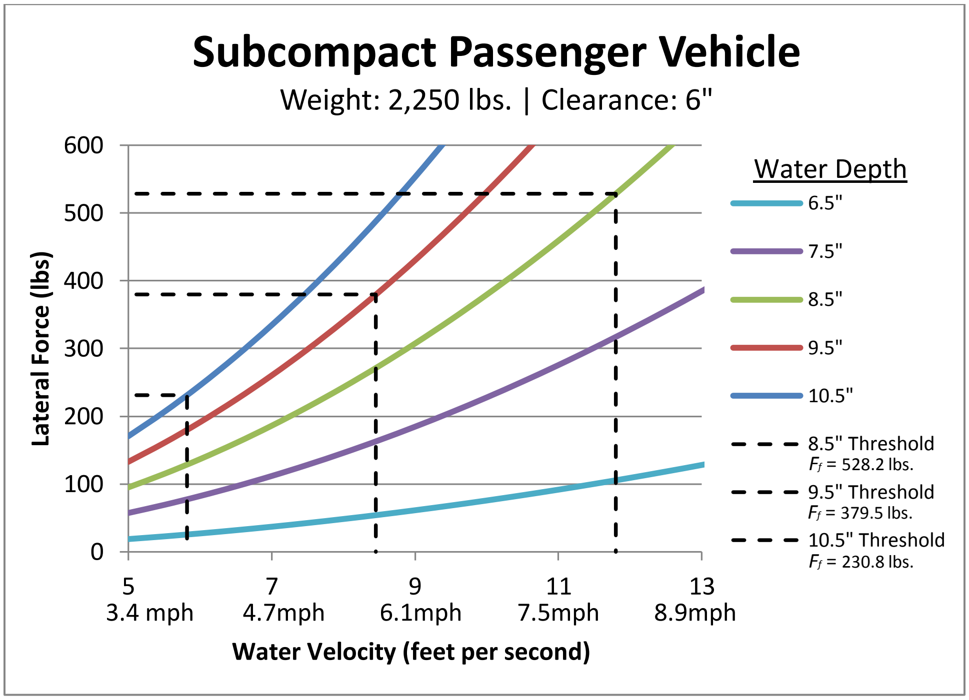


Figure 14
Subcompact passenger vehicle flood risk

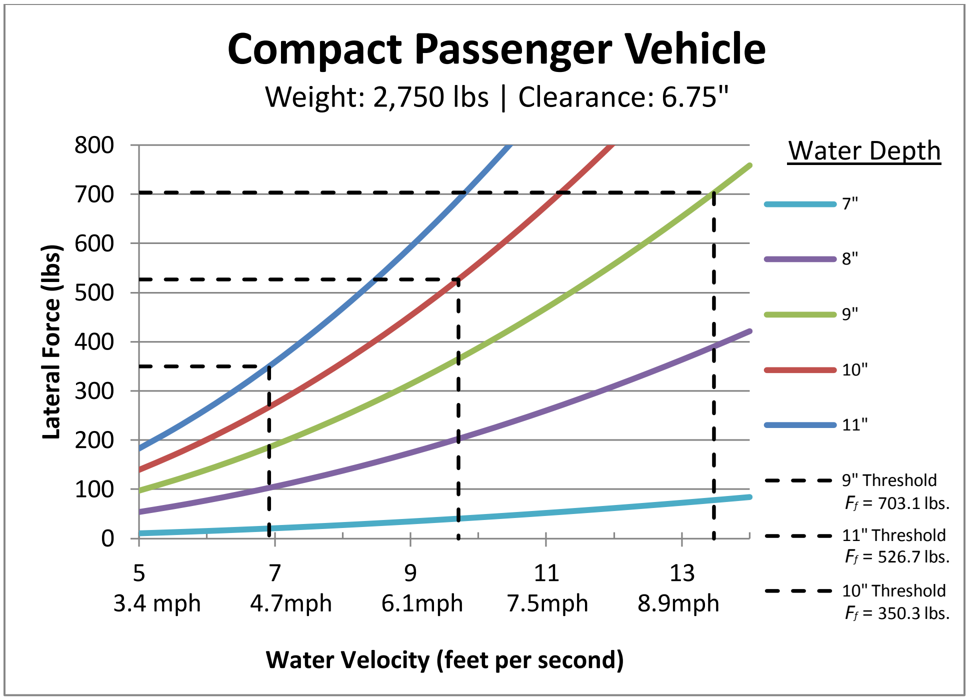


Figure 15
Compact passenger vehicle flood risk

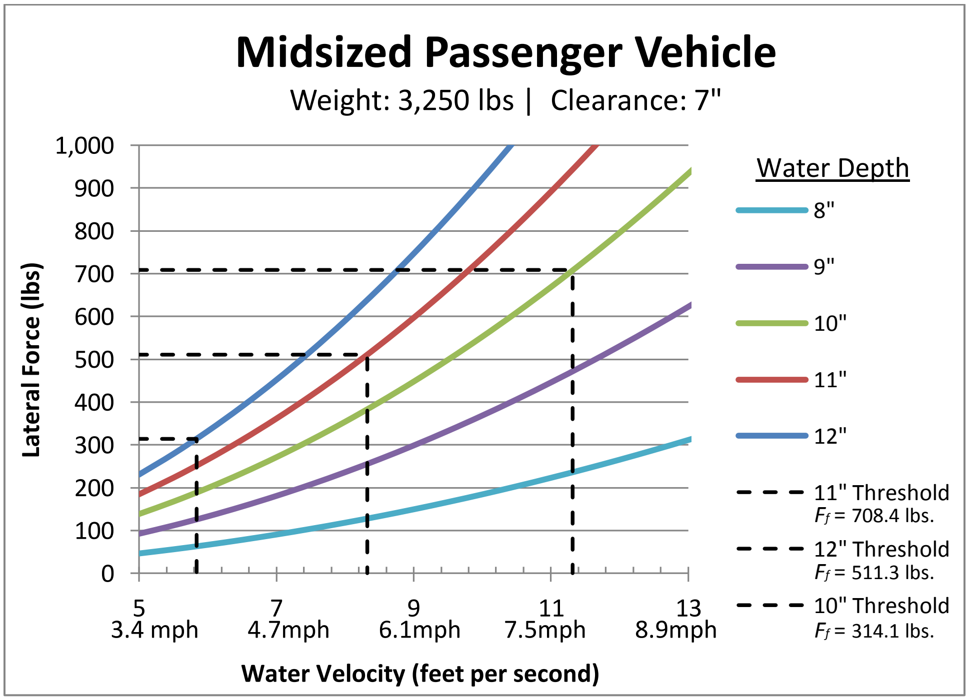


Figure 16
Midsized passenger vehicle flood risk

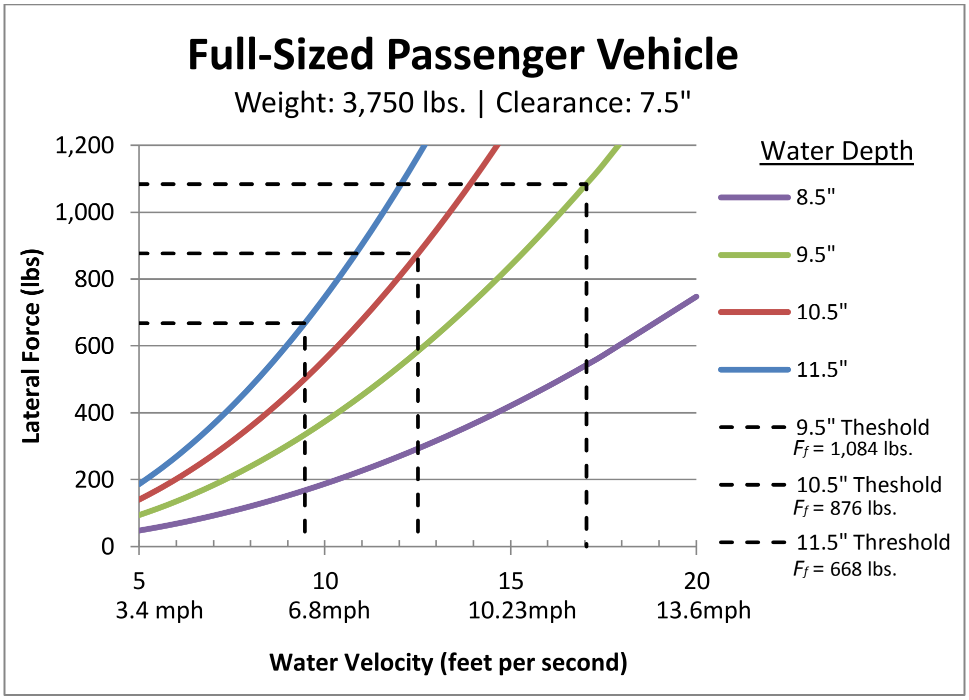


Figure 17
Full-sized passenger vehicle flood risk

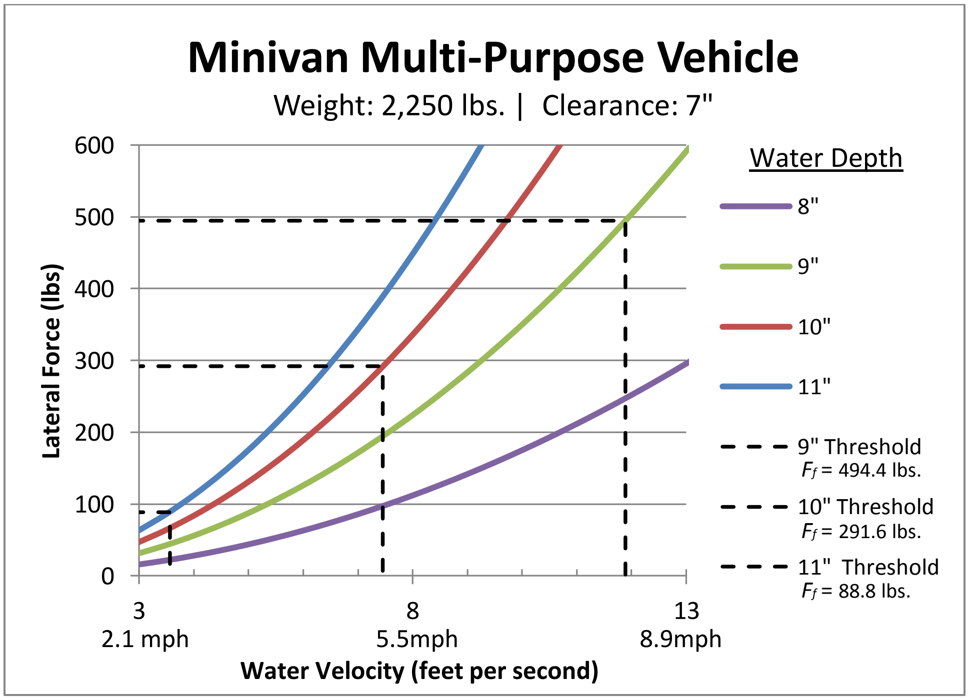


Figure 18
Minivan multi-purpose vehicle flood risk

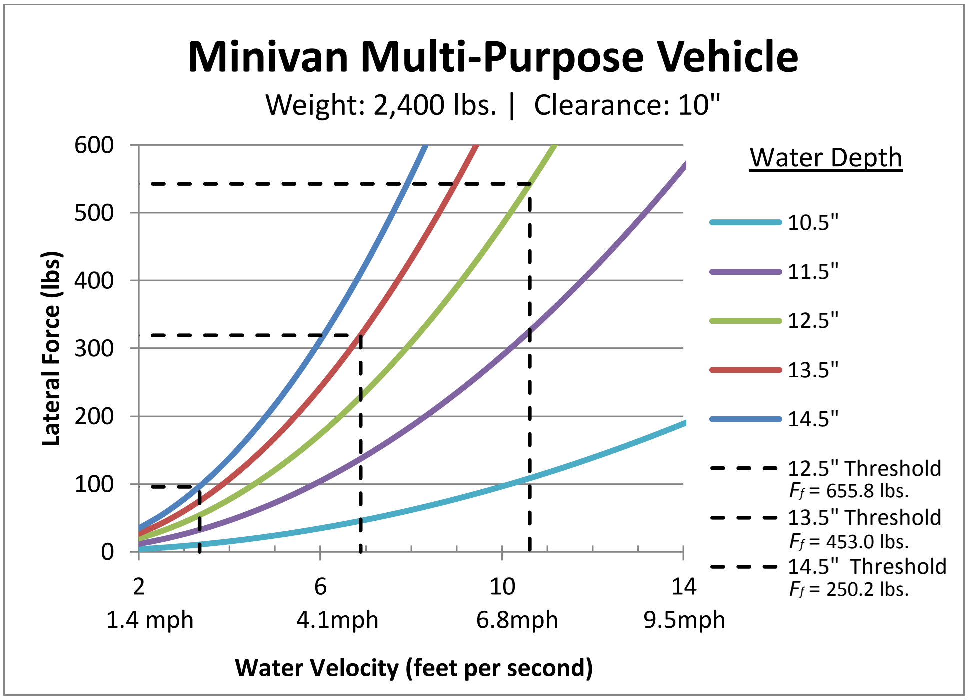


Figure 19
Full-sized multi-purpose vehicle flood risk

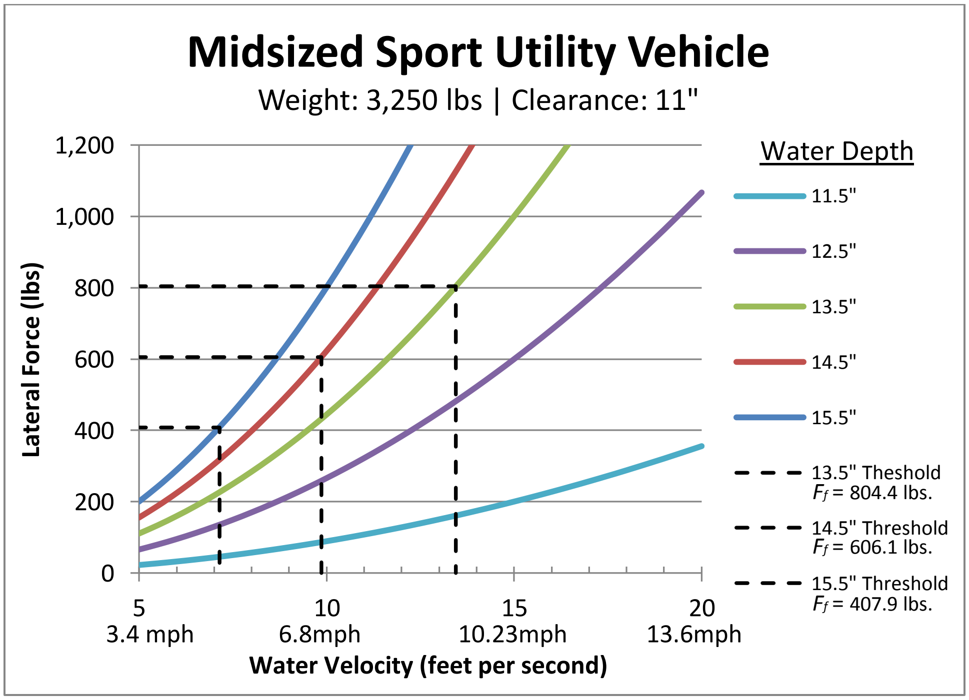


Figure 20
Midsized sport utility vehicle flood risk

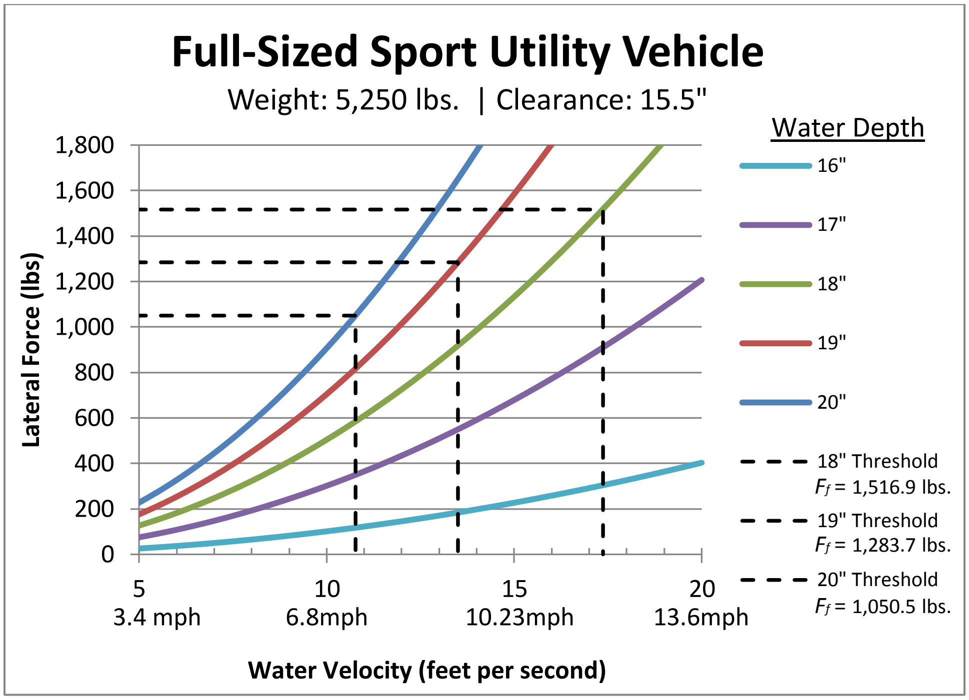


Figure 21
Full-sized sport utility vehicle flood risk

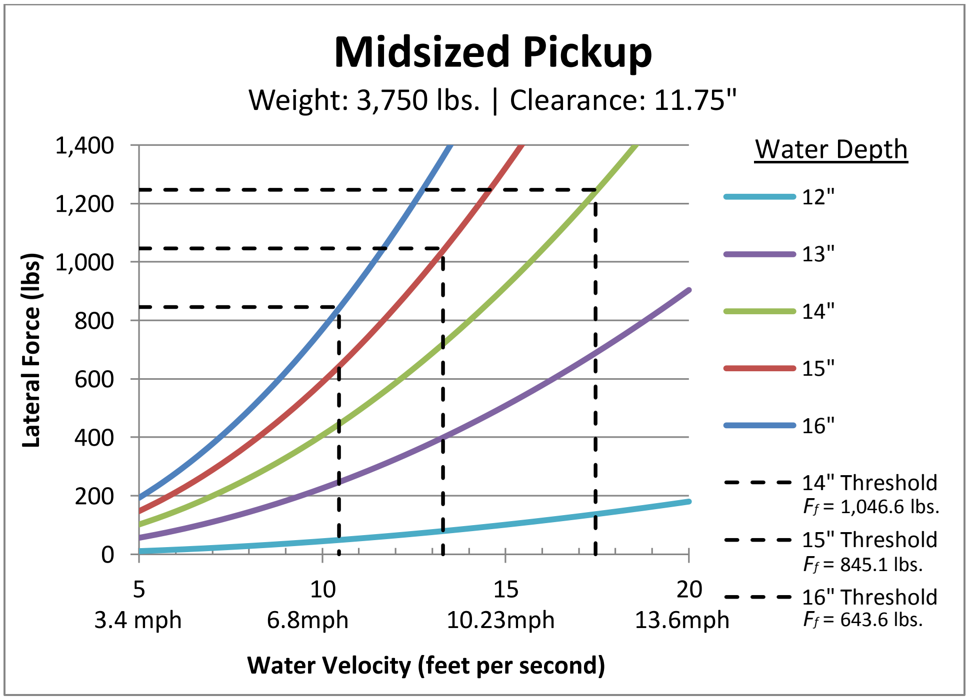


Figure 22
Midsized pickup flood risk

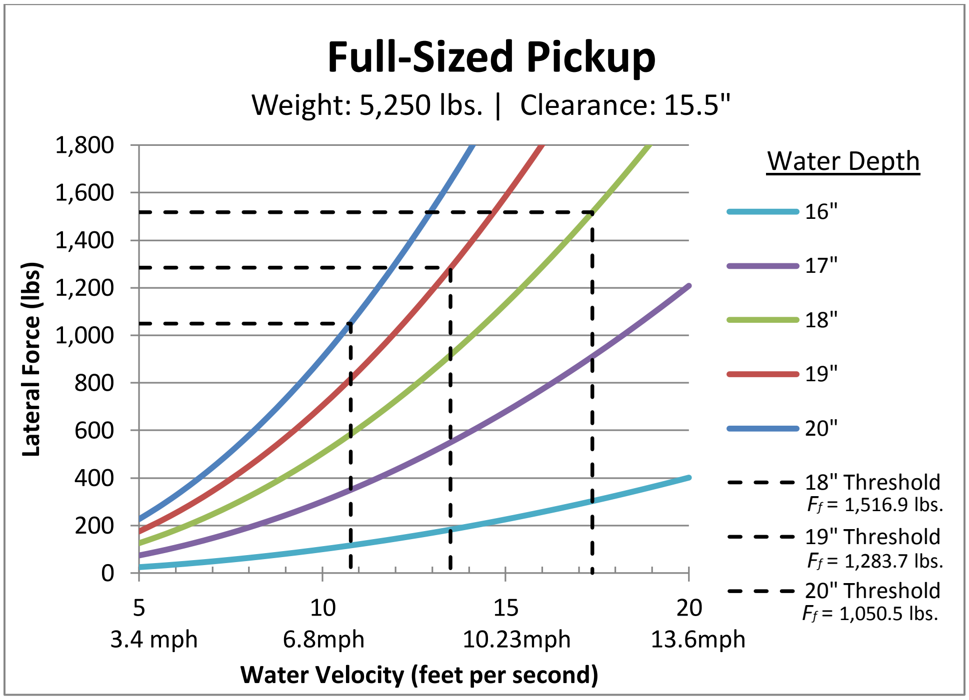


Figure 23
Full-sized pickup flood risk

Military Vehicle Vulnerability by Class. The following charts illustrate the flood risks for given water depths for each vehicle listed in Table 2. For a given water depth, the charts illustrate the increase in lateral forces relative to the velocity of the flood waters. The stability threshold, represented as a dashed line, illustrates the point at which the friction force, F_f, which is based on the product of the coefficient of friction in water and the vehicle's buoyant weight, W_b, is overwhelmed by the forces exerted by the moving flood waters. As noted earlier, estimates were based on idealized assumptions of debris-less water on evenly submerged vehicles. Variations in the vehicle construction, design, and frame were not accounted-for in the computations.

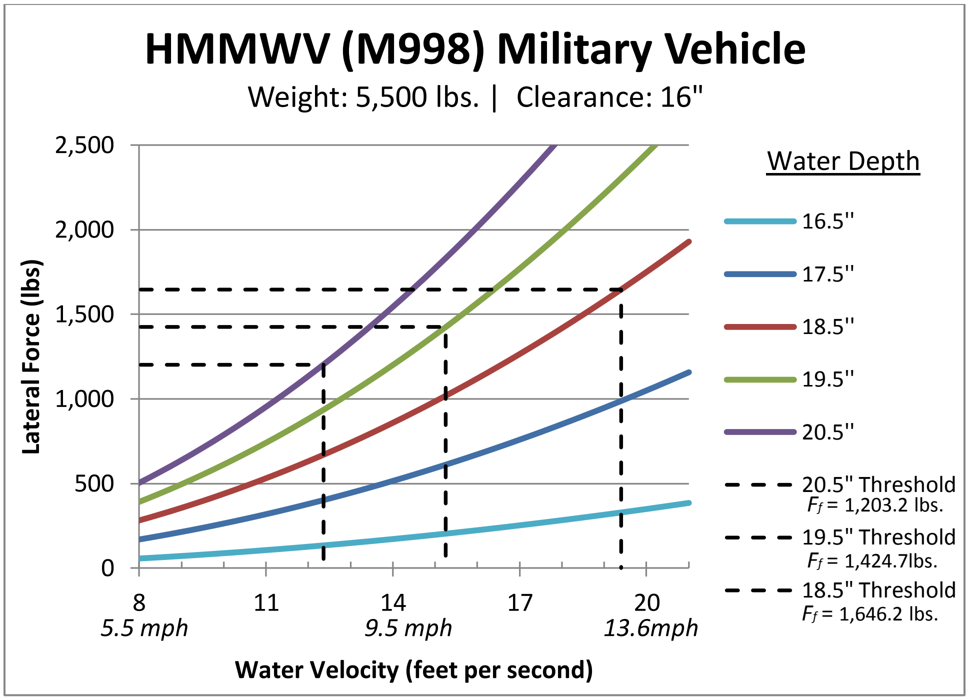


Figure 24
HMMWV (M998) military vehicle

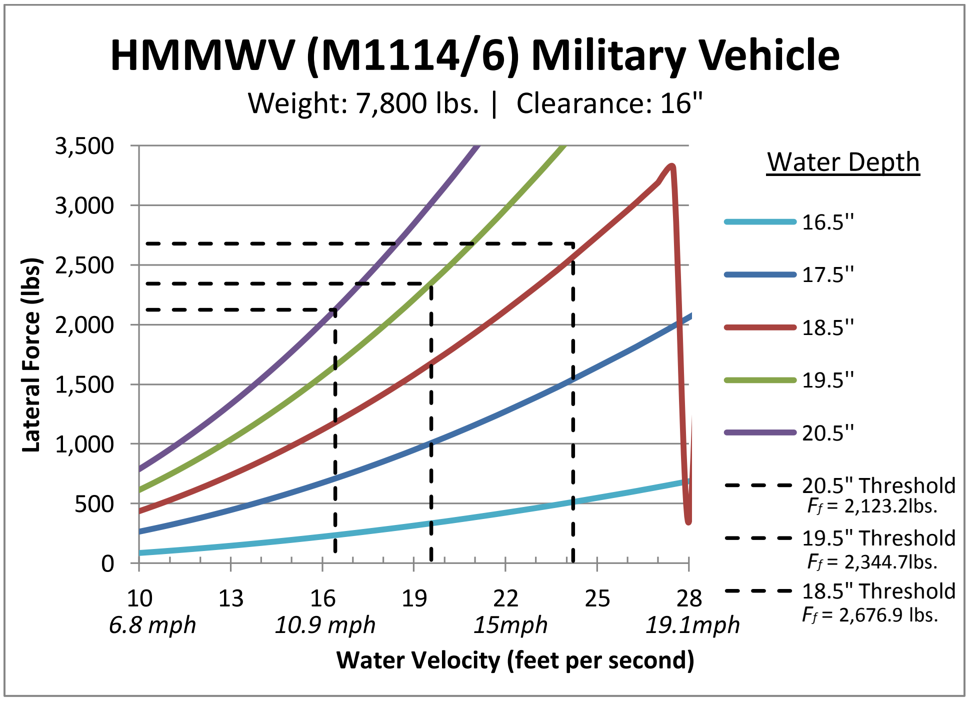


Figure 25
HMMWV (M1114/6) military vehicle

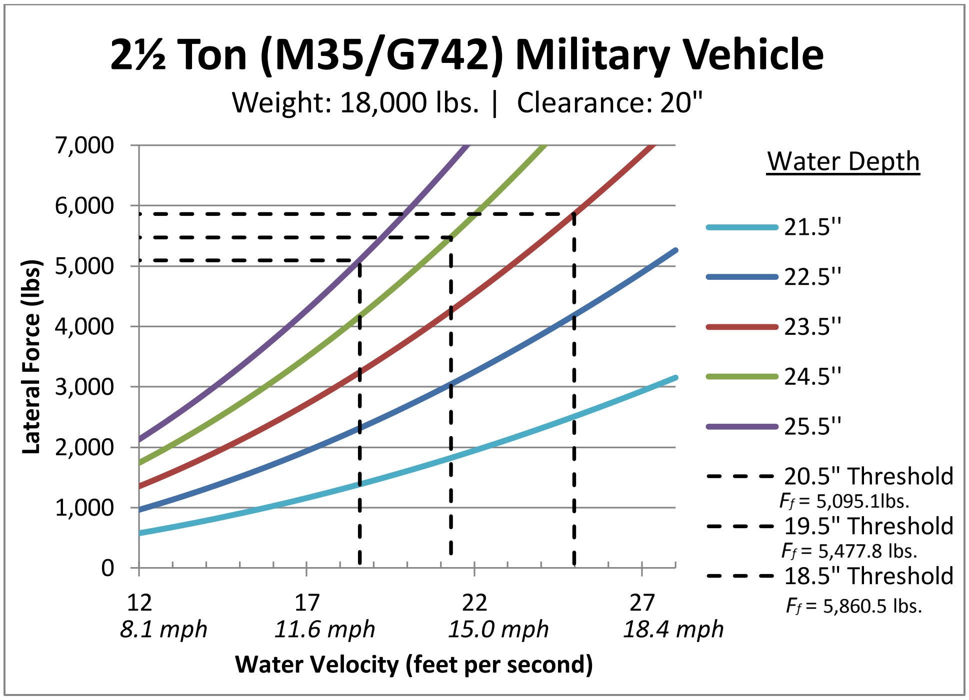


Figure 26
Deuce-and-a-half (M35) 2.5 ton military vehicle

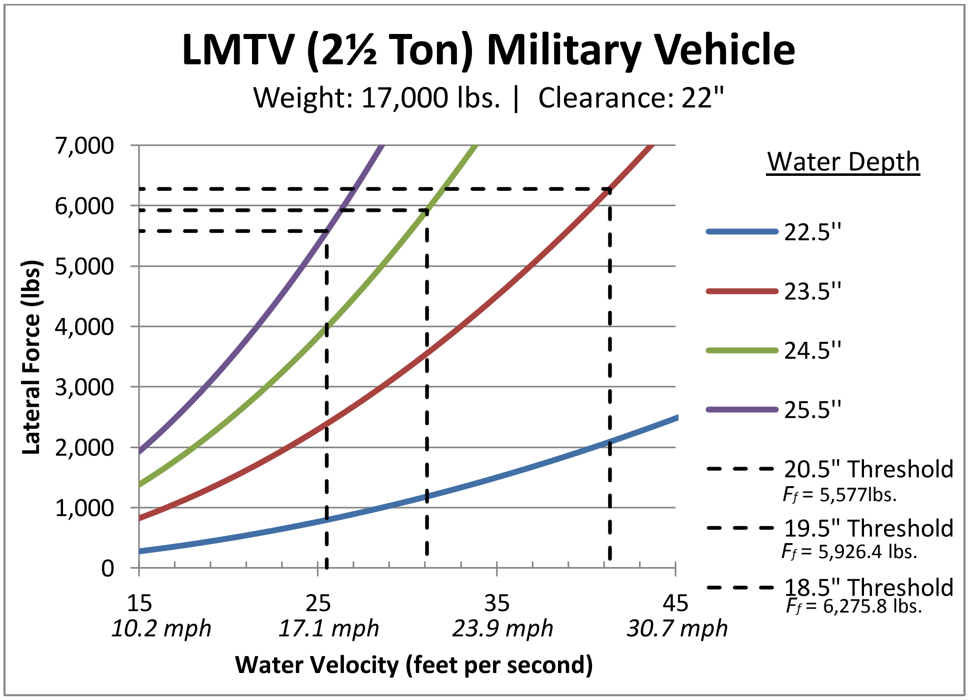


Figure 27
LMTV (2.5 ton) military vehicle

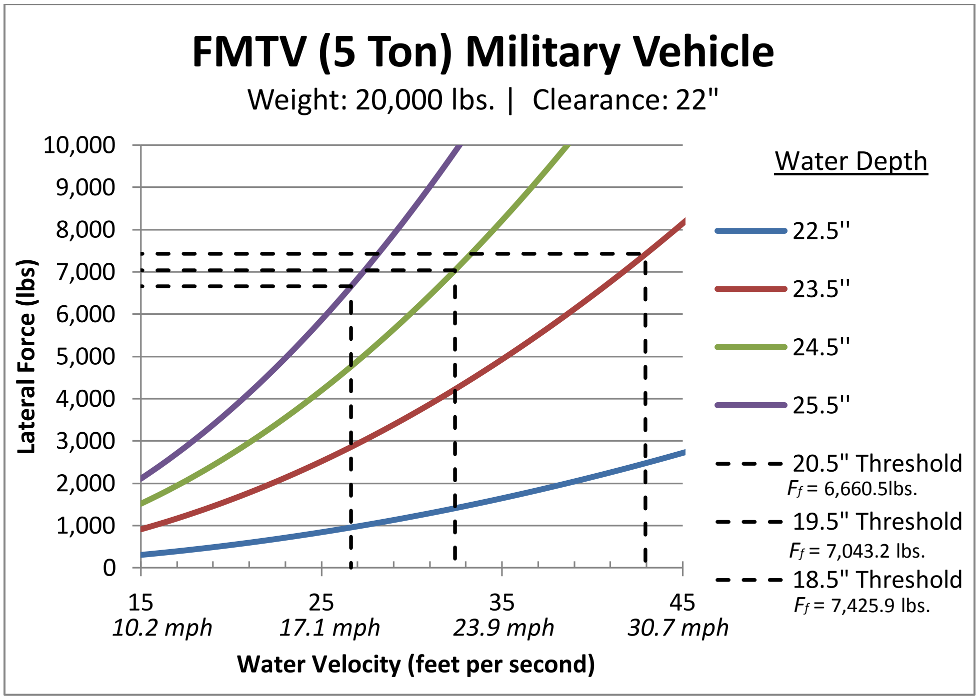


Figure 28
FMTV (5 ton) military vehicle

CONCLUSIONS

This project set out to perform research and develop techniques for quantifying the key factors that contribute to flood hazards on Louisiana roads. Two principal objectives were pursued. The first was to develop a comprehensive, scenario-based, and near real-time decision support instrument capable of synthesizing the hazards associated with flooding over vulnerable, state maintained routes located across southern Louisiana. The second objective was to research and assess the flood risk to vehicles as it relates to vehicle class and flood conditions. By compiling actionable data within a common framework, decision makers are provided with an intuitive, operational tool for assessing the flood risks due to hurricanes.

Decision Support Tool

A key objective of this project was the creation of a decision support tool capable of providing effective situational awareness over the flood hazards on vulnerable, state-maintained routes. To demonstrate and test the capabilities of this concept, an operational instrument was designed and implemented to parameterize various factors that contribute to road flooding during a hurricane. These factors include (1) road surface elevations, (2) storm surge height estimates, and (3) real-time water level observations obtained from near-by water and/or tide gauge facilities. The ArcGIS software platform was used to quantify, qualify, and display the estimated inundation over flood-vulnerable roads identified by the LADOTD.

Tool Implementation & Utilization

Deliverables. Five ArcGIS Desktop map documents (i.e., MXDs) were constructed for each LADOTD district: 02, 03, 07, 61, and 62. Inundation was computed by subtracting the road elevations provided by the LADOTD from surge heights forecasted by the SLOSH MEOW surge model published by the NWS. Inundated road segments (i.e., point features) were symbolized to depict the maximum storm surge for a given hurricane scenario. To further extend the situational awareness of this tool, the name, description, and Web link to nearest water and tide gauge facilities were added to each road point feature. The ArcGIS MXD was used to assemble and synthesize this data in order to provide a consistent framework for depicting hurricane induced storm surge over road surfaces within a district. Inundation and road characteristics are stored as feature attributes and made accessible using the default map tools provided by the ArcGIS software.

Implementation. As a proof-of-concept, this operational instrument should be made available to the decision makers who require a comprehensive and generalized summary of the hazards and their potential consequences to road flooding during a hurricane. Using the default tools and capabilities of the ArcGIS map document, end users will be able to examine the flood risks for vulnerable, state-maintained routes located in the five LDOTD districts in south Louisiana. Road segments are represented as point features symbolized to illustrate a worse-case scenario of inundation. Basic road attributes (including route name, number, control section), surface elevations, inundation estimates, and nearest water/tide gauge facility are accessible in a single, consistent, and easy to use operational framework (see Figures 9 – 12).

Data Uncertainty & Implicit Limitations

The data provided with the decision tool must be interpreted with caution. Various caveats are associated with the estimated inundation. The uncertainties and limitations presented here include those measured for SLOSH surge models and the inundation calculated for the decision support model [e.g., equation (1)].

SLOSH Surge Uncertainty. As a deterministic model, the SLOSH data products are associated with numerous caveats attributable to the parameters that are used to estimate surge. While there are many meteorological uncertainties associated with SLOSH surge forecasts, much of the discussion here will focus on the topographic and hydrographic parameters employed by the MEOW model. Topographic issues are directly related to the spatial resolution of the SLOSH basin. In particular, the model's grid cells are often too large to account for small scale topographic features. By reducing a cell's elevation value to a mean, the modeled surge estimates are effectively skewed relative to outlier elevations and, thus, do not account for the inherent variability associated with the landscape encapsulated by the cell boundaries. Also problematic for the SLOSH estimates are limitations of the hydrological data. In many instances, water measurements parameterized by the model are unevenly distributed as clusters located across the coastal zone. This has an effect of masking the occurrence of actual shallow flooding events [*2*]. Additionally, the SLOSH models do not parameterize the specific values for tide, wave, or rainfall because of a lack of available data and uncertainty associated with interpolated estimates [*3*].

Despite these caveats, comparative assessments of modeled versus actual surge heights performed by Jelensnianski et al. (1984; 1992) and others (e.g., Jarvinen & Lawrence, 1985) found that forecast model accuracy was correct within ~20% of the time when forecast simulations matched actual storm conditions *[3], [15], [16]*. However, the consistently large model error signifies a cautious interpretation of the estimates as anything beyond guidance for *potential* flood intensity. Readers interested in learning more about the uncertainties of the model and its parameters are encouraged to see Jelensnianski et al. (1992) for more details [*3*].

Limitations of the Estimated Road Inundation. The hurricane induced inundation estimated over a vulnerable route was computed by subtracting the road elevations from modeled surge heights. Various degrees of uncertainty can be attributed to the data used for these estimates. As described in equation (1), the inundation estimate consists of multiple factors, including road surface height, wave action, tidal effects, and surge height. The data represent the specific flood-vulnerable routes were based on observations that implicitly incorporates errors of omission and commission. Measurement error is also a factor for the horizontal and vertical values for the road surfaces provided with the PMS datasets. Additionally, neither the wave nor tidal affects were explicitly computed for the inundation estimate. As with the limitations of the SLOSH models noted above, wave action was excluded from this estimate due to a lack of consistent and reliable data. Because the effects of tide will vary from location to location, the inundation estimates were best facilitated using the average and maximum tide estimates for each storm surge scenario.

Vehicle Flood Risk Assessment

This study concluded with research assessing the relationship between flood characteristics (e.g., flowing versus standing water and wind driven water) and vehicle class (e.g., weight, size, and ground clearance). The research findings provided a comprehensive assessment of vehicle risk.

Risk Assessment

A simplistic approach for computing vehicle risk followed a generalized, three-staged conditional function in which the buoyancy, frictional forces, and lateral forces were combined to assess flood risk to civilian and military passenger vehicles. For each class of vehicle (see Tables 1 and 2) the net weight was reduced according to the weight displaced by rising water. Second, the lateral forces of the water applied to the vehicle were computed. Finally, the friction force of the vehicle was estimated. The vehicle is considered to be at risk when lateral forces of the water exceed the friction force of the buoyant vehicle. Equations representing the displacement, the lateral, and the frictional forces [e.g., equations (2) – (6)] were applied to for each vehicle class determine the destabilization point. For a given water depth and velocity, each chart (Figures 6 – 10) illustrated the stability thresholds (dashed line) at which a vehicle is expected to destabilized.

Flood Risk Analysis. The outcome of these findings have been compiled in Tables 3 and 4, which summarizes by type the minimum flood depth and water velocity necessary for destabilizing a vehicle.

Table 3
Summary of passenger vehicle flood risk

CLASS	BODY	MEAN CURB WEIGHT (lbs.)	MEAN LENGTH (feet)	MEAN WIDTH (feet)	MEAN GROUND CLEARANCE (inches)	WATER DEPTH NEEDED FOR NEUTRAL BUOYANCY (inches)	VELOCITY OF WATER NEEDED TO DESTABILIZE VEHICLE (ft/sec)
PASSENGER	MINI	1,750	12.5	5.5	5.5	10.40	15.66
PASSENGER	SUBCOMPACT	2,250	13	5.5	6	12.05	15.66
PASSENGER	COMPACT	2,750	14.75	5.75	6.75	12.99	16.01
PASSENGER	MIDSIZED	3,250	15.75	6	7	13.61	16.35
PASSENGER	FULL-SIZED	3,750	16	6.25	7.5	14.71	16.69
MPV	MINI-VAN	2250	15	6.5	7	11.44	17.02
MPV	FULL-SIZED	2,750	16.5	6.5	10	14.93	17.02
SUV	MIDSIZED	3,250	15.25	6.25	11	17.56	16.69
SUV	FULL-SIZED	5,250	17.25	6.5	15.5	24.50	17.02
PICKUP	MIDSIZED	3,750	15.5	6.25	11.75	19.19	16.69
PICKUP	FULL-SIZED	5,250	17.25	6.5	15.5	24.50	17.02

Table 4
Summary of military vehicle flood risk

CLASS	BODY	MEAN WEIGHT (lbs.)	MEAN LENGTH (feet)	MEAN WIDTH (feet)	MEAN GROUND CLEARANCE (inches)	WATER DEPTH NEEDED FOR NEUTRAL BUOYANCY (INCHES)	VELOCITY OF WATER NEEDED TO DESTABALIZE VEHICLE (FT/SEC)
HMMWV	M-998	5,500	15	7.1	16	25.93	17.79
	M-1114/6	7,800	15	7.1	16	30.08	17.79
2.5 Ton	M-35/G-742	18,000	23	8	20	38.81	18.88
FMTV	M-1078-81 LMTV	17,000	21	8	22	41.46	18.88
	M-1083-84 FMTV	20,000	23	8	22	42.90	18.88

Assessment Uncertainties

Vehicle Classification. This research revealed a lack of consistency for vehicle classification. Numerous independent federal agencies and non-government organizations have adopted vehicle classification schemes that are too often incompatible. In many instances, agencies like the U.S. Environmental Protection Agency, ANSI, and NHTSA have adopted inconsistent classification criteria that address the particular mandates of the agency. As a consequence, little can be done to correlate the research results of the data, much less identify a unified vehicle classification scheme. Accordingly, this research adopted a schema that represented a combination of the different criteria used by these agencies. While by no means a panacea, it proved sufficient for the scope of this study.

Assessed Flood Risk. The flood risk to both passenger and military vehicles were assessed using simplistic equations that generalize the flood conditions, vehicle dimensions and weight, and the water pressure and forces applied to the vehicles. Vehicle weight value was a significant factor for computing buoyancy and frictional forces. For this research, a vehicle's curb weight was utilized – the weight (in lbs.) of a standard configuration with gasoline. The more appropriate gross vehicle weight rating (GVWR), which represents the combination of curb weight and passengers with cargo, was not used in the risk equations and thus was not available to account for the combined weight of cargo and passengers. Furthermore, the tire configurations (i.e., the weight, area, shape, and buoyancy) were unaccounted for in this assessment.

Vehicle design is also a factor for these measurements. Because of the inherent uncertainties and lack of available data, this assessment could not precisely account for unique design characteristics of vehicles (e.g., blunt vs. aerodynamic shape) or the mass of the floodwaters (e.g., floating detritus, surge momentum, or wind effects). Similar is the arbitrary dependence on the AASHTO assigned constant, *k*, used to measure dynamic hydrostatic pressure on a submerged, square ended object. While sufficient for pier construction in rivers and lakes, the applicability to a vehicle is questionable, and worthy of further refinement.

Despite these generalizations and noted omissions, the provided flood risk presents vehicle risk assessments were previously unavailable to decision makers.

RECOMMENDATIONS

The goals for this project were to develop an operational instrument and empirical research examining the consequences of flooding on Louisiana's roads. To that end, a decision support tool was developed as a proof of concept to represent the potential flooding over flood-vulnerable, state maintained routes. The tool was augmented with research examining the flood risk to various vehicle classes.

On May 8, 2012, the decision support tool was demonstrated to the project review committee (PRC), at which time the tool and the data were evaluated. Data supporting the situational awareness of surge induced flood hazards during multiple hurricane scenarios were compiled and synthesized within a framework. The PRC was asked to provide comments and recommendations regarding the user interface and overall effectiveness of the tool to present the flood risk to vulnerable routes.

Critiques from the committee were primarily concentrated on the tool's effectiveness as a programmatic instrument. However, all present agreed that the tool successfully presented the data in a comprehensive and intuitive interface necessary for establishing situational awareness from an operational perspective. Comments regarding the age and accuracy of the PMS data were also provided. Having met the objectives, the PRC recommended the tool be further evaluated by the Assistant Secretary of Operations, Rhett Desselle.

As per the comments of the PRC, the tool was presented to Desselle on May 18, 2012. Also presented were the preliminary results of the flood risk assessment by vehicle type. Recognizing the data limitations regarding wind induced wave actions, the parameters and implementation strategy for the decision support tool was approved and received a recommendation to proceed as designed. Desselle provided recommendations for presenting the flood risk relative to vehicle type.

All recommendations have been addressed for this report. Additional recommendations for future implementations of this research are being discussed.

Inundation Modeling Enhancements

The existing technique for estimating surge inundation over vulnerable routes was computed using the SLOSH storm surge models published by the NWS. Specifically, the MEOW data product was used to determine the surge over a road surface relative to a given hurricane scenario. The uncertainties of these surge models notwithstanding, the inundation calculations performed for this project were arduous, requiring multiple software products (e.g., ArcGIS, MS Access, and multiple custom scripts) and many hours to complete.

Consequently, the computational requirements performed for this study were too rigid to support real-time updates.

Indeed, much of the data utilized by this project is updated on a regular schedule. For instance, the SLOSH surge products are updated frequently with new surge estimates. In many instances, the NWS publish storm-specific surge estimates days prior to landfall. Integrating surge data or even the most current road elevations is essential for ensuring effective situational awareness and decision making.

Updates for Future Data Requirements

The recommendations presented here cover the data utilized for the inundation estimates.

Recommendations. Data requirements for estimating inundation should utilize additional sources and include more real-time data products.

Road elevations provided by the LADOTD PMS data sets were questioned by members of the PRC. While an accuracy assessment of this data was beyond the scope of this contract, the uncertainty of the elevation values make clear the need for optional use of multiple sources of data. Implementation of an inundation algorithm capable of integrating multiple and real-time data sources would make for a more efficient inundation estimating framework.

Such an implementation could combine the hypothetical data products, such as the MEOW and MOM surge data, as well as real-time SLOSH models, which are typically published 48 hours prior to a storm's landfall. The algorithm could be further enhanced with the most current road elevations, as well as real-time content from LADOTD personnel reports and/or eye-witness accounts submitted *in-situ*.

Additionally, better integration of hydrologic data is suggested. For this project, contemporary wave models lacked the spatial and temporal resolution needed to provide meaningful inundation estimates. As such, future inundation estimates should identify and incorporate adequate sources of water level data for riverine, lacustrine, and flash-flood event. Furthermore, integration of the tide and water gauge real-time data as model parameters should be pursued. Incorporating local effects with surge estimates can reduce uncertainty and provide a more comprehensive assessment of the risk.

Decision Support Tool Enhancements

To provide for a more robust operational instrument, newer computational techniques that are more robust and agile are recommended to support real-time decision making. Future applications of this tool should be designed and developed as a custom Web based application that can both calculate and present the inundation estimates more efficiently than ArcGIS software.

Updates for Future Decision Support Tools

While effectively used for this proof of concept, the ArcGIS software platform is a sophisticated and process driven tool, which is better suited for data manipulation, analysis, and development. Utilization of ArcGIS requires specialized skills and knowledge, which limits its applicability during emergency events. Additionally, ArcMap executes instructions and performs analysis linearly, and thus requires more time to complete. Implementation of a custom tool that is Web-based can be more efficient for decision makers. Such a tool would require less training, and could more effectively integrate multiple, real-time data products published by authorities sources.

Recommendations. Future implementations of this tool should utilize customized computational techniques that are more robust and agile, which are necessary to support real-time decision making.

If implemented as a Web-based application, the tool could be customized to more effectively address the user interface requirements of decision makers. Furthermore, a Web approach can more fully deliver the dynamic content recommended above, thus making it easier to establish situational awareness.

Because it would be Web-accessible, more individuals from different locations could access the information without license restrictions or cumbersome software requirements. As a consequence, the tools would require fewer specialized skills, as the majority of the data manipulation would occur on the server side, thus only delivering the requested content to the client.

Vehicle Flood Risk Assessment Enhancements

The flood risk was assessed by vehicle class using a simplistic application of Archimedes principals of buoyancy and Pascale’s principles of water pressure. While these results were elementary in their constitution, the analysis was able to produce estimates of the flood conditions capable of destabilizing the static inertia of a given automobile stalled in moving flood waters. Despite the success, a number of limitations to the approach were identified that dealt mostly with heterogeneous vehicle classification techniques, the influence of vehicle design/shape on pressure and buoyancy, and the implications associated with this type of risk assessment.

Overcoming Analytical Limitations

A significant factor in determining vehicle vulnerability relates to distinguishing vehicles by type. For example, what are the criteria for differentiating a compact passenger from sports car, a cross-over from a hatchback, or a midsize SUV from a small MPV? Research efforts failed to identify a consistent scheme for vehicle classification. Though multiple independent agencies employ some type of vehicle classification scheme, none were sufficiently consistent to be applicable to this study. Accordingly, a custom vehicle hierarchy had to be adopted.

Another issue of note is the difference between curb weight and gross vehicle weight rating. Vehicle weight is a significant factor for assessing buoyancy and ultimately flood risk. Curb weight is the most common weight value assessed for a vehicle, and describes the weight of a standard configuration automobile with fuel. Alternately, the GVWR, which is less commonly referenced, describes a vehicle's curb weight and that of its passengers and cargo. While the GVWR is a more appropriate weight value for this analysis, it was excluded because of inconsistent reporting.

Finally, the unique design characteristics of a vehicle will influence the degree to which a vehicle destabilizes due to rising flood waters. Hydrostatic pressure applied to a submerged object will vary according to its shape as well as the density of the water. Vehicle design (e.g., ground clearance and weight) and styling (e.g., aerodynamics) will ultimately have significant impact on a vehicle's stability within moving water. The count, shape, area, and weight of the tires on a vehicle are also significant. Additionally, debris carried within the water will further influence the stability characteristics. Existing data published by the AASHTO account for pressure of flowing water striking a square ended pier. This value was used as a proxy for the pressures applied to the submerged portion of a vehicle. However, additional research is necessary to derive alternate constant values can better account for vehicle shape.

Recommendations. Future research should address these noted limitations in order to provide for a more realistic assessment of risk. Specific recommendations are to devise a comprehensive, hierarchical vehicle classification scheme that distinguishes vehicles according to size, weight, clearance, and function. Vehicle buoyancy should be measured using GVWR weight ratings instead of the more commonly reference curb weight. Hydrostatic dynamic pressures should be more accurately assessed relative to vehicle aerodynamic design and water mass.

Overcoming Social Challenges

Drowning in submerged vehicles is a leading weather related cause of death in the United States. Accordingly, both FEMA and the NWS have made public awareness a significant priority for mitigating flood fatalities. For instance, the “turn around, don’t drown” (TADD) public awareness campaign unambiguously presents the deadly consequences of driving a vehicle into flood waters *[17]*.

Recommendations. Publishing vehicle specific risk assessments can result in the unintentional consequence of passively endorsing flood-risk complacency among the general public. A challenge for future research will be to identify an investigative strategy that will simultaneously broaden knowledge and awareness of vehicle flood risk without compromising the mitigation efforts and motivation of the TADD campaign.

EPILOGUE

Evaluation of the Tool During Tropical Storm Debby

Shortly after submitting the data and draft report, Tropical Storm Debby formed in the Gulf of Mexico. The storm prompted a request by the LADOTD Operations section head to provide an estimate of potential inundation for Louisiana Highways 1 and 23. The request was issued on the evening of June 23, 2012. The storm forecast for the NWS advisory is depicted in Figure 26 *[18]*. Because the storm track did not directly match any of the estimates developed for the decision support tool, a custom inundation risk assessment was derived for this event.

The PMS data points used for Highways 1 and 23 were extracted from the PMS database utilized by this project. The SLOSH MEOW data representing the New Orleans basin was used to estimate surge. Following the procedures depicted earlier, highway elevations were subtracted from the surge estimates to compute inundation risk. The data was symbolized and provided as a custom decision support tool for the LADOTD Operations section.

As a second proof of concept, the data was published online with a custom web mapping application to determine the effectiveness of such a tool during an event. Vulnerable road data were combined with the latest advisory GIS data layers to provide near real-time situational awareness. An identify tool was developed to allow decision makers to effectively "click" on vulnerable road point features. This identify functionality returned a call-out window that depicted attributes of the road feature, including elevation, surge estimate (in feet), and forecasted flood inundation (in feet). Nearby water and tide gauge data were also provided with the web application.

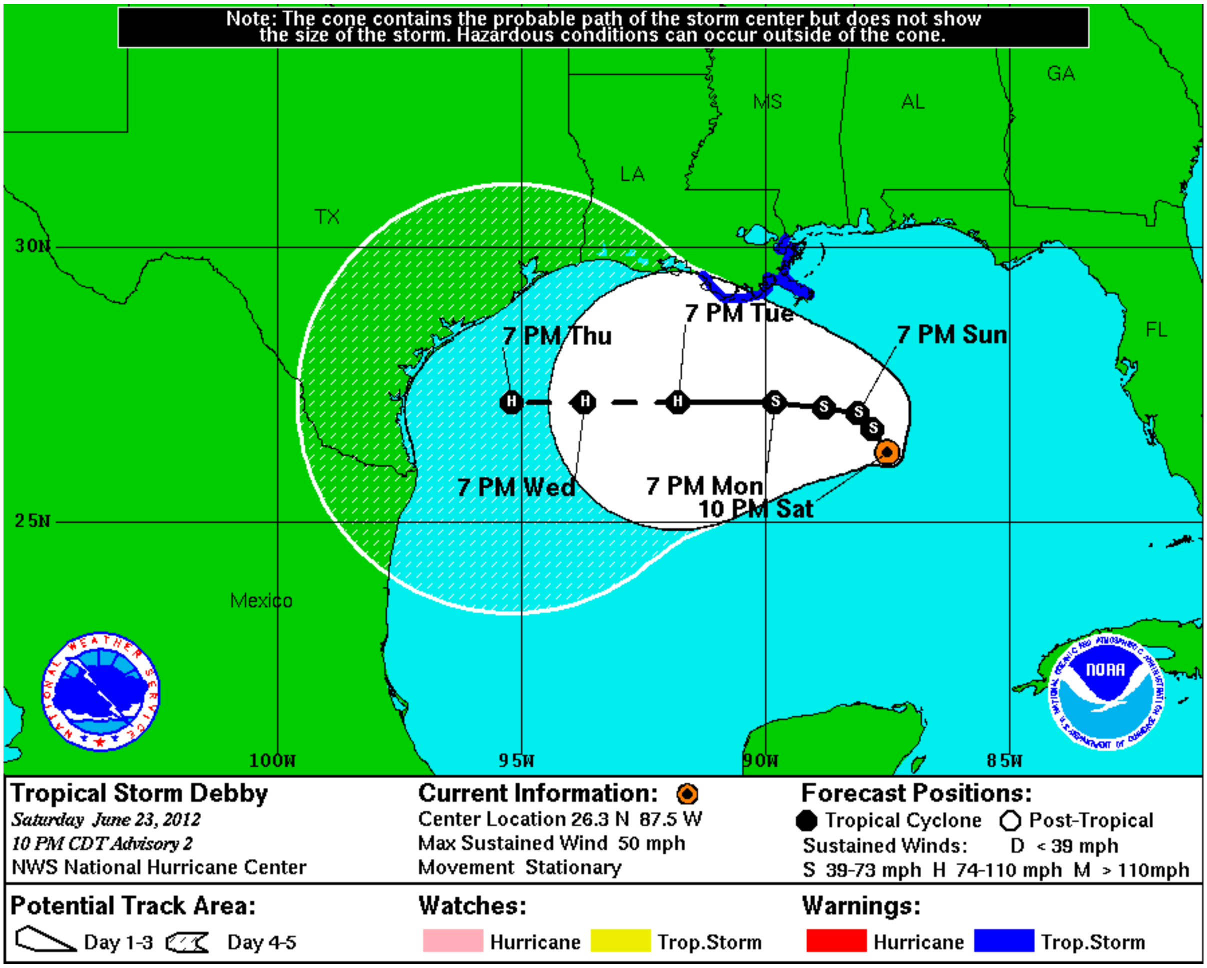


Figure 29
Tropical Storm Debby advisory number 2: 10 pm CST, Saturday, June 23, 2012

Lessons Learned

While this web application was intentionally not distributed, this effort resulted in valuable experiences that can improve future applications. In the positive column, the web-based application functionality proved very effective for risk assessment and situational awareness, particularly the identify tool which presented inundation estimates for road segments. The web framework also made it possible for the end user to choose from various operational layers (e.g., storm track forecasts, wind field estimates, surge estimates, radar, and more) and basemap layers (e.g., high-resolution imagery, topographic maps, and high-contrast elevation topography). Furthermore, the content available to the web application was responsive and fast. Lastly, the ability to update event-specific content in near real-time was also advantageous, further supporting situational awareness.

A few problems were also noted during this evaluation. In particular, the GIS data layers provided by the NHC created workflow problems that often delayed content updates and in some instances caused misinterpretations of the data. The advisory GIS data published and distributed by the NHC used a naming convention that causes certain functions within ArcGIS to crash. To compensate, the files had to be manually renamed before deployment. Consequently, the solution created delays in the workflow. A request to correct the problematic naming convention was submitted to the NHC. While acknowledged, data protocols used by the NHC prohibit such changes from being implemented in mid-season. As such, the submitted recommendations will be considered for later years. Additional data issues related to units used to depict the wind speeds of the storm. Currently, the NHC references wind speed in knots per hour. Unit conversion from knots to miles per hour was recommended for LADOTD use, further delaying the deployment of the data. A recommended solution for these issues must include automation scripts that can accommodate and resolve these issues for future scenarios.

Conclusion. In all, the efforts undertaken during Tropical Storm Debby demonstrated that such web-based applications are achievable. Indeed, deploying this decision support as a web-based application will have many benefits for the Department's response efforts. Accordingly, migration of the provided decision support tool as a web-based application is recommended.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
AGL	above ground level
ANSI	American National Standards Institute
C4G	Center for GeoInformatics
CO-OPS	Center for Operational Oceanographic Products and Services
ESRI	Environmental Systems Research Institute, Inc.
EPA	Environmental Protection Agency
GCS	Geographic Coordinate System
GIS	geographic information systems
GDB	file geodatabase
GVWR	gross vehicle weight rating
HMMWV	High Mobility Multipurpose Wheeled Vehicle (AKA humvee)
FMTV	Family of Medium Tactical Vehicles
ft.	foot (feet)
in.	inch(es)
IT	information technology
km	kilometer(s)
LA	Louisiana
LADOTD	Louisiana Department of Transportation and Development
LMTV	Light Medium Tactical Vehicle
LSU	Louisiana State University
LTRC	Louisiana Transportation Research Center
lbs.	pound(s)
MEOW	maximum envelope of water
MOM	maximum of MEOW
MPV	Multi-Purpose Vehicle
MTV	Medium Tactical Vehicle
MXD	ArcGIS map document (*.mxd)
NAD-27	North American Datum of 1927 (horizontal)
NAD-83	North American Datum of 1983 (horizontal)
NAVD-88	North American Vertical Datum of 1988 (vertical)
NHC	National Hurricane Center
NHTSA	National Highway Traffic Safety Administration
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service

PMS	pavement management system
sec.	second(s)
SLOSH	sea, lake, and overland surges from hurricanes
SUV	sport utility vehicle(s)
TADD	“turn around, don’t drown”
URL	uniform resource locator
US	United States
USGS	United States Geological Survey
UTM	Universal Transverse Mercator (coordinate system)

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APPENDIX

Table 5
PMS data field descriptions

Name	Description
DIRECTION	Direction (1-primay, 2- secondary) "L" and "T" changed to "2"
ROWPATH	Path structure to video image
FILENAME	Raw data file name that data was reduced from.
ROUTE	Route Number
OID	Auto Number key used by Arcview
FOFFSETFR	Beginning control section log mile of subsection
LEAD	Lead in and out code
CSECT	Control Section
VLATITUDE	GPS latitude supplied by vendor at location of image (NAD 1983 in Decimal Degrees to 6 decimal places)
VLONGITUDE	GPS longitude supplied by vendor at location of image (NAD 1983 in Decimal Degrees to 6 decimal places)
V_ELEV	Vender Elevation for GPS supplied by vendor at location of image (Use NAVD 1988 standard measured in feet, relative to MSL, to 2 decimal places)
FBEGCHAIN	ARAN begin chainage
ORIG_DIRECTION	Direction (1-primay, 2- secondary, L-LTRC, T-Truck lane) Matches Visidata files Direction field
SBET	Identifies whether SBET data was available
V_ELEV_ELLIPS	Vender Elevation for GPS supplied by vendor at location of image, used when SBET unavailable

Table 6
Routes subject to inundation by storm surge

DISTRICT	PARISH	ROUTE	DESCRIPTION OF LOCATION
02	Jefferson	LA 45	South of LA 302
02	Jefferson	LA 3257	South of LA 302
02	Jefferson	LA 301	All
02	Jefferson	LA 45	South of Intracoastal Waterway
02	Jefferson	LA 3257	All
02	Jefferson	LA 303	All
02	Jefferson	LA 560-4	All
02	Jefferson	LA 23	Alliance to Deer Range
02	Lafourche	LA 1	south of Golden Meadow flood gates
02	Lafourche	LA 3090	All
02	Orleans	US 11	CS 018-01 Log mile 4.6 to 4.8
02	Orleans	US 90	CS 006-90 log mile 13.7 to 14.6

(continued)

02	St. Charles	LA 626	CS 282-31 log mile .86 to 2.56
02	St. Charles	US 61	CS 007-03 log mile 13.32 to 18.98
02	St. Charles	LA 306	South of levee
02	Terrebonne	LA 665	All
02	Terrebonne	LA 56	South of Boudreaux Canal Locks
02	Terrebonne	LA 57	Dulac area and south
02	Terrebonne	La 3011	All
02	Terrebonne	LA 55	South of Madison locks
02	Terrebonne	LA 315	first 2 miles near Houma
DISTRICT	PARISH	ROUTE	DESCRIPTION OF LOCATION
03	Iberia	La. 14	055-07 (0 - 2)
03	Iberia	La. 329	235-01 (0-3)
03	Iberia	La. 83	240-02, 240-03 (1-7.7)
03	Iberia	La. 85	236-02 (Isolated Segments)
03	St. Mary	La. 83	240-02, 239-02 (0 - 7)
03	St. Mary	La. 319	239-01
03	St. Mary	US-90	424-05 (16 - 18)
03	St. Mary	La. 317	243-01 (0 - 6)
03	Vermilion	La. 3147	857-66
03	Vermilion	La. 82	194-03, 207-01, 215-01, 194-07(0.0 to 5.1)
03	Vermilion	La. 35	207-02 (0.0 - 3.6)
03	Vermilion	La. 91	212-01 (0 - 1.5)
03	Vermilion	La. 333	194-06
03	Vermilion	La. 693	857-11
03	Vermilion	La. 330	397-01 (2. 5.98), 397-02, 397-03
03	Vermilion	La. 3267	857-68 (Isolated segments)
03	Vermilion	La. 690	857-22, 857-67
03	Vermilion	La. 689	857-35
03	Vermilion	La. 688	857-36
03	Vermilion	La. 331	857-37
03	Vermilion	La. 685	857-33
03	Vermilion	La. 339	216-01 (0 - 3)
03	Vermilion	La. 89	397-04 (0 - 2.5)
03	Vermilion	La. 14	055-06, 055-31 (Erath and Delcambre)
DISTRICT	PARISH	ROUTE	DESCRIPTION OF LOCATION
07	Calcasieu	LA 384	Cameron Parish Line to just north of Intracoastal canal
07	Calcasieu	LA 27	CS 031-04 from Cameron Parish Line to Carlyss
07	Calcasieu	LA 384	CS 382-04 north of Cameron Parish Line
07	Calcasieu	LA 385	Cameron Parish Line to Lake Charles Airport

(continued)

07	Cameron	LA 82	TX line to Vermillion Parish
07	Cameron	LA 27	Holly Beach toward Hackberry
07	Cameron	LA 27	Creole to Gibbs town bridge (also small section north of bridge
07	Cameron	LA 1143	All
07	Cameron	LA 1144	South end
07	Cameron	LA 384	Section of CS 195-01 just east of JCT LA 385
07	Cameron	LA 385	Just south of Calcasieu parish line
DISTRICT	PARISH	ROUTE	DESCRIPTION OF LOCATION
61	Ascension	LA 935	
61	Assumption	LA 663	
61	Pointe Coupee	LA 411	
61	Pointe Coupee	LA 81	
61	St. James	LA 18	
DISTRICT	PARISH	ROUTE	DESCRIPTION OF LOCATION
62	LIVINGSTON	LA 441	LA 442 - ST. HELENA PARISH LINE
62	LIVINGSTON	LA 16	LA 447 - LA 1026
62	LIVINGSTON	LA 1032	LA 1033 - LA 16
62	LIVINGSTON	LA 22	LA 444 - LA 16
62	LIVINGSTON	LA 1039	All
62	LIVINGSTON	LA 16	LA 1030 - LA 1024
62	LIVINGSTON	LA 1040	NATALBANY RIVER BOTTOM
62	LIVINGSTON	LA 1038	
62	LIVINGSTON	LA 1033	LA 16 - LA 1032
62	LIVINGSTON	LA 447	I-12 - LA 16 S. END
62	LIVINGSTON	LA 447	LA 1019 - LA 63
62	LIVINGSTON	LA 64	LA 16 - AMITE RIVER
62	ST. JOHN	LA 3188	US 61 - I-10
62	ST. JOHN	LA 44	LA 628 - LA 3223
62	ST. JOHN	I-55 SVC. RD.	I-10 - MANCHAC
62	ST. TAMMANY	LA 1077	SOUTH OF LA 22
62	ST. TAMMANY	LA 434	SOUTH OF US 190
62	ST. TAMMANY	LA 433	US 190 - US 11
62	ST. TAMMANY	US 11	LA 433 - LAKE PONTCHARTRAIN
62	ST. TAMMANY	LA 433	I-10 - US 90
62	ST.	US 90	RIGOLETS - MS STATE LINE

(continued)

	TAMMANY		
62	ST. TAMMANY	US 190	US 90 - 3MILES WEST OF WHITE KITCHEN
62	TANGIPAHOA	LA 1249	I-12 - LA 22
62	TANGIPAHOA	US 51	I-12 - LA 22
62	TANGIPAHOA	LA 1040	US 51 BYPASS - LA 43
62	TANGIPAHOA	I-55 SVC. RD.	MANCHAC - I-12
62	TANGIPAHOA	LA 445	US 190 - LA 22