URBAN FLASH FLOOD RISK ASSESSMENT AND INUNDATION MODEL UTILIZING GIS FOR TERRE HAUTE, INDIANA

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ABSTRACT

Use of ArcGIS to examine flash flooding variables and produce a flash flood risk assessment and inundation model for Terre Haute, Indiana. Risk assessment, produced within ArcGIS, indicates that an increase in developed area leads to an increase in very high flash flood risk area and majority of very high risk area resides in developed areas of Terre Haute. Inundation model, produced using ArcGIS and Python, indicates that the proposed model can determine locations of flash flooding, but spatial extent of model predicted flooding is not reliable based on field validation.

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TABLE OF CONTENTS

ABSTRACT iii

ACKNOWLEDGMENTS iv

LIST OF TABLES vii

LIST OF FIGURES viii

LIST OF EQUATIONS x

INTRODUCTION AND RESEARCH QUESTIONS 1

Introduction 1

Research Questions and Hypotheses 6

DATA AND METHODS 9

Data 9

Methods 13

RESULTS 36

Flash Flood Risk Assessment 36

Flash Flood Inundation Model 43

DISCUSSION 62

Flash Flood Risk Assessment 62

Flash Flood Inundation Model 65

Model Limitations 71

Conclusions 74

REFERENCES 76

APPENDIX A: Example of inundation model python code 81

LIST OF TABLES

Table 1 Land use reclassification used in flash flood risk assessment. 16

Table 2 Weighting scheme for flash flood factors in Terre Haute, IN. 18

Table 3 Comparative analysis of flash flood risk areas between 2001 and 2006. 40

Table 4 Land use breakdown of very high risk flash flood areas. 40

Table 5 Modeled results for various storm intensities and durations. 52

Table 6 Comparison of observed versus modeled results for 19 validation locations..................61

LIST OF FIGURES

Figure 1. Map Terre Haute, Indiana, study area of research...7

Figure 2. Relationships between flash flooding variables. 20

Figure 3. 15-minute rainfall intensity curve for a 2 year storm event in Indiana. 25

Figure 4. Curve number and runoff equations. 28

Figure 5. Flowchart of inundation model. 31

Figure 6. Diagram of validation method. 35

Figure 7. Flash flood risk assessment for study area in 2001. 38

Figure 8. Flash flood risk assessment for study area in 2006. 39

Figure 9. Spatial distribution of very high flash flooding risk...41

Figure 10. Land use of very high risk flash flooding areas. 42

Figure 11. Modeled flash flooding extent of a 2 year, 15 minute storm event. 44

Figure 12. Modeled flash flooding extent of a 2 year, 2 year storm event. 45

Figure 13. Modeled flash flooding extent of a 2 year, 3 year storm event. 46

Figure 14. Modeled flash flooding extent of a 2 year, 6 year storm event. 47

Figure 15. Modeled flash flooding extent of a 100 year, 15 minute storm event. 48

Figure 16. Modeled flash flooding extent of a 100 year, 2 year storm event. 49

Figure 17. Modeled flash flooding extent of a 100 year, 3 year storm event. 50

Figure 18. Modeled flash flooding extent of a 100 year, 6 year storm event. 51

Figure 19. Location of the 26 selected validation areas...55

Figure 20. Observed and modeled flooded areas for validation locations in the northwestern part of the study area. 56

Figure 21. Observed and modeled flooded areas for validation locations in the north-central part of the study area. 57

Figure 22. Observed and modeled flooded areas for validation locations in the northeastern part of the study area. 58

Figure 23. Observed and modeled flooded areas for validation locations in the southwestern part of the study area. 59

Figure 24. Observed and modeled flooded areas for validation locations in the south-central part of the study area. 60

Figure 25. Validation sites 18 (left), 21 (center), and 25 (right).. 72

LIST OF EQUATIONS

Equation 1. Shape Ratio..13

Equation 2. Stream Density. 14

CHAPTER 1

INTRODUCTION AND RESEARCH QUESTIONS

Introduction

According to Sanyal and Lu (2004), “Among all kinds of natural hazard[s] of the world flood[ing] is probably most devastating, wide spread and frequent”. Flash flooding causes significant damage every year, with flooding over the past decade in the US costing $1,225.01 million per year in damage and resulting in 52.8 fatalities per year (National Weather Service, 2003-2012). While some parts of the United States, like the Mississippi river valley, experience periodic and damaging flooding as a matter of fact, most of the United States is susceptible to flash flooding, a particular type of flooding that can cause significant damage to structures and humans. According to the National Weather Service (2010), a flash flood is defined as:

> *A flood caused by heavy or excessive rainfall in a short period of time, generally less than 6 hours. Flash floods are usually characterized by raging torrents after heavy rains that rip through river beds, urban streets, or mountain canyons sweeping everything before them. They can occur within minutes or a few hours of excessive rainfall.*

These flash floods can result in significant economic damage due to structural damage to buildings via high flow velocities (Pistrika & Jonkman, 2010). More alarmingly they also can cause significant human casualties due to the lack of warning associated with them. The most effective ways to mitigate the effects of flooding are to determine areas that are the most susceptible and implement either mechanical structures, to address the intense amount of rainfall associated with flash flooding, or non-mechanical public policies, to reduce the chance of humans or buildings residing in flood prone areas.

Mechanical structures for flood mitigation include various engineering interventions to contain the flow of water, such as levees, channels, or revetments. These mechanical structures have proven to be beneficial in reducing flood damages, having saved over $280 billion dollars in damages from 1991 to 2000 (Brody, Kang, & Bernhardt, 2012). However, there are limitations and shortcomings associated with structural approaches for flood mitigation. These range from flooding exceeding the design capacity of the structure resulting in higher damages than if the area was unprotected, to adding to adverse environmental conditions for the surrounding ecosystem (Brody et al., 2012).

Non-mechanical mitigation techniques on the other hand, are based on the principle of changing human activity to reduce the risk of flood damage. These non-mechanical mitigation strategies are usually public policies or land use restrictions that prevent human activity in flood prone areas and direct the activities or growth towards less susceptible areas. There are benefits and disadvantages of implementing non-mechanical flood mitigation strategies. A major benefit is the cost associated with non-mechanical mitigation. The United States Army Corp of Engineers have spent roughly $100 billion throughout the United States since the 1940s to erect flood mitigation structures, where in contrast there is minimal direct cost for implementing non-mechanical mitigation policies or land restrictions (Brody et al., 2012). However, there are some non-mechanical implementations that could be more effective. One such program is the National

Flood Insurance program, which provides insurance to those people living in flood prone areas as long as there is a minimum amount of local protection against flooding. This program has been criticized because it may actually promote development and activities in flood prone areas, which increases the chance of flood related damages occurring (Brody et al., 2012).

While both mechanical structures and non-mechanical policies are both ways to mitigate flash flooding, if these mitigations are placed in the wrong place they will not be effective.

Determinates of Flash Flooding

Even though flash floods can occur anywhere after intense rainfall during a short period of time, there are morphological characteristics that make certain areas more prone to flash flooding (Youssef, Pradhan, & Hassan, 2011). Multiple studies have examined how morphological characteristics, such as basin shape, basin size, stream density, and basin relief, contribute to flash flooding (Dawod, Mirza, & Ghamdi, 2011; Youssef et al., 2011). Some of the characteristics that influence flash flooding which will be included in this research are as follows: drainage basin size, basin shape, stream density, impermeability of soil, flow accumulation, basin slope, elevation, etc.

Basin size is one morphological feature of drainage basins that contribute to flash flooding. The size of the basin influences the timing of runoff, which is a significant factor in flash flooding. Large drainage basins allow more time for runoff from the uppermost part of the basin to reach the drainage outflow, which gives the runoff a greater chance of infiltrating into the soil. Also since the runoff has to travel a greater range of distances throughout the basin, it allows the runoff throughout the basin to arrive at the drainage output point in a staggered nature, which allows for less build up of water thus reducing the risk of flooding (University Corporation for Atmospheric Research, 2010).

Basin shape is another drainage basin characteristic that influences flash flooding. The way that basin shape influences flash flooding is similar to how basin size influences flooding. Basin shape influences the amount of time it takes for surface runoff to reach the drainage output of the basin. In a basin that has a round shape, the runoff all has to travel a similar distance to reach the output, and thus reaches this point at a similar time. This great influx of water all reaching the output at the same time can result in the water building up and flooding occurring. In contrast, basins with a more elongated shape have water from throughout the basin reaching the drainage output at different times, resulting in less water building up and a lower chance of flooding (University Corporation for Atmospheric Research, 2010).

Stream density is also an important basin characteristic that influences flash flooding. Stream density is defined as "the length of all channels within the basin divided by the area of the basin" (University Corporation for Atmospheric Research, 2010). Basins that have a higher stream density allow for the basin to drain more quickly after a storm event, which increases the possibility for flooding to occur since runoff will reach the drainage output quicker. It is also noted that basins that have a lower stream density tend to have soils that are more well-developed and these well developed soils have greater infiltration rates which reduces the amount of surface runoff. This reduction of surface runoff due to the greater infiltration of well-developed soils also reduces the chances of flooding in a basin (University Corporation for Atmospheric Research, 2010).

Land use is also of importance when it comes to flash flooding. Changes to the land use can result in increased surface runoff and can cause rapid and expansive changes in pre-existing runoff and hydrological processes (Booth, 1990). Change in the land use from forest or grassland to developed results in increased surface flow due to changes in the impermeability of the ground surface. This increase in flow rates due to urbanization can result in these urban areas to flood with much lower precipitation than surrounding areas that are not as urbanized (University Corporation for Atmospheric Research, 2010).

The characteristics that will be included in this study that are associated with flash flooding are elevation, slope, and flow accumulation. These characteristics are all inter-related in how they affect flooding. The surface runoff produced by a storm event will flow from a higher elevation to a lower elevation, so flooding will occur most of the time at lower elevations (Youssef, Pradhan, & Hassan, 2011). Slope affects flash flooding because it moves surface runoff to drainage output quicker and also influences the infiltration rate of the surface runoff into the soil. Areas with a greater slope have lower infiltration rates, which result in a greater volume of surface runoff (University Corporation for Atmospheric Research, 2010).

Using these variables describing basin morphology, climate, and land use, it is possible to create a multi-criteria flash flooding risk assessment to assess the most flood prone areas, as well as create a model to simulate flooding depth and extent for a storm of a particular magnitude. This thesis will address the data needed, methods, and broader implications associated with assessing the flash flooding risk and creating a flash flooding inundation model for Terre Haute, IN.

Study Area

Terre Haute is the county seat of Vigo County, located along the west central portion of Indiana, shown in Figure 1. According to the 2010 United States census, Terre Haute has a population of 60,785 and a land area of 34.54 square miles (2014). The western boundary of Terre Haute is defined by the Wabash River, which serves as a output for the storm drainage system of the city. According to a 2005 digital elevation model (DEM) for Terre Haute, the elevation ranges from 450.9 to 607.1 feet above sea level. Elevation is highest in the eastern portion of Terre Haute and drops as you head west, with the lowest elevations observed next to the Wabash River.

Research Questions and Hypotheses

This research focuses on two broad research questions and four related hypotheses.

First, given that land cover and land use are among the most variable characteristics which affect flooding and flash flooding, and among the easiest to manage through zoning or other public policy changes, part of this research will address which land use classifications, either developed/barren, wetland, crop/pasture, shrub/rangeland, or forest, are most susceptible to flash flooding. To address this question, I will test the following hypotheses:

> H1: Regardless of the urban drainage system, increases in impermeable land covers will increase flooding area.
>
> H2: A majority, greater than 50%, of the highest risk areas for flash flooding will reside in urbanized areas, rather than the surrounding undeveloped areas of Terre Haute.

Second, this research considers how typical precipitation events, and rarer more severe events as well, impact flooding inundation area and depth. Given that global climate change is predicted to modify precipitation patterns throughout the United States in the future, this focus has particular importance for current and future development in Terre Haute. This research will

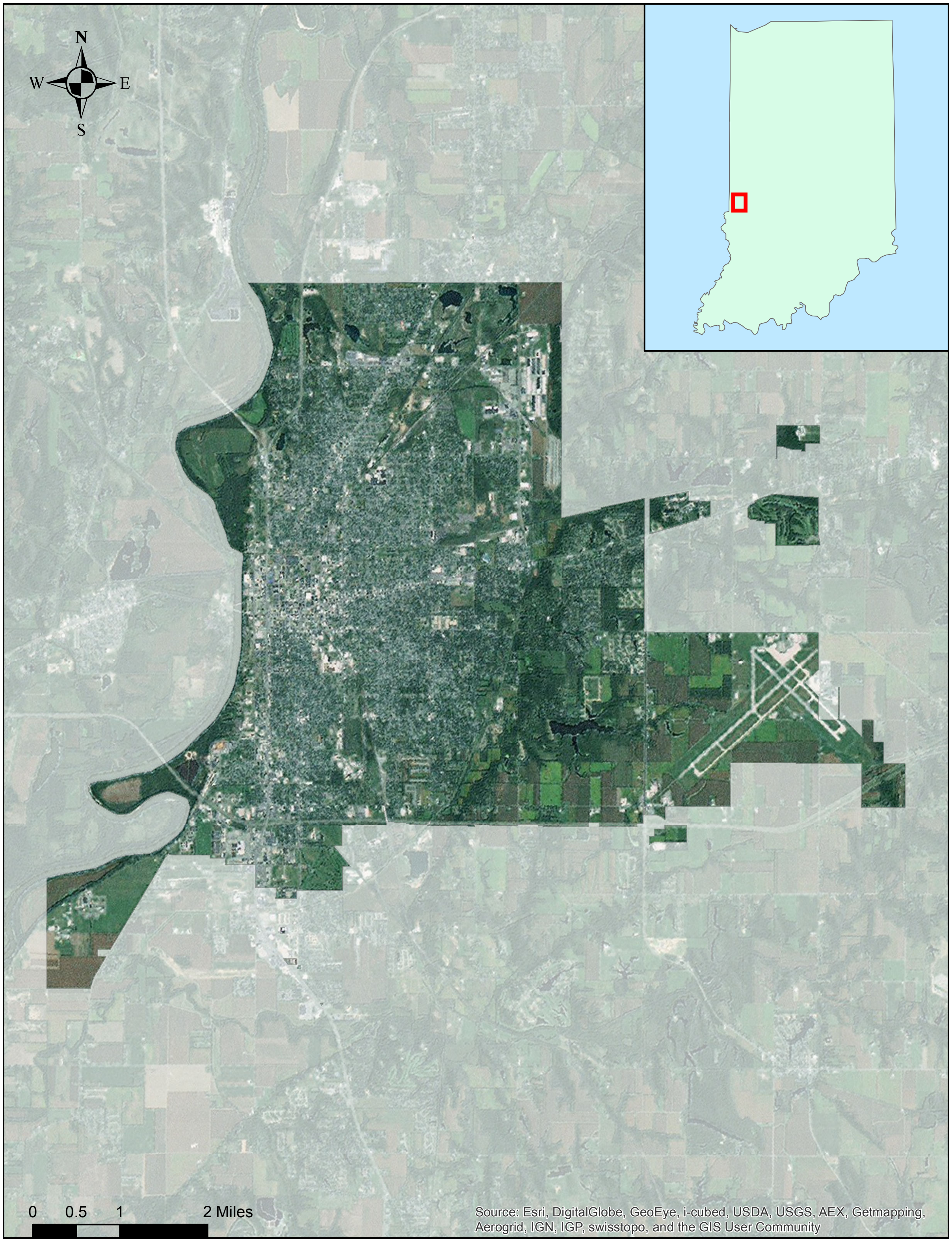

Figure 1. Map Terre Haute, Indiana, study area of research.

address a very pertinent question in regard to flash flooding storm events: Which areas of Terre Haute are prone to flooding during typical and atypical precipitation events? To address this question, I will test the following hypotheses.

H3: High magnitude, low frequency storm events will increase the inundated area compared with low magnitude, high frequency storm events.

H4: Model predictions are a reasonable way to identify areas that are prone to flash flooding under a variety of storm events.

CHAPTER 2

DATA AND METHODS

Data

Various sets of data are needed to complete the two distinct processes involved in this study: 1. The generation of a flash flood risk assessment map for Terre Haute, IN and 2. The completion of a comprehensive flash flood inundation model.

A. Flash Flood Risk Assessment

The following data, which can be obtained from the Indiana Geographic Information Council via www.indianamap.org, from the Indiana Spatial Data Portal at gis.iu.edu, or from the United States Department of Agriculture Web Soil Survey at http://websoilsurvey.nrcs.usda.gov/app/, are needed to create a flash flood risk map for Terre Haute, IN.

Watershed data for Terre Haute is necessary to derive numerous variables that are associated with flash flooding. The watershed data used in this study, which was obtained from www.indianamap.org, was the Hydrologic Unit Code (HUC) 14 subwatershed boundaries for Indiana. According to the United States Department of Agriculture, “Hydrologic unit boundaries define the aerial extent of surface water drainage to a point”(2013). HUC 14 is the

7th and smallest in area level of hierarchical hydrologic units that the U.S. Geological Survey created. These subwatersheds are required to calculate the basin size, basin shape, and drainage density using GIS functions. This data was created in 1991 and consists of a 1:24,000 polygon shapefile with a UTM zone 16N coordinate system.

A Digital Elevation Model (DEM) for Vigo County, IN is also needed to derive some variables associated with flash flooding. This 1.5 meter by 1.5 meter resolution DEM, which was obtained from the Indiana Spatial Data Portal at gis.iu.edu, was created in 2005 with the UTM zone 16N coordinate system and its vertical units in feet. This DEM will be used to determine the elevation and calculate the slope and flow accumulation for Vigo County.

The next pieces of data necessary for the flash flood risk assessment were land use rasters for Vigo County, IN. Different land use types contribute more to flash flooding than other land types. The land use layer will allow us to give a weight to each land type in Terre Haute, IN and the surrounding area. Weighting of land types will be accomplished by categorizing each land use into one of the following hazard level classifications: Very high = 10, high = 8, moderate = 5, low = 2, and very low = 1. Examples of land use categories are forested, wetlands, developed, etc. Land use layers from 2001 and 2006 will be used to determine if changes in land use will change distribution of risk classifications. The spatial resolutions of these layers are 30 meters by 30 meters with the UTM zone 16N coordinate system. These rasters consist of pixels of different numerical values that are associated with specific land uses, for example pixels with a value of 82 represent a land use of cultivated crops. A list of land use values and more detailed description on the defined land use type is provided in the metadata for this data.

Data describing the detailed stream/river channel locations for Vigo County, IN was also necessary for the flash flood risk assessment portion of this study. This data, which was obtained from www.indianamap.org, consisted of a 1:24,000 line shapefile that showed the location and length of each stream, river, canal, and ditch in Indiana using the UTM zone 16N coordinate system. The stream/river channel locations are combined with calculated basin areas to calculate the stream density for each subwatershed.

Finally, data defining the soil properties for the study area were needed as part of the risk assessment. For this study, hydraulic conductivity is the soil property that was used in the risk assessment as a factor of flash flooding. Hydraulic conductivity for surface soils is necessary to determine areas most susceptible to flash flooding. This data was obtained from the United States Department of Agriculture Web Soil Survey. The data are polygon shapefiles using the GCS_WGS_1984 coordinate system. This data contains a value, *Ksat_Rep*, that contains information for the representative hydraulic conductivity of the soils within the study area.

B. Flash Flood Inundation Model

For the flash flood inundation model, results of the risk assessment will be combined with the data described below to produce flooding depth and extent.

A DEM of Vigo County, IN is also necessary to develop an inundation model for Terre Haute. This DEM is the same as the DEM listed above in the Flash Flood Risk Assessment section and was used to determine starting cells in which water will begin to be added to the inundation model. The DEM also provided an elevation for the inundation model to check against to determine if a cell should be considered inundated or not.

Rainfall Intensity Curves are necessary to determine the amount of precipitation that falls over the study area for each storm event investigated. These curves, which are in PDF format, are obtained from the Indiana Department of Natural Resources Division of Water at http://www.in.gov/dnr/water/4897.htm. These intensity curves provide a modeled amount of rainfall that will fall in an area for storms of a certain magnitude over a given period of time. These curves will be used to interpolate how precipitation falls over the study area for each storm event examined in this study. An example of a rainfall intensity curve map is shown in Figure 1.

Precipitation amounts collected from weather stations scattered across the greater Terre Haute area are necessary to validate the modeled results to observed storm events. This precipitation information will be used after a storm event to determine which of the modeled storms is closest to the overall precipitation amount recorded for the storm event and will be used for validation comparison. This data was obtained from the National Weather Service Advanced Hydrologic Prediction Service at http://water.weather.gov/precip/download.php. This is a point shapefile using the HRAP_Sphere coordinate system and contains a field, *globvalue*, which is the amount of precipitation, in inches, that fell within the past 24 hours.

Data on the location and capacity of the sewage drainage system for Terre Haute was necessary to calculate the amount of precipitation becomes necessary to cause surface runoff and contribute to flash flooding. Terre Haute uses the sewage drainage system as its storm water drainage system. The city of Terre Haute has provided a line shapefile using the NAD_1983_StatePlane_Indiana_West_FIPS_1302_Feet projected coordinate system on the sewage and storm system.

Finally, soil properties for the study area are used to calculate the amount of precipitation infiltration that naturally occurs during a rainfall event. This data can be obtained via the United States Department of Agriculture Natural Resources Conservation Service’s Web Soil Survey. This shapefile includes information on the hydrologic soil group of each soil within the study area, which is an estimation of potential surface runoff and soils are classified into one of four groups, A through D, based on their rate of infiltration (United States Department of Agriculture, 2014). Using the hydrologic soil group information along with land use data, a composite curve number can be calculated, which is used to calculate surface runoff.

Methods

The following section outlines the methods that were used to address the research question and hypotheses. This section is broken up into two individual methodologies: 1. The flash flood risk assessment and 2. The flash flood inundation model for Terre Haute, IN.

A. Flash Flood Risk Assessment

The flash flood risk assessment analysis was performed in ESRI's ArcMap 10. The data listed in the previous section were added to ArcMap 10.1 and various processes were implemented to create the following variables: subwatershed size, subwatershed shape, stream density for each subwatershed, elevation, slope, flow accumulation, hydraulic conductivity and land use classification. Some variables were provided directly by the downloaded data, but others were generated using tools built into ArcMap, as described below:

i. Subwatershed Size: Variable already included in downloaded data. Area is in square meters.

ii. Subwatershed Shape: The tool "Zonal Geometry as Table" will be used to determine the length of the major and minor axis for each subwatershed. The major axis is the longest calculated distance within each subwatershed with vertices on the subwatershed boundary. The minor axis is the shortest calculated distance within each subwatershed with vertices on the subwatershed boundary. Those measurements were then used to calculate the shape ratio:

$$\textit{Shape Ratio} = min/maj \qquad [1]$$

Where *min* is the length of the minor axis and *maj* is the length of the major axis. A shape ratio close to 1 indicates that the subwatershed is round, and the further away from 1 the ratio is, the more elongated is the subwatershed.

iii. Stream Density: The stream/river channel data needs to be associated with a subwatershed. In order to link that stream data to its corresponding subwatershed, the "Spatial Join" tool was used. As a result, each stream segment is associated with its corresponding subwatershed and the total length of all streams in a subwatershed is calculated. This stream length sum was used to calculate stream density, via the field calculator, as follows:

$$Stream\ Density = l/A \qquad [2]$$

Where l is the sum of the lengths of all the stream/river channels in a subwatershed, and A is the area of the subwatershed.

iv. Elevation: The elevation variable is already present in the DEM data obtained from the Indiana Spatial Data Portal and the units of vertical elevation are feet.

v. Slope: The "Slope" tool, within spatial analyst tools, was used on the DEM of Vigo County to calculate the degree slope for each pixel in the Vigo County DEM.

vi. Flow Accumulation: The "Flow Accumulation" tool, within the spatial analyst tools, will use a Flow Direction, derived from the Slope dataset described above, to determine the accumulated flow into each cell. The result of the flow accumulation tool provides the total number of cells within the processing area that flow into that particular cell, thus cells at lower elevations, and at the pour point of subwatersheds, will have higher flow accumulation values.

vii. Hydraulic Conductivity: Hydraulic conductivity values are provided in the obtained data. Data contains low, high, and representative hydraulic conductivity values for each individual area and for this study, the representative value will be used. The representative hydraulic conductivity value is "a parameter controlling the average behavior of groundwater flow within an aquifer at a given scale" (Sanchez-Vila et al., 2006).

viii. Land Use/Classification: Land use categories already derived and provided in obtained data for 2001 and 2006. Values are reclassified as shown in Table 1.

Table 1. Land use reclassification used in flash flood risk assessment.

Original Value	Land Use	Reclassified Value
11	Open Water	0
21	Developed, Open Space	1
22	Developed, Low Intensity	1
23	Developed, Medium Intensity	1
24	Developed, High Intensity	1
31	Barren Land	1
41	Deciduous Forest	2
42	Evergreen Forest	2
43	Mixed Forest	2
52	Shrub/Scrub	3
71	Herbaceous	3
81	Hay/Pasture	4
82	Cultivated Crops	4
90	Woody Wetlands	5
95	Emergent Herbaceous Wetlands	5

Developing Weights for Flash Flood Risk Assessment

After the variables were created, a weighting system was then employed to adjust how these variables influence flash flooding potential. Kourgialas and Karatzas (2011) examined the relationships between some of the variables described above to create a weighting scheme for flooding in Greece. This study replicated the method used by Kourgialas and Karatzas for the Terre Haute, IN area and generated the weighting scheme shown in table 2. In their weighting scheme, Kourgialas and Karatzas (2011) categorized each variable into the following hazard level classifications based on Jenks Natural Breaks: Very high = 10, high = 8, moderate = 5, low = 2, and very low = 1. A similar classification system is seen in the "Descriptive Level" and "Proposed Weight of Effect" columns in table 2. For the "Hydraulic Conductivity" variable, the Jenks Natural Breaks method of creating levels of classification determined that four levels were more appropriate than five, so the very low and low levels were combined and the lower of the proposed weights was used. Also of note, for the "Flow Accumulation" variable, Jenks Natural Breaks did not show much variation between risk levels, thus geometric interval was used to determine level classifications since it showed better variation. Kourgialas and Karatzas (2011) then integrated all the variables into an overall weighting scheme that accounted for each variable having a different level of influence on flash flooding. They determined the overall weighting factors for each variable by taking into consideration the effect each variable has on the other variables. Relationships between variables, if there were any, were either classified as major or minor, defined by user interpretation of the level of relatedness between variables. After all relationships were defined, the amounts of major and minor variables were totaled for each variable. In order to distinguish between each type of effect, one point was assigned to major effects and a half-point was assigned to the minor effects. This method of determining the

Table 2. Weighting scheme for flash flood factors in Terre Haute, IN.

Factor	Domain of Effect	Descriptive Level	Proposed Weight of Effect (a)	Rate (b)	Weighted Rating (a x b)	Total Weight	Percentage (%)
Hydraulic Conductivity	≤ 2.82	Very High	10	2.5	25	61.25	12.17
	2.82001 - 9.17	High	8		20		
	9.170001 - 28.23	Moderate	5		12.5		
	28.23001 - 91.74	Low - Very Low	1		3.75		
Basin Area	40,762,743 - 47,881,848	Very High	10	2	20	52	10.33
	30,931,597 - 40,762,742	High	8		16		
	26,637,533 - 30,931,596	Moderate	5		10		
	19,066,421 - 26,637,532	Low	2		4		
	≤ 19,066,420	Very Low	1		2		
Basin Shape	0.757286 - 0.781913	Very High	10	2	20	52	10.33
	0.632280 - 0.757285	High	8		16		
	0.427224 - 0.632279	Moderate	5		10		
	0.312118 - 0.427223	Low	2		4		
	≤ 0.312117	Very Low	1		2		
Stream Density	0.001351 - 0.001489	Very High	10	1	10	26	5.17
	0.001326 - 0.001350	High	8		8		
	0.001232 - 0.001325	Moderate	5		5		
	0.001049 - 0.001231	Low	2		2		
	0.000983 - 0.001048	Very Low	1		1		
Elevation (feet)	450 - 482	Very High	10	4.5	45	117	23.25

	483 - 512	High	8		36		
	513 - 547	Moderate	5		22.5		
	548 - 580	Low	2		9		
	581 - 645	Very Low	1		4.5		
Slope (degree)	40 - 81	Very High	10	3	30	78	15.5
	22 - 39	High	8		24		
	10 - 21	Moderate	5		15		
	4 - 9	Low	2		6		
	0 -3	Very Low	1		3		
Flow Accumulation (Geometrical Interval)	12,921,069 - 78,130,448	Very High	10	1.5	15	39	7.75
	2,130,109 - 12,921,068	High	8		12		
	344,403 - 2,130,108	Moderate	5		7.5		
	48,901 - 344,402	Low	2		3		
	0 - 48,900	Very Low	1		1.5		
Land Use	Developed or Barren	Very High	10	3	30	78	15.5
	Wetland	High	8		24		
	Crop or Pasture	Moderate	5		15		
	Shrub or Rangeland	Low	2		6		
	Forest	Very Low	1		3		
SUM						503.25	100

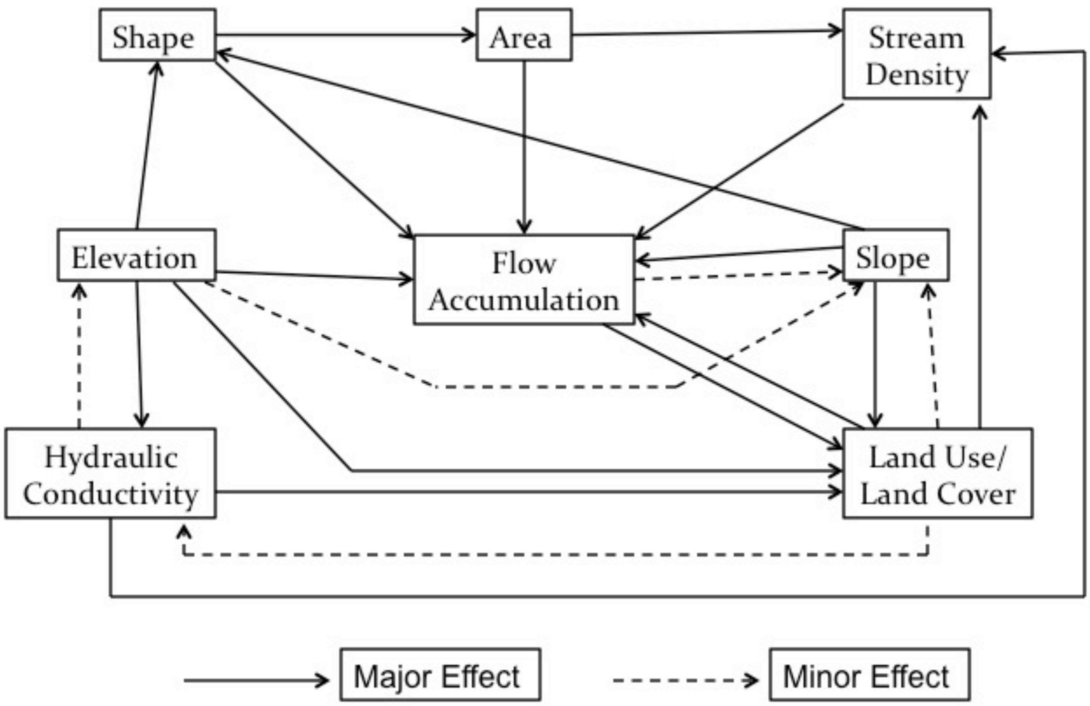

Figure 2. Relationships between flash flooding variables.

relationships between the variables was performed for the Terre Haute, IN area as well. The final relationship between variables used in this study is listed in Figure 2.

The rate for each variable was then determined by adding all the major/minor relationship points for each variable. The result of the relationship point summation is recorded in the "Rate" column in Table 2. Using the "Proposed Weight of Effect" and "Rate" columns, a weighted rating can then be calculated for each classification level for each variable, as recorded in the "Weighted Rating" column. All of the weighted rating values are then added together and recorded in the "Total Weight" column for each variable, as well as the overall sum of all of the total weights for each variable being calculated. The final column in table 2, "Percentage", is the "Weighted Rating" value for each variable divided by the sum of all the "Weighted Rating" values. This percentage is the percentage that each individual variable will contribute to the flash flooding risk assessment.

For example, look at elevation in Table 2. The range of elevation values, domain of effect, are broken up into five distinct descriptive levels based on Jenks Natural Breaks. Each individual descriptive is given a proposed weight of effect, which gives the elevation its individual weighting scheme. Based on the relationships defined in Figure 2, a rate is then assigned to elevation in the rate column. This rate is calculated by giving major relationships between variables a value of 1.0 and minor relationships a value of 0.5. As seen in Figure 2, elevation has a major effect on hydraulic conductivity, shape, flow accumulation, and land use and a minor effect on slope. The summation of all the relationship values is 1+1+1+1+0.5, which equals 4.5, the rate for elevation. The proposed weight for elevation is then multiplied by the calculated rate to give us the weighted rating. The weighted ratings are then added together to give the total weight for the elevation variable. For elevation it is 45+36+22.5+9+4.5, which equals 117. After the total weight for each variable has been calculated, the percentage that each variable contributes to the flash flood risk assessment is calculated by dividing the individual variable's total weight by the sum of all variable's total weights.

After creating the weighting scheme, the next step in the risk assessment process is converting the data to proper formats that can be utilized in ArcMap to produce the risk assessment. This requires each variable be reclassified so that it reflects the level classification proposed in Table 2. The spatial data sets that are in vector format need to be converted to rasters, because the combination of layers to produce the risk assessment requires raster data. The "Polygon to Raster" tool, within the conversion tools, converts the vector polygons to rasters. Next, using the "Reclassify" tool, within the spatial analyst tools, each variable was reclassified based on the value ranges in the "Domain of Effect" column. After each variable has been reclassified, all the variables need to be combined by their percentage of effect to determine the overall flash flooding risk distribution for the Terre Haute, IN area. By using the "Weighted Sum" tool, within the spatial analyst tools, all of the individual rasters were combined into one overall weighted raster based on the percentage that each raster contributes towards flash flooding, this percentage for each variable is displayed in "Percentage" column in Table 2. The process described above takes percentage of effect and combines it in a spatially-aware final product, which shows which parts of the study area are affected. The product of the weighted sum analysis, when classified by five Jenks Natural Break classes, shows very low, low, moderate, high, and very high flash flooding risk areas for the Terre Haute area.

After the flash flooding risk assessment was produced, the very high risk areas needed to be isolated to address the first set of research questions. Using the "Set Null" tool, within the spatial analyst tools, all values less than the lowest very high risk value were set as a null value, which leaves only the very high risk area visible. Then using the “Extract by Mask” tool, within the spatial analyst tools, the very high risk areas within the Terre Haute city boundaries were isolated from the very high risk areas of the surrounding area.

B. Flood Inundation Model

Once a flash flood risk assessment has been produced, the next step is to create an inundation model that predicts flooding extent for a storm event of a given magnitude over a specific interval of time. This required examining precipitation data for the Terre Haute area to determine the spatial distribution of rainfall during a flash flood producing storm system. To determine the precipitation distribution for storms of various magnitudes and durations, rainfall intensity curves for various storm scenarios were used to interpolate precipitation amounts for the study area (described in more detail, below). Rainfall intensity curves provide hypothetical rainfall amounts for various storm events based on composite values derived from rainfall distribution of computer-modeled storms. Interpolation of these curves assumes that rainfall is continuous over the entire study area, where as actual storms exhibit irregular patterns that may produce rainfall in isolated portions of the study area at different times. These curves range from duration of less than 1 hour to 10 days and storm magnitudes of a 1-year storm to a 100-year storm, with a 100-year storm being of much greater magnitude and less probability of happening in a given year than the 1-year storm. For this study, 15-minute, 2 hr, 3 hr, and 6 hr durations will be examined for 2 year (typical) and 100-year (atypical) storm events.

The creation of the flash flood inundation model will resemble a method proposed by a study using GIS to develop an urban flood model on a university campus (Chen et al., 2009). Using information on the spatial distribution and amount of precipitation for a storm event, land properties, and the sewer drainage system, the amount of surficial runoff for the storm event was calculated. Runoff was calculated using Curve Number (CN) method, which was developed by the US Natural Resources Conservation Service. This process uses geologic and soil information to assign a unique CN value for each area, which can then be used to estimate surface runoff

Figure 3. 15-minute rainfall intensity curve for a 2 year storm event in Indiana from http://www.in.gov/dnr/water/4897.htm.

through a series of mathematical equations (Dawod, Mirza, & Ghamdi, 2011). Even though the CN method was originally developed to address runoff in agricultural settings, there is a section in chapter 9 of the National Engineering Handbook that addresses curve numbers for urban and residential land (United States Department of Agriculture, 2004). For this study, a composite CN was derived using land use and soil classifications. Soil data obtained from the United States Department of Agriculture Web Soil Survey contains information on the hydrologic soil groups for each soil in the study area. Using the land use and soil hydrologic soil group, a specific CN can be obtained. A CN is determined for each land use/hydrologic soil group in each subwatershed, then a composite CN is derived for a subwatershed based on area of all CN's. The composite CN is then used in the equations shown in Figure 3 to determine the amount of runoff for a storm event.

The calculated amount of runoff is then combined with the DEM of Vigo County and the risk assessment data previously created, to develop an inundation model for Terre Haute. Due to fact that the coarsest spatial resolution data layer in this study is 30 by 30 meters, the 1.5 by 1.5 meter resolution DEM had to be coarsened to 30 by 30 meter to maintain spatial continuity. This was accomplished by using the "Resample" tool, within the data management tools; the DEM is changed to 30 by 30 meter pixels. Next, the DEM needed to be converted from feet to inches. This was accomplished by using the raster calculator to create a new raster, which is the quotient of the original DEM divided by 12. Also, the tools used within the inundation model require that the data models of layers being used cannot be 32-bit floating integer. Unfortunately, the DEM data is 32-bit floating point, so the data needed to be converted to a data type that is supported by the "expand" tool (employed and described below). In order to accomplish this, the DEM was multiplied by 10,000, so that inch, tenth of an inch, hundredth of an inch, and thousandth of an inch additions could be made to the inundation model.

$CN = 1000/(10+S)$

$I_a = 0.2S$

$Q = (P-I_a)^2/((P-I_a) + S)$ $\quad$ $P > I_a$

$Q = 0$ $\quad$ $P \leq I_a$

where:
Q = depth of runoff in inches
P = depth of rainfall in inches
I_a = Initial abstraction in inches
S = maximum potential retention in inches

$QT = (Q*A)-(t*D)$

where:
QT = Runoff volume (in^3)
Q = Runoff depth (in)
A = Watershed area (in^2)
t = Time (s)
D = Volume of storm water conveyed by underground drainage system (in^3/s)

Figure 4. Curve number and runoff equations from United States Department of Agriculture (2004).

In order for the inundation model to run, the model requires locations where it can start adding water. In this study I used locations known as sinks to be the areas where the model began adding water iterations. Sinks are cells within a DEM in which all of the surrounding cells are greater in elevation (Wu et al., 2008). Even though sinks can be created due to the input errors or interpolation artifacts in DEM creation (Wu et al., 2008), in this study they best represent where flash flooding will occur in a natural landscape. Using the “Sink” tool, within the spatial analyst tools, sinks can be found within almost any DEM. These sinks can then be placed in a new spatial dataset by employing the “extract by mask” tool; in this manner, sink locations that reside in the very high flash flood risk areas can be isolated, which was used in this study to select places to add water to the model. These very high risk area sinks are what is used as the base wet cells in the inundation model.

The next step in the inundation model process is to add water to the model and iterate through flooded cell expansions. The overall goal is to keep adding iterations of water to the model, which will in turn increase the flooded area. A cutoff is necessary to determine when the iterations need to stop before the calculated surface runoff is exceeded. For this study, a 95% of calculated surface runoff cutoff was selected, so when the calculated volume after an iteration is within 5% of the calculate runoff, iterations will cease. While this step could be manually performed for each iteration within ArcMap, Python scripting is used in this study to develop a process of automatically iterating through each expansion. When creating a model script in Python, the user must first import in site packages and toolsets that are going to be used in the analysis. For this study, the site packages ArcPy and NumPy are imported. Then variables to be used within the model need to be created and filled with layers or data. The variables that were created are as follows:

i. *Surface_runoff*: The calculated surface runoff derived from the curve number method.

ii. *Beginning*: Starting sink locations in which water will begin to be added to.

iii. *DEM*: Original 30 by 30 meter DEM of Terre Haute.

iv. *Iteration*: Numbers of current iteration.

v. *total_flood_vol*: Total flood volume that has been added to the model.

vi. *vol_ratio*: Ratio of water added to the model to the overall calculated surface runoff.

vii. *x*: The amount of water to be added in each iteration.

Once these initial variables were created, the process of iterating through the model could begin. An overview of the general steps within the Python model is shown in Figure 4. The first step is to add *x* amount of water, up to a maximum of one inch in the first iteration, to the starting cells. This was accomplished by using the raster calculator to create a new raster, *flood_wadd*, with *x* added to the initial elevation of the starting cells, which will then be known as wet cells within the model. After this water addition has been completed, the wet cells need to be expanded to their eight neighboring cells. Using the "Expand" tool, within the spatial analyst tools, the value of the wet cells were expanded into their neighboring cells and this value takes the place of the original elevation value. The result of this expansion results in the creation of a new raster, *flood_expand*. Next, a subtraction of *DEM* from *flood_expand* occurs, which will

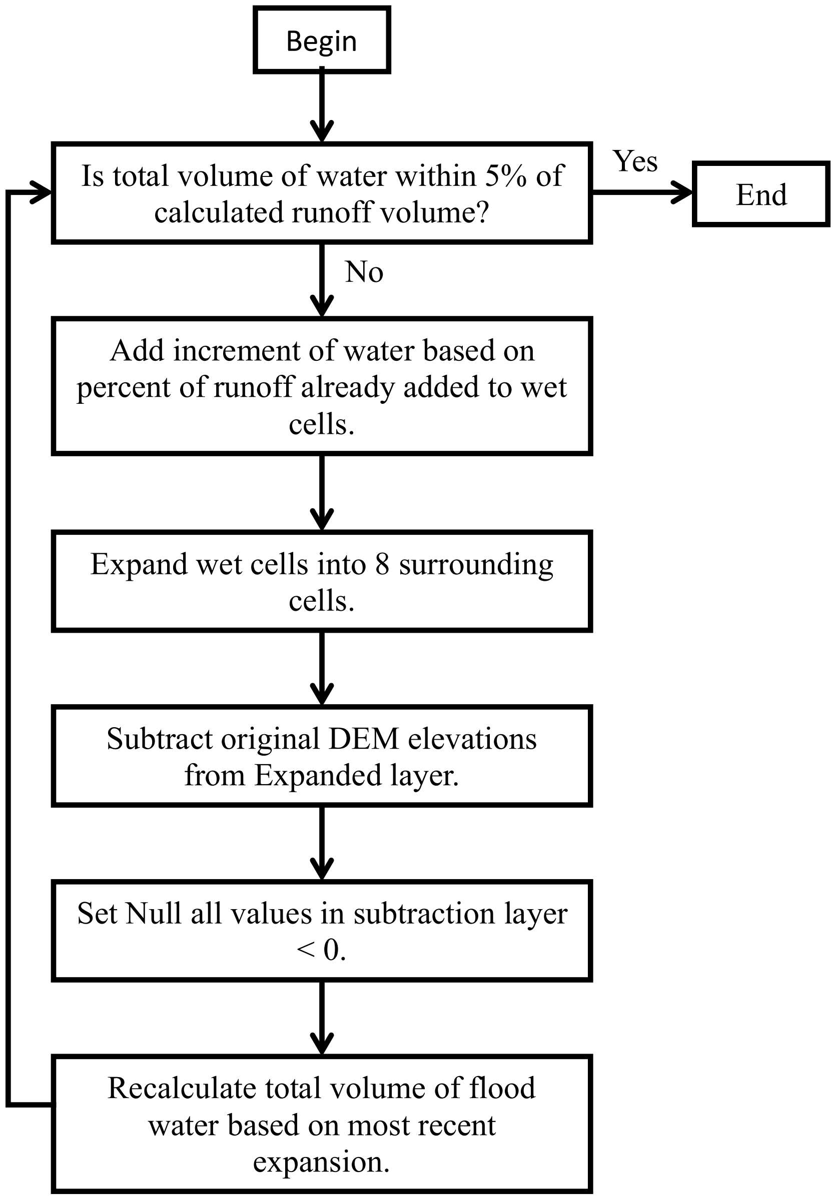

Figure 5. Flowchart of inundation model.

highlight areas where flood expansion will result in the water level being greater in elevation than the base elevation. This subtraction is performed by using the raster calculator and results in the creation of a new subtraction raster, *flood_diff*. After determining which cells will actually become wet, all of the other cells need to be set to null. Using the set null tool, a raster, *flood*_depth, will be created containing all values within the *flood_diff* raster with a value less than 0 will be set to null, thus isolating the cells which water expansion will result in flooding. Subsequently this *flood_depth* raster also provides the depth of water for the wet cells, which is necessary to calculate the volume of water presently added to the model. The *flood_depth* raster is then multiplied by 30 square meters to determine the volume of water added to each cell, resulting in the creation of the *flood_vol* raster. Then the overall area of the wet cells are calculated and recorded in the raster named *flood*_area. Zonal statistics are then calculated on the *flood_vol* raster based on the zone defined in the *flood_area* raster. The zonal statistics provides the total volume of water that has been added to the model through this iteration, as the variable *total_flood_vol*. The ratio of added water to the total calculated surface is then determined and recorded as *vol_ratio*.

The next part of the inundation model is where the Python script iterates using *While* statements. The script is set up to work in such a way that while the volume of added water to calculated surface runoff is under a certain ratio, it continues to add an inch of water to each wet cell for each iteration. Once the ratio is exceeded, the script quits adding an inch of water and for the next iteration another *While* statement goes into effect which adds a tenth of an inch of water to each wet cell. The script continues to iterate through the following addition increments until the total volume added to the model is within 5% of the calculated surface runoff, or is one iteration past when even the lowest increment is added: inch, tenth of an inch, hundredth of an inch, and thousandth of an inch. The result of the script produces a raster that shows how flooding is spatially distributed throughout Terre Haute for the various storm magnitudes and durations.

C. Model Validation

Any modeling process must have a validation step, though validating this particular model is difficult given the lack of spatially explicit citywide flooding data. Chen et al. (2009) validated their GIS based inundation model by comparing modeled flood depth and actual flooded depths recorded for historical storms at particular locations. Searches for historical data regarding the extent and depth of flooded areas during storm events for Terre Haute did not yield any data. Therefore the validation approach used in this study consists of modeling a variety of typical and atypical storm events, and then using the modeled flood locations as a way to target validation visits during storm events that match, or are predicted to match, the modeled events. Though this will yield only flood-presence data, it is the only practical way to validate model outputs given the scale of this project.

Presence-only data have been used to successfully validate models, but are not perfect indicators of model performance. When validating a model, a robust set of statistical procedures is used to calculate the differences between the predicted and actual observations for presence data and comparing that to the differences between predicted and actual observations for the absence data. However, with presence-only modeling, absence data are not available to compare presence data to, which increases the uncertainty of the model (Ottaviani et al., 2004). Another limitation of presence-only data is the spatial accuracy of the presence data (Ottaviani et al., 2004). This issue of spatial accuracy is addressed by building coordinate geometry (COGO) polygons of observed flooding at locations the model predicts flooding will occur. The presence-only locations will be determined by largest flooded areas determined by the 100-year, 6-hour storm event model. This storm event gives us a worse-case scenario that will indicate areas where flooding is most likely.

In order to utilize presence-only validation, this study employed opportunity sampling during field verification. First, storm events with flash flooding potential need to be determined. Storm systems that have the following severity potentials issued in a statement by the National Weather Service (NWS) were deemed appropriate for collecting data: severe thunderstorm watch, severe thunderstorm warning, flash flood watch, or flash flood warning. When these storm warnings were issued, arrangements were made to collect data when or if the storm affected the study area. If a storm system with the any of the above warnings failed to produce data, the next such storm system with any of the proposed NWS issued statements was used.

Figure 5 depicts the overall method for collecting the validation data. When at a location that the model predicts will experience flooding, a safe location was chosen to stand and observe the extent of the flooding. Using a GPS application on the observer's smartphone, the decimal degree coordinates were taken for the observer's standing position. Next, using a compass and rangefinder, the azimuth, Θ, determined off of magnetic north and distance from the observation point to various points, x and y, of the observed flooding area will be recorded. These data are then imported into ArcMap and using the azimuth and distance data with the "Bearing Distance to Line" tool, within the data management tools, distance lines are created for each point surrounding the observed flooded area. Finally, creating polygons that snap to the end of each of the distance lines will provide the field observed flooded areas (Figure 5).

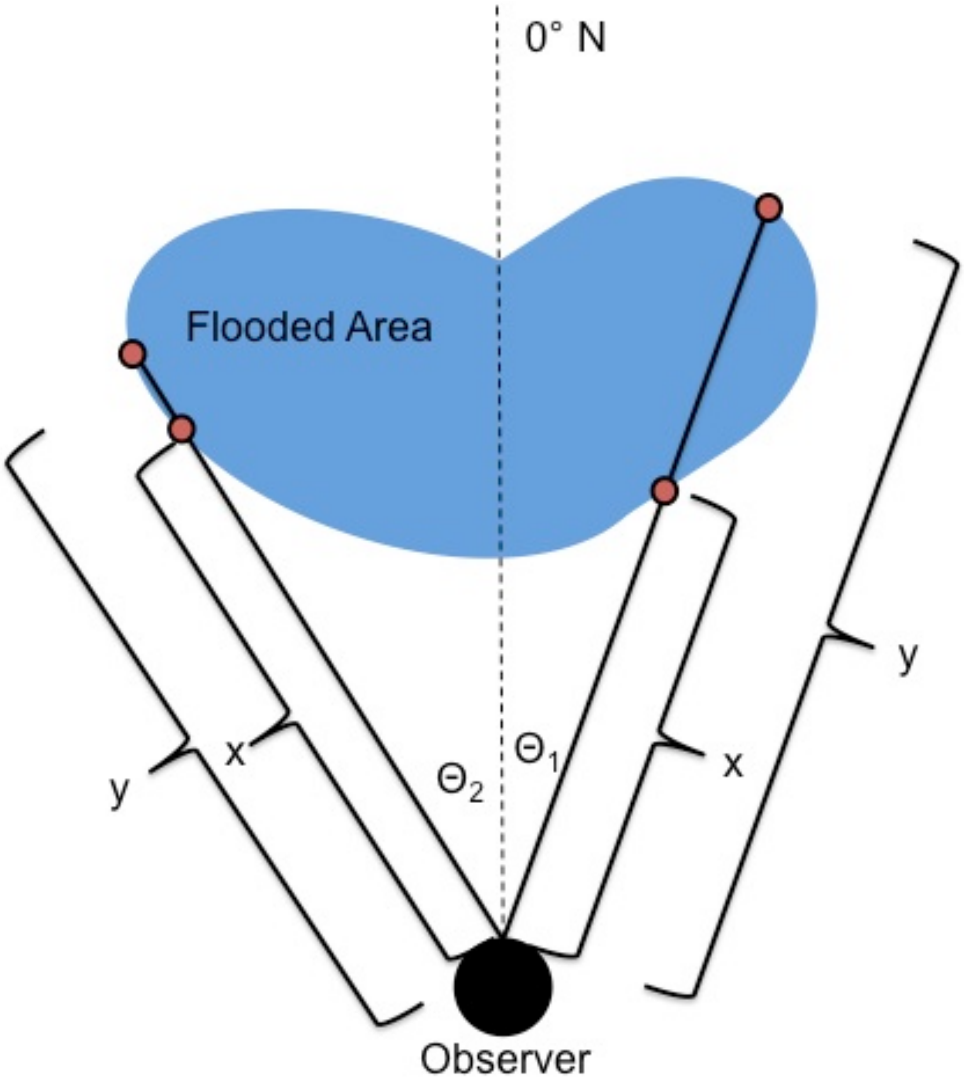

Figure 6. Diagram of validation method.

CHAPTER 3

RESULTS

This chapter presents the results of the data analysis required to address the research questions. The data analysis was conducted using the processes outlined in Chapter 2. There were two main goals that influenced the collection, creation, and analysis of data. The first goal was to develop a flash flood risk assessment for Terre Haute, which would highlight areas within the city that are the most prone to flash flooding. The second goal was to create a flash flood inundation model for Terre Haute, which would provide an estimation of the spatial distribution of flooded areas during storms of various magnitudes and intensities. These goals were accomplished through the application of the methods described in Chapter 2, and the results are as follows.

Flash Flood Risk Assessment

1. Effect of land use on flash flooding risk

The following results address the research questions regarding the flash flooding risk assessment for Terre Haute. The first research question examined if changes in land use affect flash flooding risk in Terre Haute. The comparison of land use for the years 2001 and 2006 were used to examine this question. Figures 6 and 7 and Table 3 show the results of the flash flood risk assessment for the years 2001 and 2006. Figures 6 and 7 show the spatial distribution of the risk assessments for 2001 and 2006 respectively. Table 3 shows the comparison of the differences between the risk assessments for the different years examined. For 2001, the percentage of the total land area that falls within each risk level is as follows: 9.75% very high risk, 25.28% high risk, 26.59% moderate risk, 24.55% low risk, and 13.84% very low risk. For 2006, the percentage of total land area that falls within each risk level is as follows: 10.19% very high risk, 24.11% high risk, 27.85% moderate risk, 23.34% low risk, and 14.51% very low risk. Between 2001 and 2006 there was an increase in the very high, moderate, and very low risk areas and a decrease in the high and low risk areas within the risk assessment.

2. Examination of land use of very high risk areas

The second research question pertaining to the flash flood risk assessment examines which land uses constitute the very high risk areas. Figure 8 highlights the spatial distribution of the very high risk areas. Figure 9 breaks down the very high risk areas into the following land use categories: developed or barren, wetland, forest, crop or pasture, and shrub or rangeland. Table 4 shows the numerical breakdown of each land use for the very high risk areas and the percentage each land use is of the total very high risk area. For the very high flash flooding risk area, the land use percentage is as follows: 55.36% developed or barren, 29.12% crop or pasture, 11.68% wetland, 3.71% forest, and 0.13% shrub or rangeland.

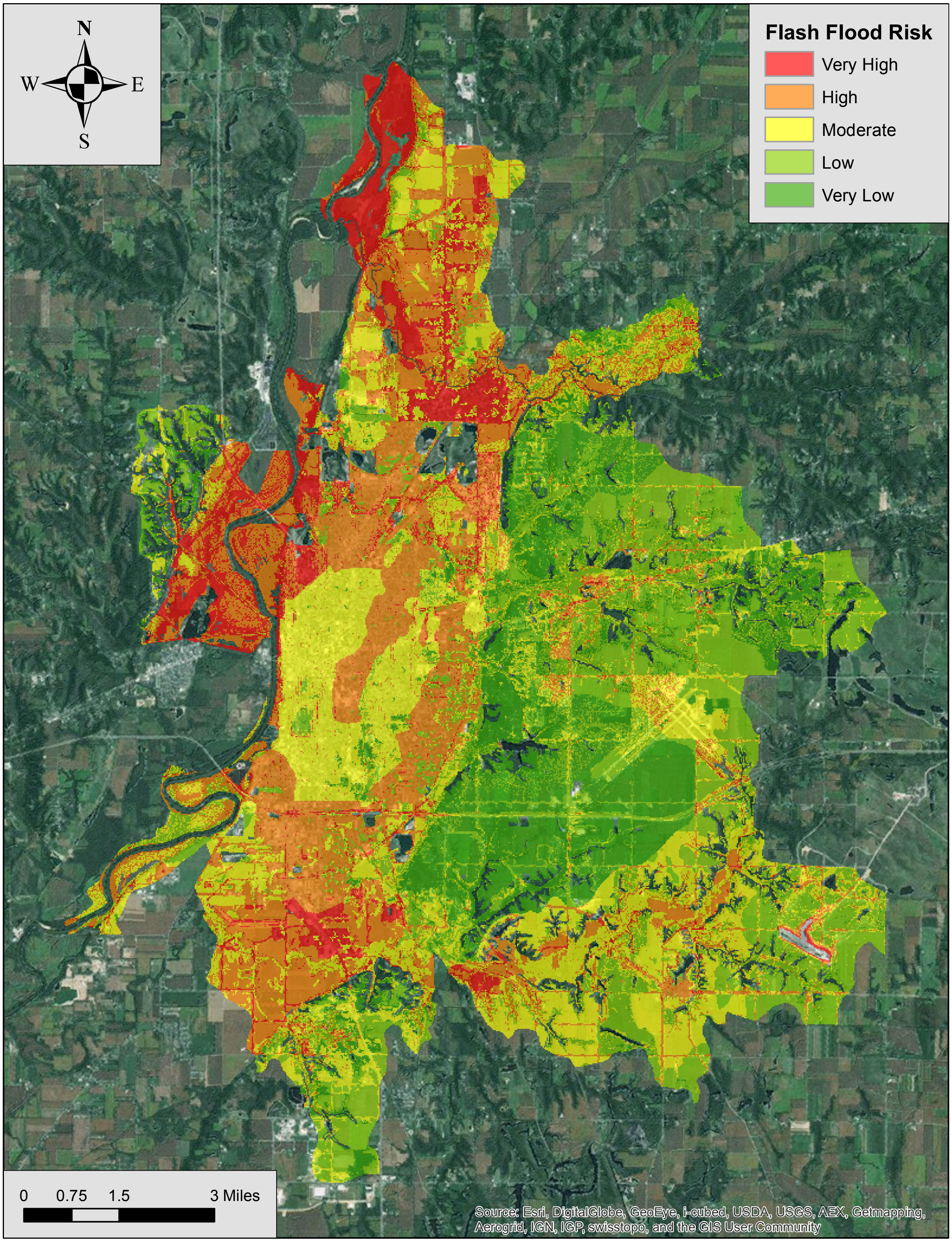

Figure 7. Flash flood risk assessment for study area in 2001.

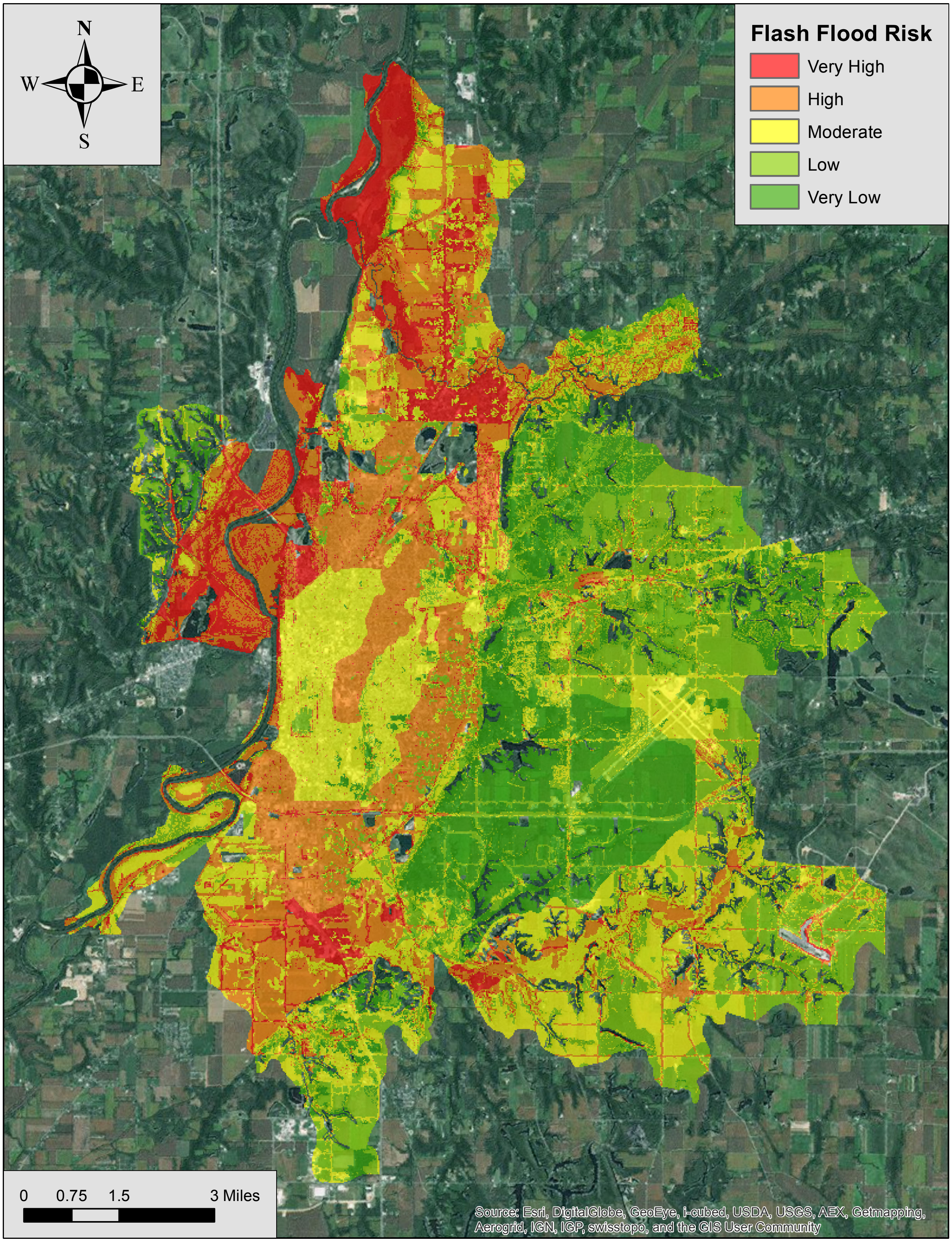

Figure 8. Flash flood risk assessment for study area in 2006.

Table 3. Comparative analysis of flash flood risk areas between 2001 and 2006.

Risk	2001		2006	
	Area (km^2)	**% of Total Area**	**Area (km^2)**	**% of Total Area**
Very High	25.46	9.75	26.82	10.19
High	66.02	25.28	63.46	24.11
Moderate	69.44	26.59	73.30	27.85
Low	64.11	24.55	61.45	23.34
Very Low	36.14	13.84	38.20	14.51
SUM	261.17	100	263.22	100

Table 4. Land use breakdown of very high risk flash flood areas.

Land Use	Very High Risk Area (km^2)	Percent of Very High Risk Area
Developed or Barren	14.8446	55.36
Wetland	3.1329	11.68
Crop or Pasture	7.8084	29.12
Shrub or Rangeland	0.036	0.13
Forest	0.9936	3.71
Sum	**26.8155**	**100**

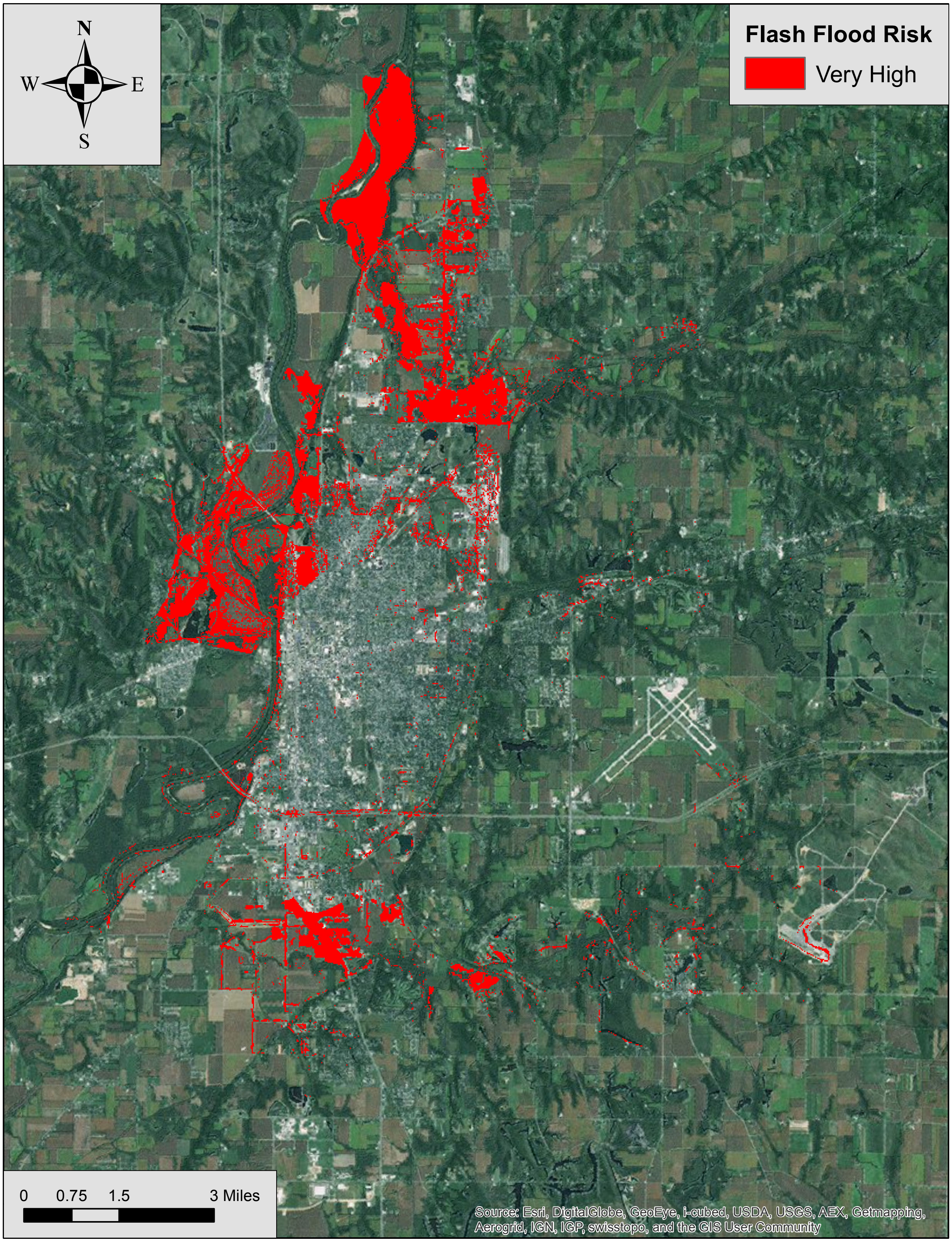

Figure 9. Spatial distribution of very high flash flooding risk.

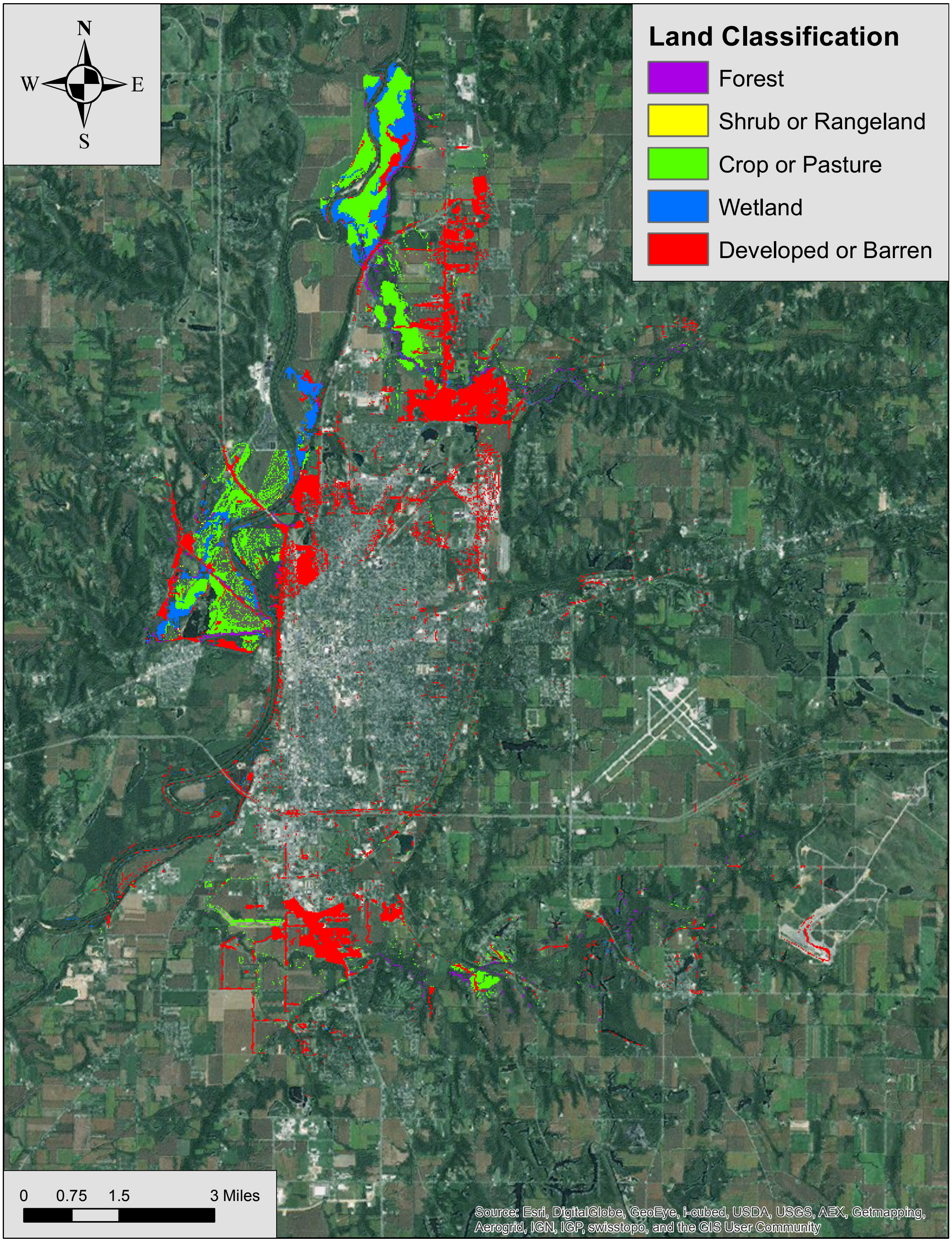

Figure 10. Land use of very high risk flash flooding areas.

Flash Flood Inundation Model

1. Modeled Results

The second part of this study developed an inundation model that would estimate the extent of flash flooding for storms of varying intensity and duration. Figures 10 through 17 show the modeled results of the following storm intensities and durations: 2 year – 15 minute, 2 year – 2 hour, 2 year – 3 hour, 2 year – 6 hour, 100 year – 15 minute, 100 year – 2 hour, 100 year – 3 hour, and 100 year – 6 hour. Table 5 displays the detailed modeled results for each storm intensity and duration combination investigated in this study, and lists the total calculated runoff for each storm event, the total number of modeled iterations along with the number of individual iterations at certain water amounts, the final volume of water added to the model calculated after the last iteration, the ratio of modeled volume to calculated volume, the number of flooded patches for each storm event, and the overall flooded area for each storm event.

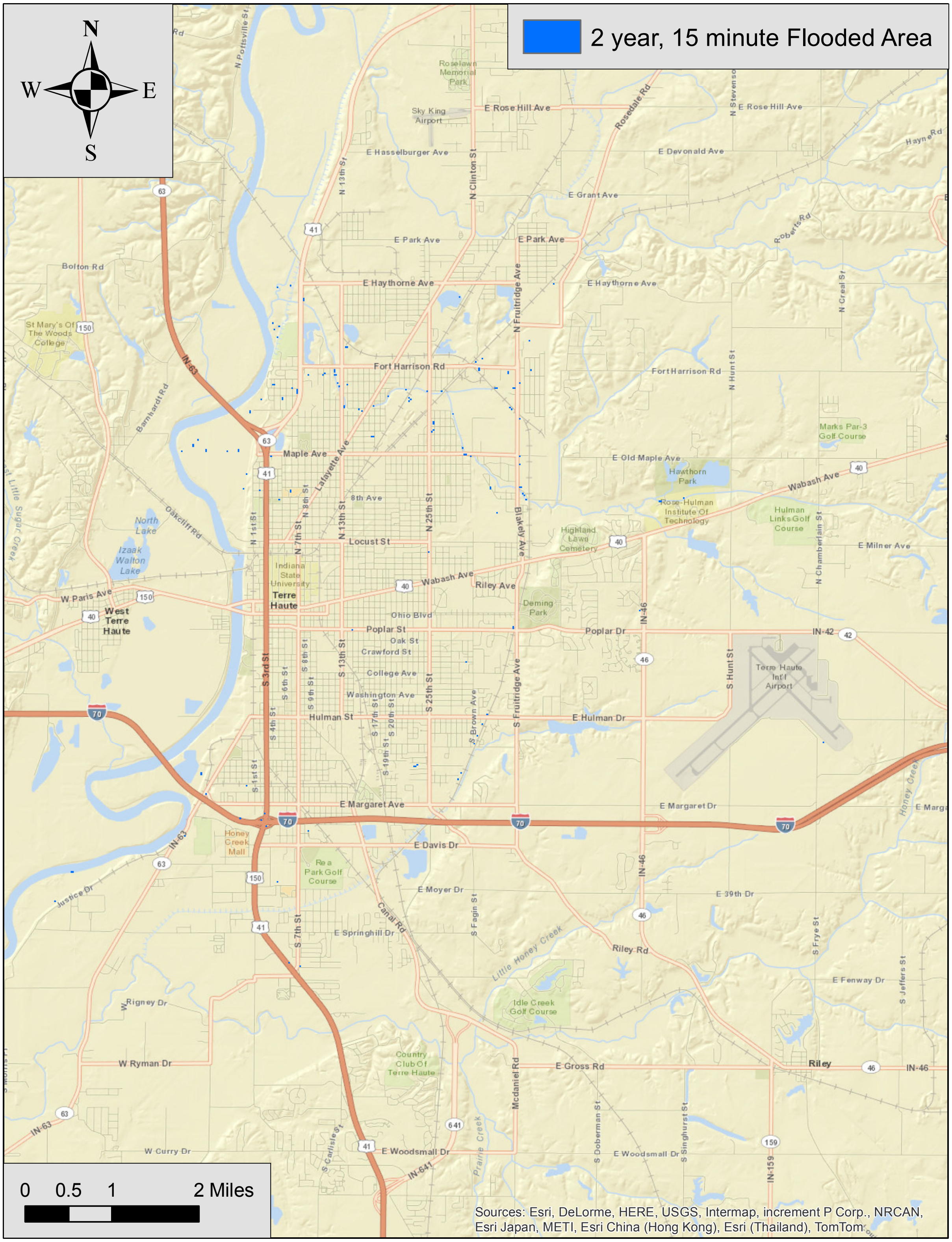

Figure 11. Modeled flash flooding extent of a 2 year, 15 minute storm event.

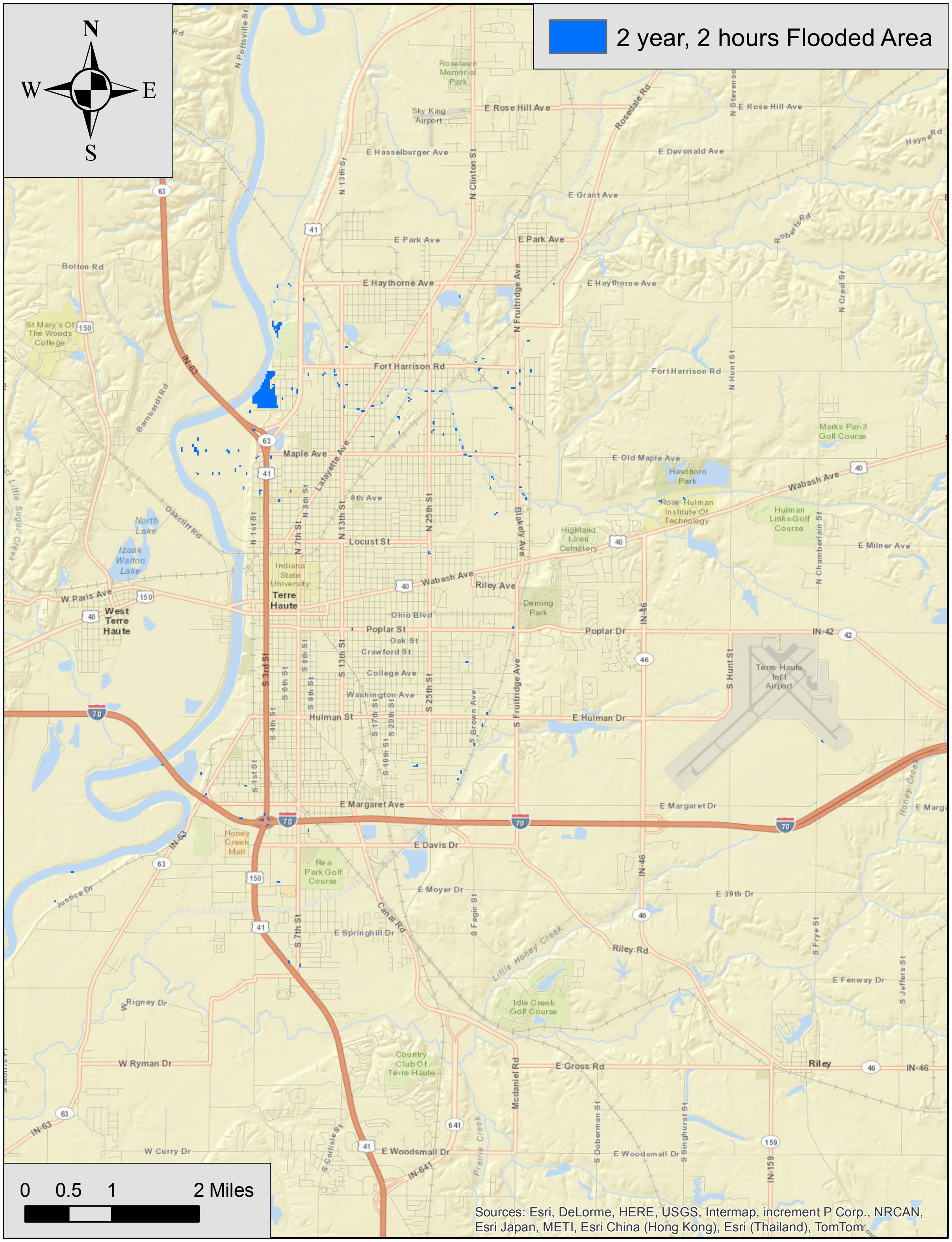

Figure 12. Modeled flash flooding extent of a 2 year, 2 hour storm event.

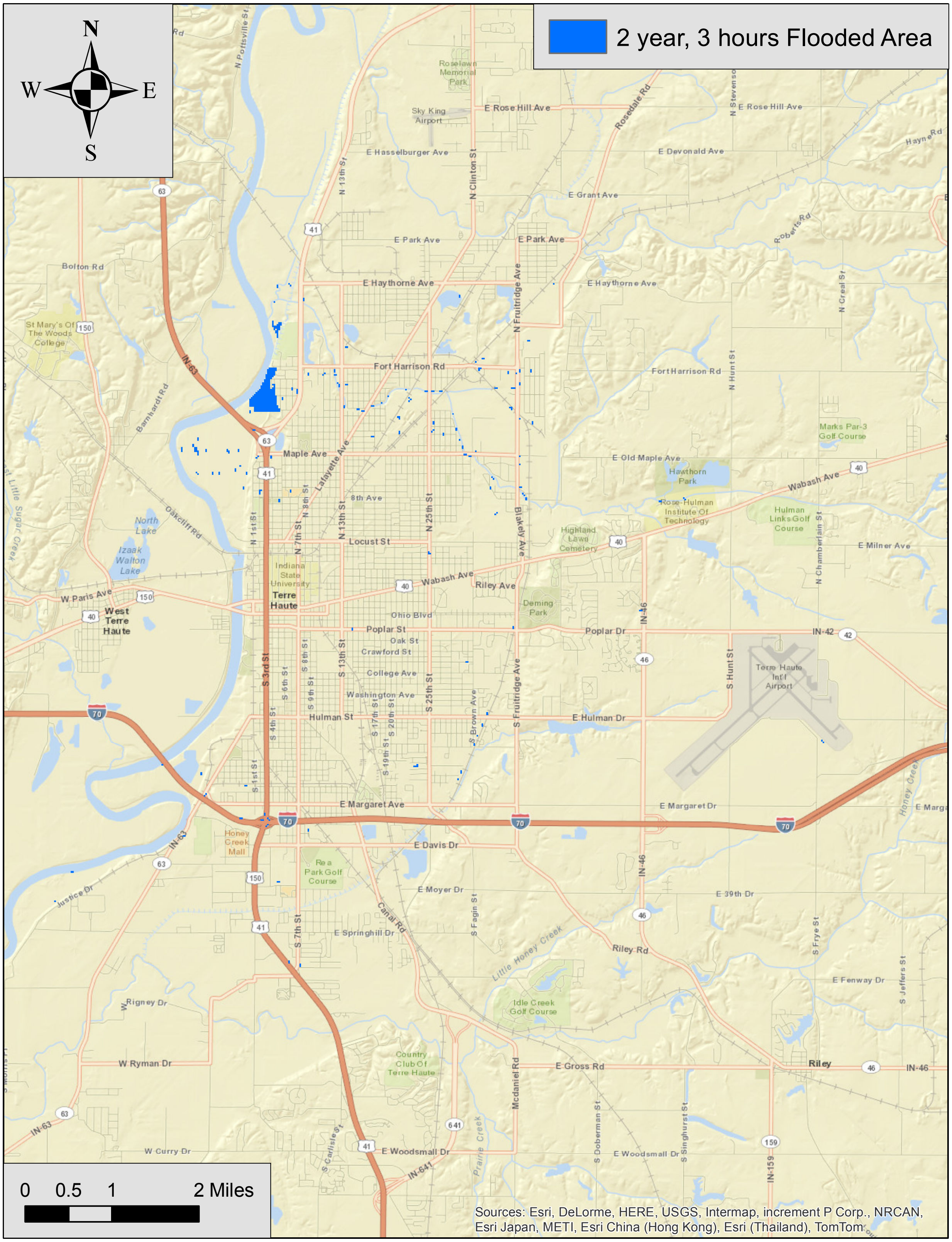

Figure 13. Modeled flash flooding extent of a 2 year, 3 hour storm event.

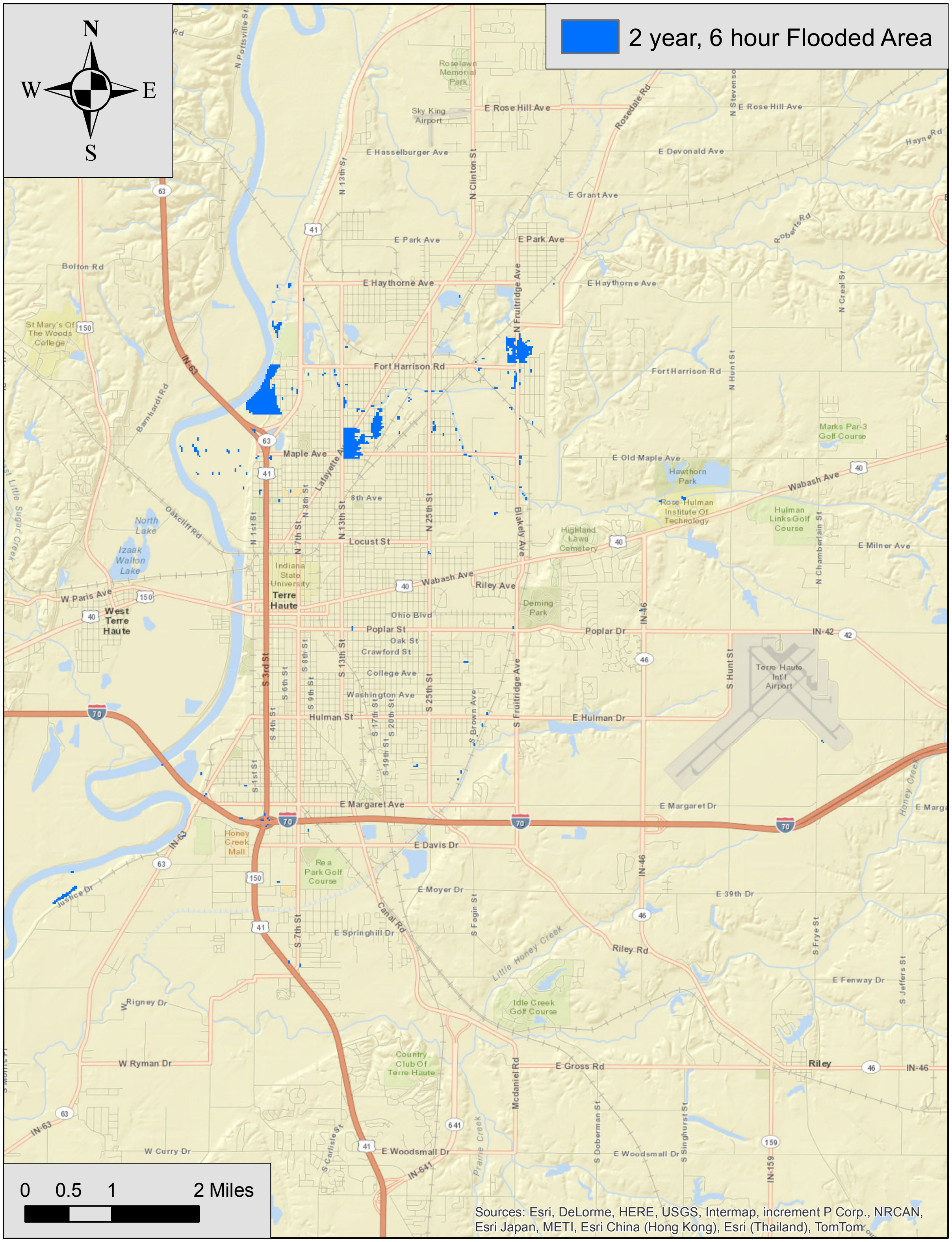

Figure 14. Modeled flash flooding extent of a 2 year, 6 hour storm event.

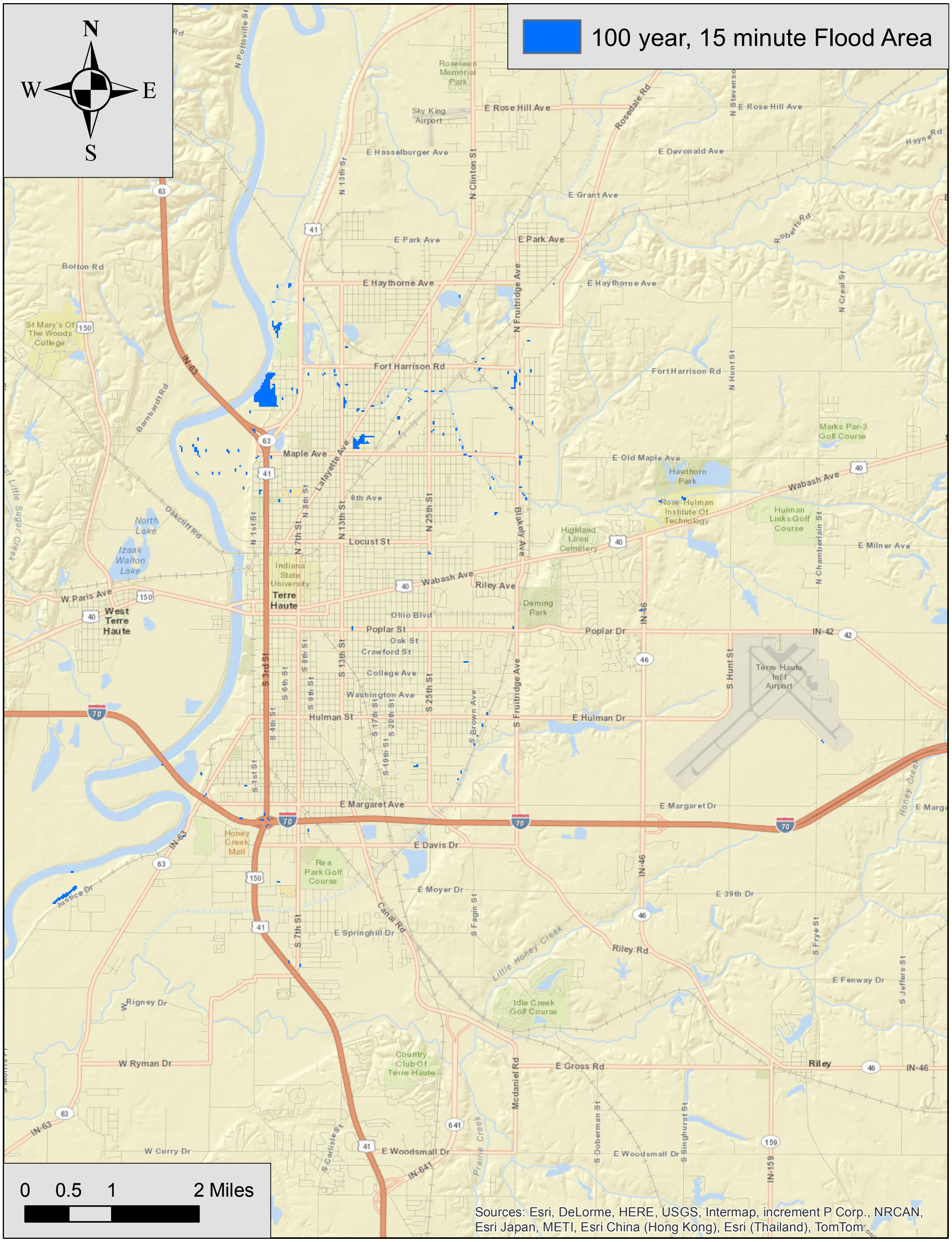

Figure 15. Modeled flash flooding extent of a 10 year, 15 minute storm event.

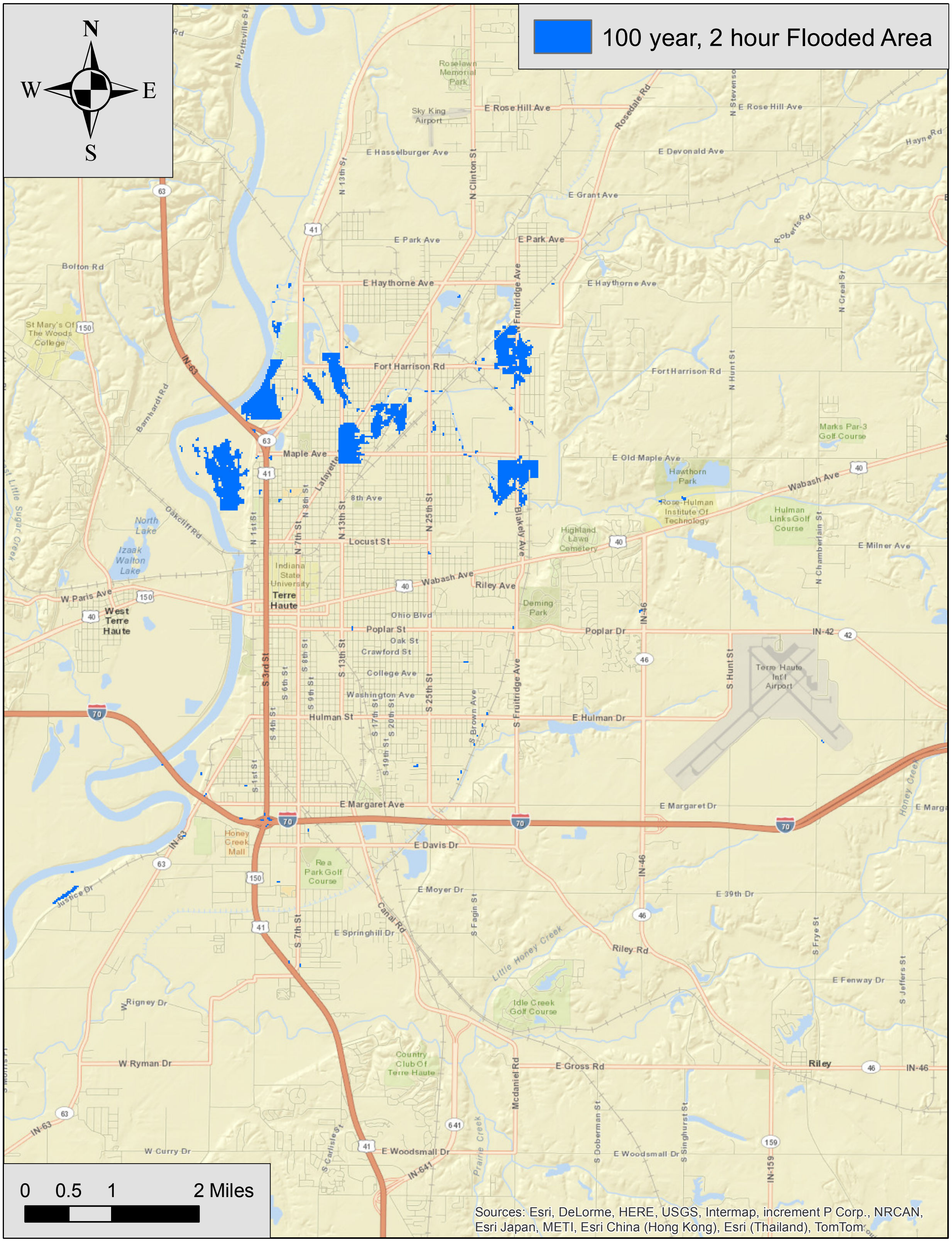

Figure 16. Modeled flash flooding extent of a 10 year, 2 hour storm event.

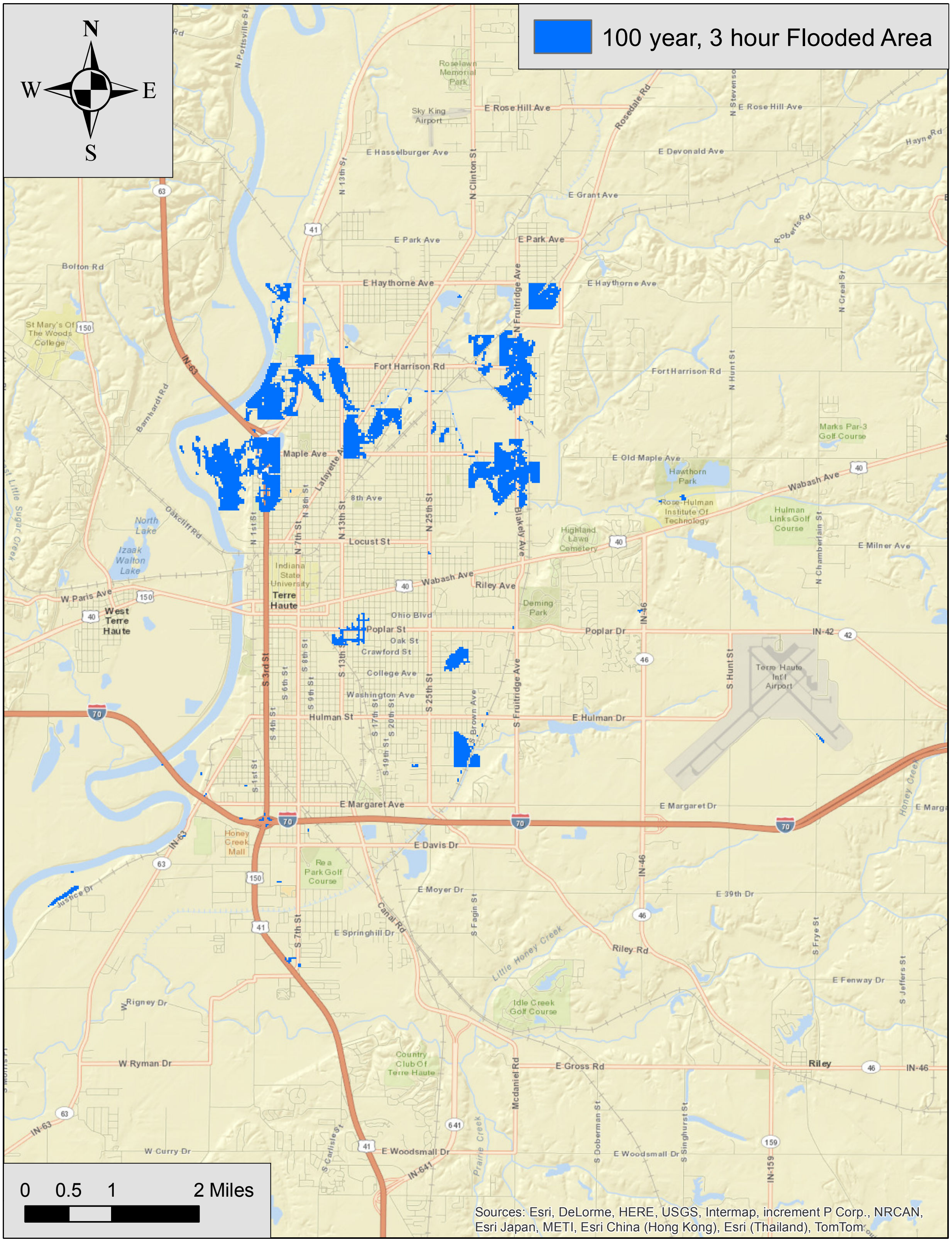

Figure 17. Modeled flash flooding extent of a 10 year, 3 hour storm event.

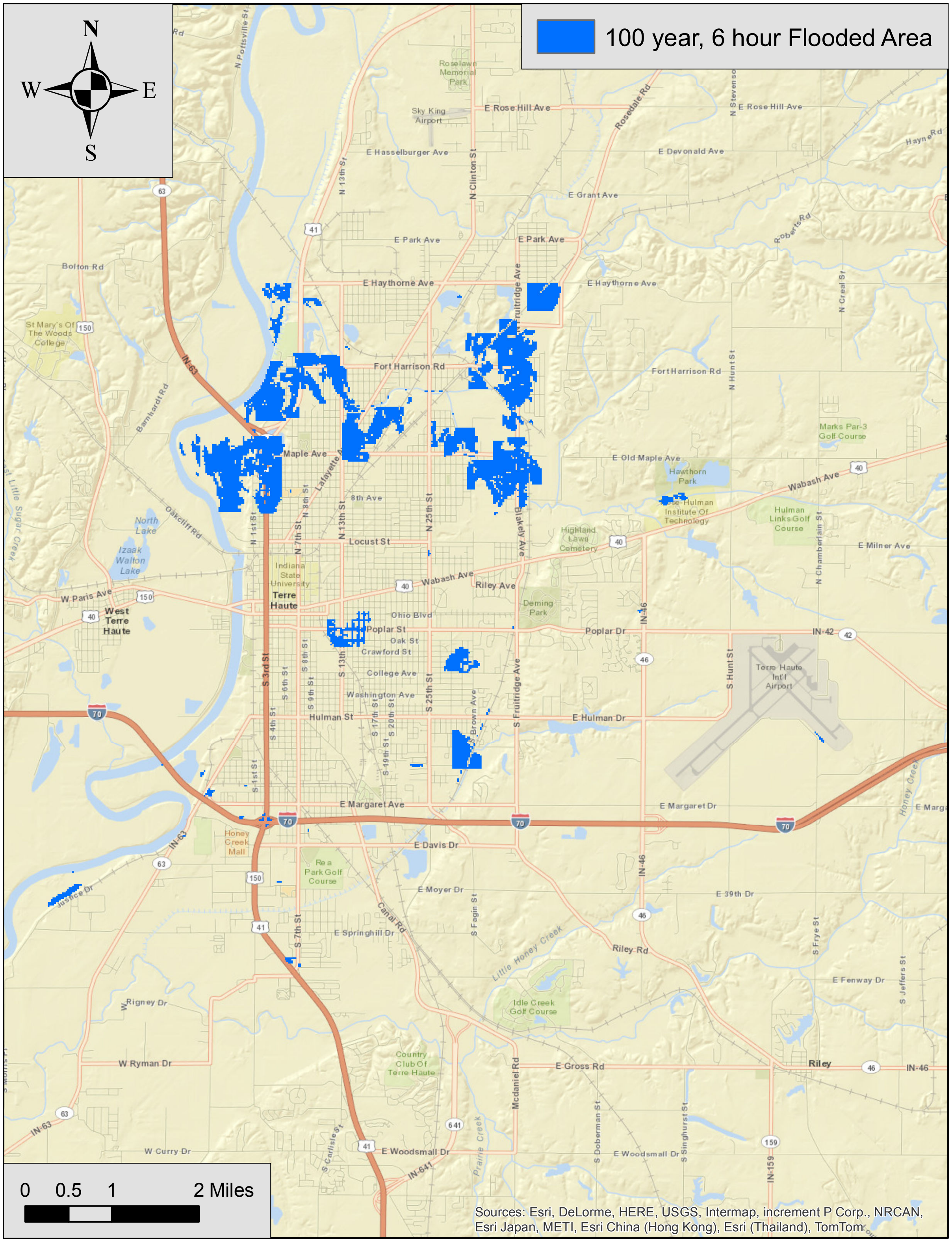

Figure 18. Modeled flash flooding extent of a 10 year, 6 hour storm event.

Table 5. Modeled results for various storm intensities and durations.

Storm Event	# of Iterations	1 Inch Iterations	1/10 Inch Iterations	1/100 Inch Iterations	1/1000 Inch Iterations	1/10000 Inch Iterations
2yr15min	1	0	0	0	0	1
2yr2hr	28	0	0	21	1	6
2yr3hr	30	0	0	21	2	7
2yr6hr	18	1	2	4	11	0
100yr15min	13	1	0	5	7	0
100yr2hr	21	3	4	1	13	0
100yr3hr	18	8	1	2	7	0
100yr6hr	19	12	1	1	5	0

Storm Event	Calculated Runoff (in^3)	Final Volume (in^3)	Volume Ratio	Number of Flooded Patches	Total Flooded Area (m^2)
2yr15min	2.38E+08	5.66E+08	2.38	98	119700
2yr2hr	5.93E+10	5.89E+10	0.99	115	430200
2yr3hr	7.61E+10	8.25E+10	1.08	115	486000
2yr6hr	1.27E+11	1.27E+11	1.00	112	1039500
100yr15min	4.86E+10	5.02E+10	1.03	114	513900
100yr2hr	3.20E+11	3.05E+11	0.96	86	3006000
100yr3hr	4.23E+11	4.13E+11	0.98	76	5278500
100yr6hr	5.63E+11	5.45E+11	0.97	63	7159500

2. Model Validation

On April 3rd, 2014, Terre Haute experienced a storm event that met specifications outlined in Chapter 2 (insert summary of specifications) which allowed for field data collection for validation of the model. As described in Chapter 2, validation sites were selected by identifying areas the model predicted would experience the most flooding in a worst-case scenario, the 100 year – 6 hour storm event. Once worst-case scenario areas of greatest flooding were determined, more exact locations to investigate were determined by selecting a flooded areas in a lowest intensity, shortest duration storm, 2 year – 15 minute, which were within the previously defined worst-case areas. In areas where there was no flooded area for the 2 year – 15 minute storm event within those predicted for a 100 year – 6 hour storm event, a random location was chosen to observe. Figure 19 shows the selected validation locations based on the above mentioned method. While performing the validation the following sites were inaccessible due to poor terrain or being on private property: 13, 14, 15, 20, 22, 23, and 24.

After collecting the field data, the model that best represented the amount of precipitation observed for the April 3rd storm event had to be determined. According to the National Weather Service, between 1.14 and 1.57 inches of rain fell across the study area over the period of 24 hours. Given that the models do not exceed a 6 hour storm event, duration did not factor into consideration for choosing a validation model; only amount of precipitation involved in the storm event was considered. Based on precipitation amounts, I determined that the 2 year – 15 minute storm event most accurately reflected the precipitation amount observed in the actual storm event, and thus the validation comparison was based off of that model. Figures 18 through 23 show the observed flooded areas along with the modeled flooded areas for each validation location. Table 6 provides data on the 19 observed validation locations and provides a comparison of the modeled versus observed results.

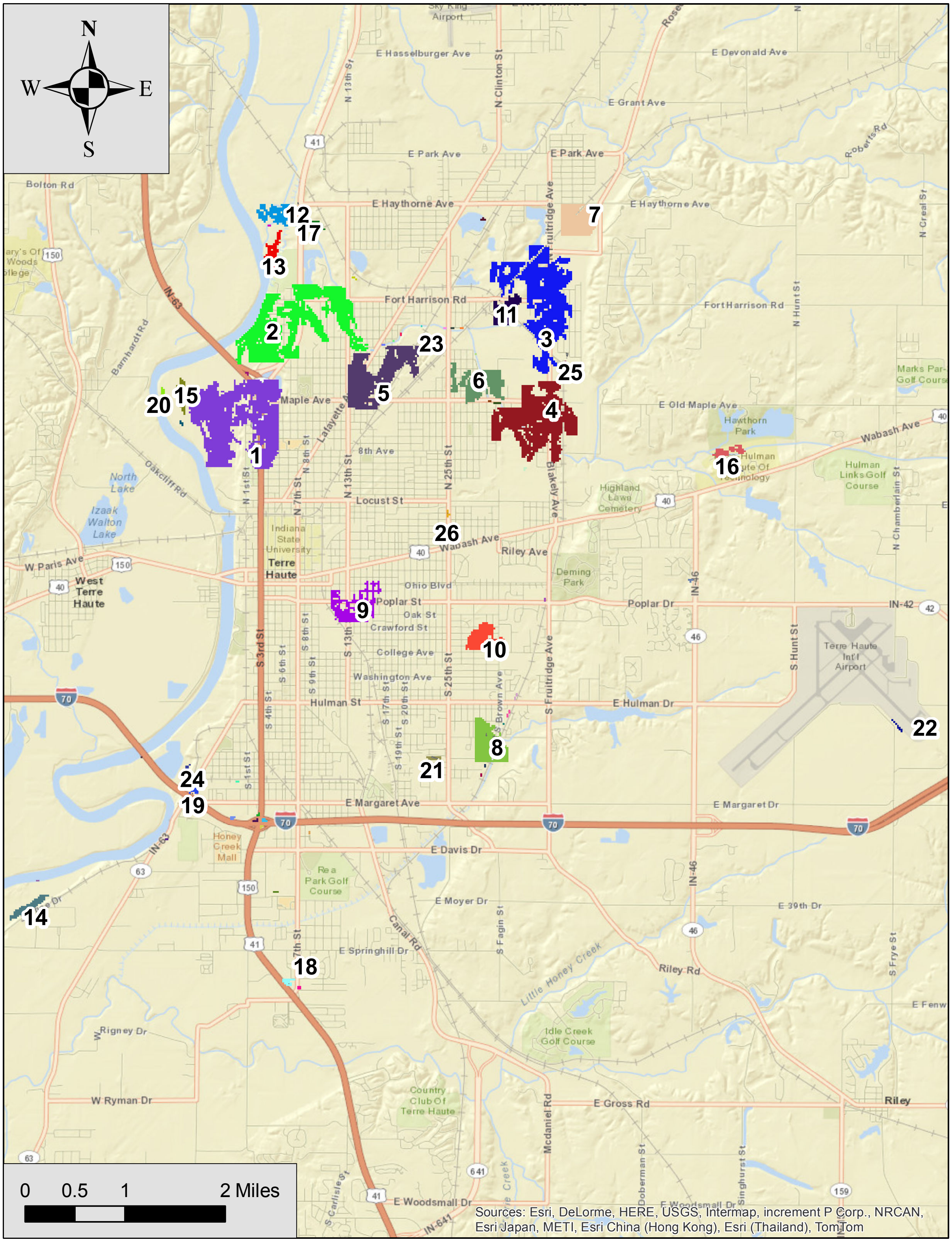

Figure 19. Location of the 26 selected validation areas.

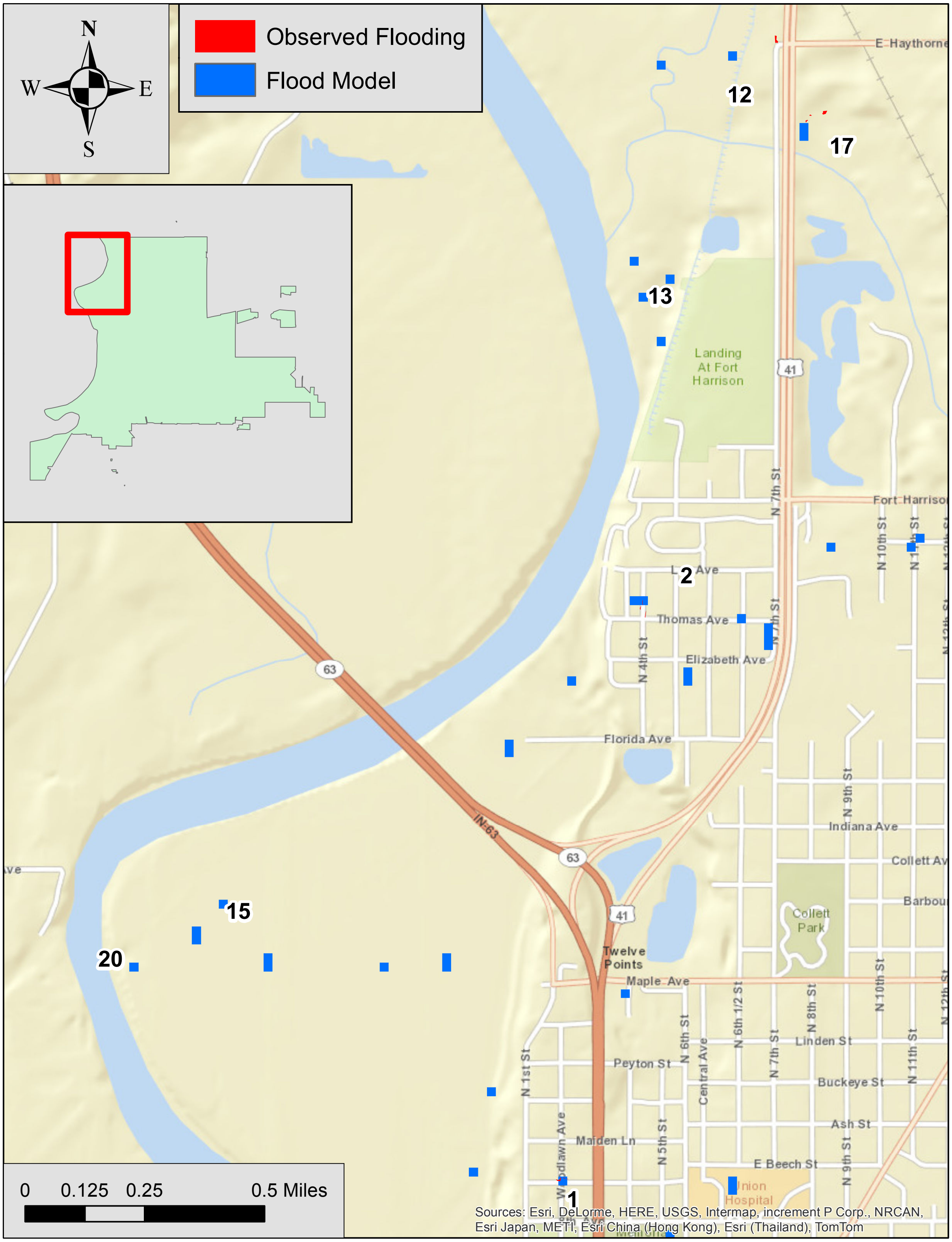

Figure 20. Observed and modeled flooded areas for validation locations in the northwestern part of the study area.

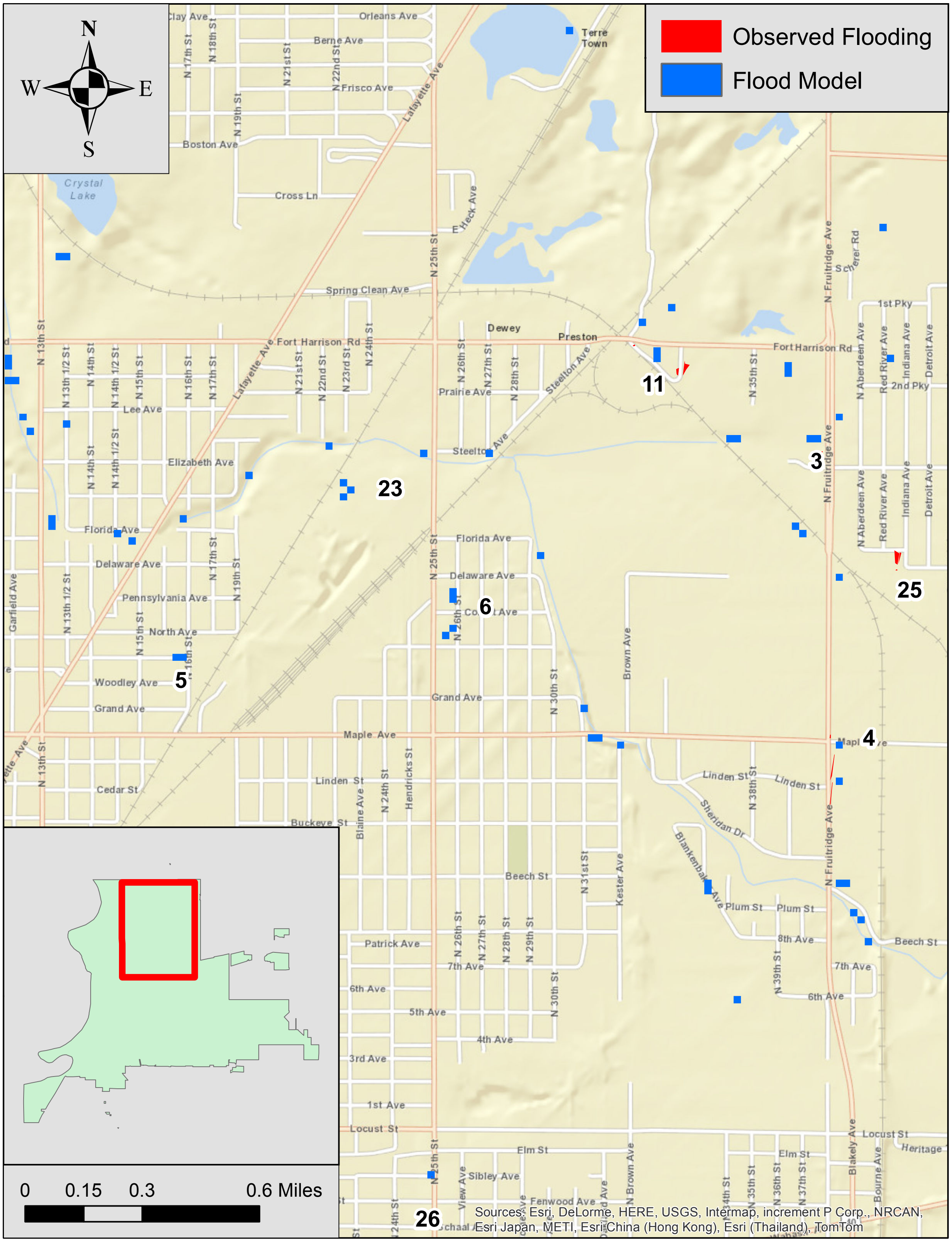

Figure 21. Observed and modeled flooded areas for validation locations in the north-central part of the study area.

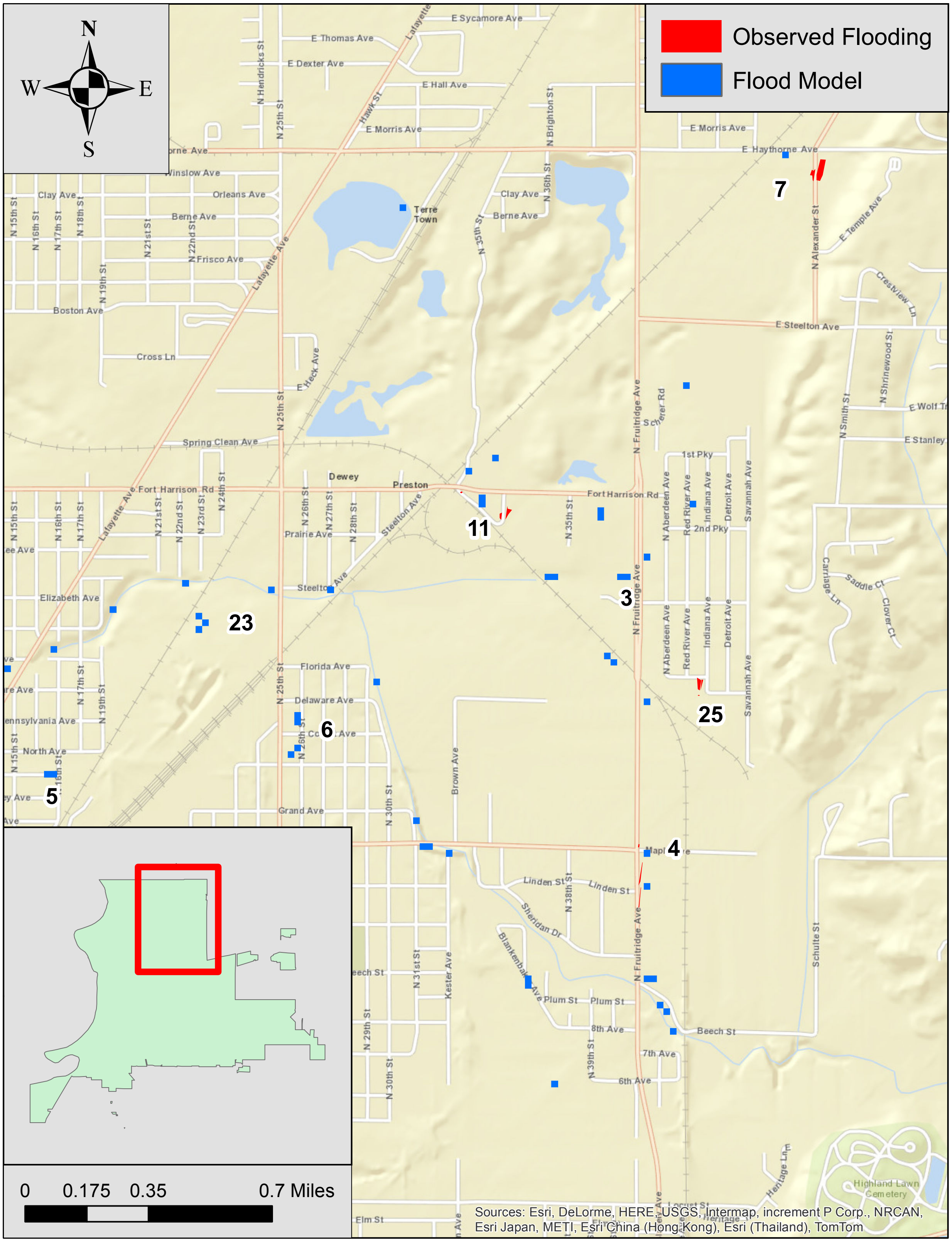

Figure 22. Observed and modeled flooded areas for validation locations in the northeastern part of the study area.

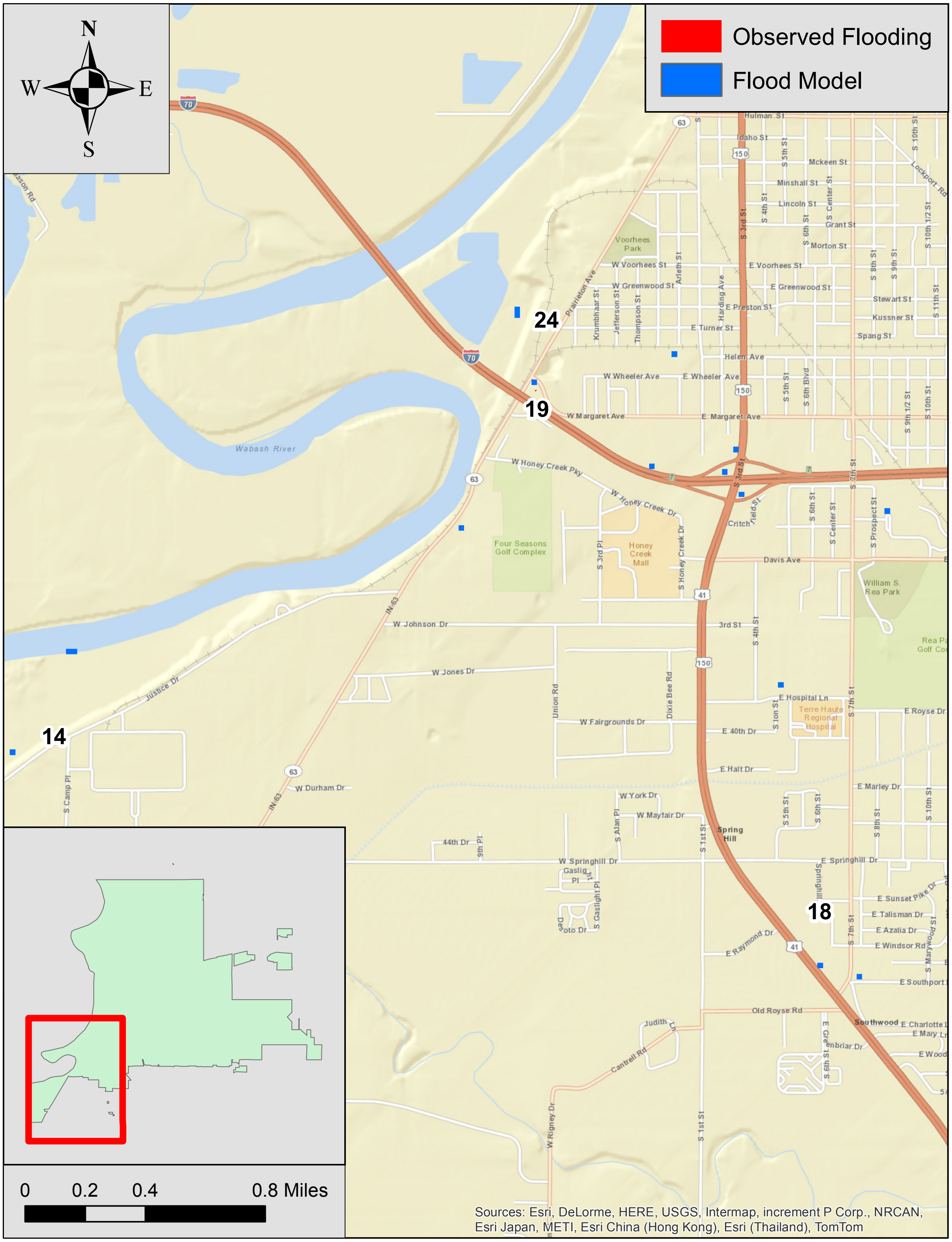

Figure 23. Observed and modeled flooded areas for validation locations in the southwestern part of the study area.

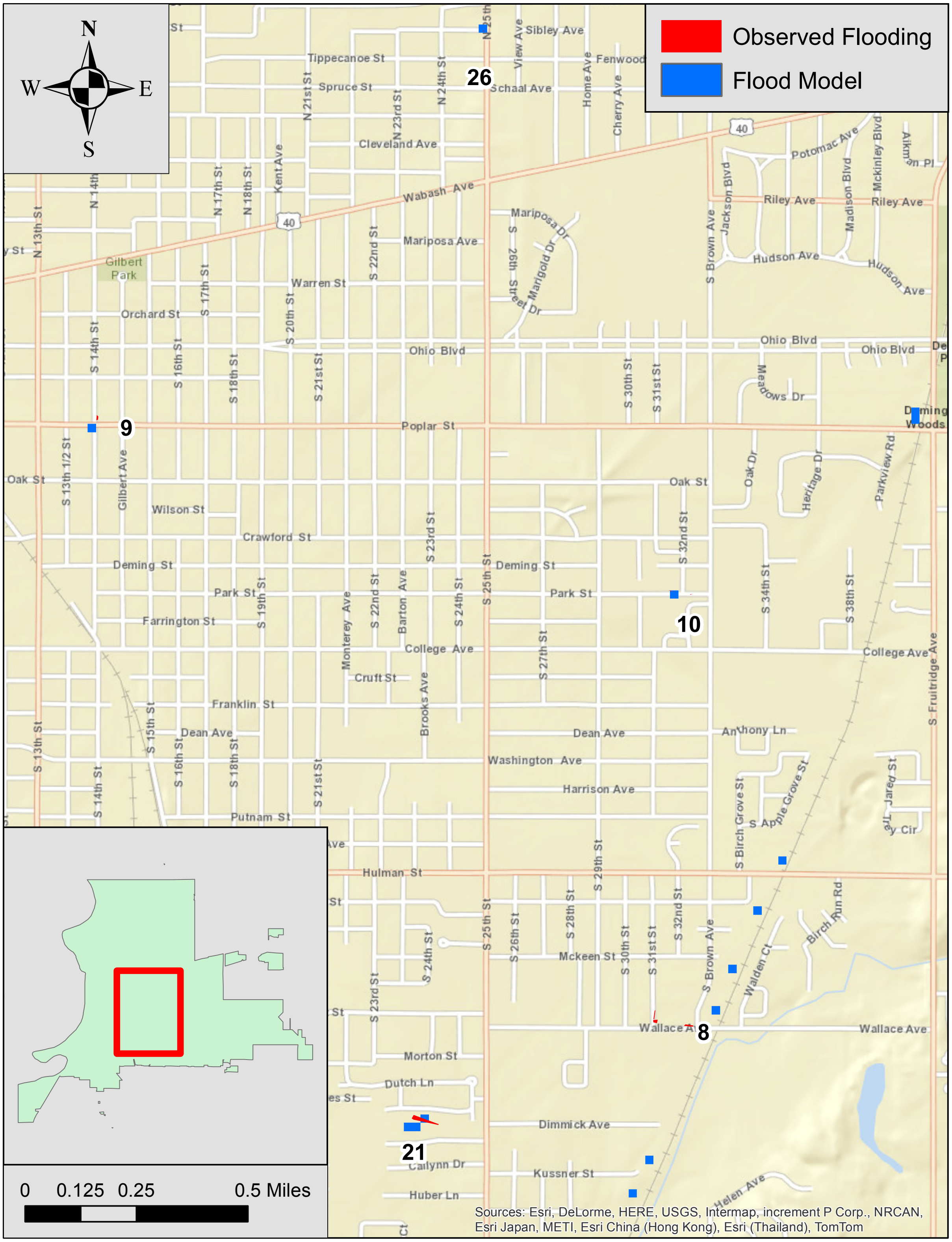

Figure 24. Observed and modeled flooded areas for validation locations in the south-central part of the study area.

Table 6. Comparison of observed versus modeled results for 19 validation locations. Percent Error is the difference between the field observed value (Field Observations) and the model result (2yr15min) multiplied by 100, then divided by the field observed value.

Site	2yr15min Model (m^2)	Field Observations (m^2)	Number of field Observations	Largest Field Observation	Smallest Field Observation	Percent Error
1	900	88.89	2	71.31	17.58	912.5
2	1800	61.66	3	26.80	16.33	2819.2
3	1800	140.65	1	140.65	140.65	1179.8
4	1800	709.82	3	384.64	63.31	153.6
7	900	3049.82	2	2406.23	643.59	70.5
8	900	373.55	4	153.08	10.87	140.9
9	900	95.52	1	95.52	95.52	842.2
10	900	13.51	2	12.72	0.79	6561.4
11	1800	833.15	3	552.43	47.29	116.0
12	900	168.24	1	168.24	168.24	434.9
16	900	219.40	2	187.01	32.39	310.2
17	1800	191.49	3	135.22	23.00	840.0
18	900	3.86	1	3.86	3.86	23192.6
19	900	47.99	1	47.99	47.99	1775.3
21	2700	1006.65	1	1006.65	1006.65	168.2
25	900	939.37	3	729.77	21.58	4.2
26	900	9.67	1	9.67	9.67	9205.1

CHAPTER 4

DISCUSSION

This chapter discusses the results and how they address the research questions and hypotheses presented in Chapter 1. The following chapter is divided into two main sections, one discussing the flash flood risk assessment and the other discussing the flash flood inundation model.

Flash Flood Risk Assessment

The first half of this study consisted of developing a flash flood risk assessment for Terre Haute, IN. The flash flood risk assessment portion of this study had two main goals in mind:

1. Will an increase in developed area result in a rise in flash flood risk?
2. What land cover constitutes the highest flash flooding risk areas for Terre Haute?

The first question to be examined will be if a change in impermeable area leads to a change in flash flooding risk. Hypothesis 1 indicates that an increase in impermeability would lead to an increase in flash flooding risk. Using the method described in Chapter 2, flash flooding risk was determined for the years 2001 and 2006. Land use in Terre Haute has changed very little over the 2001 to 2006 period, with most changes occurring in land use classes such as developed or crops. Given the limited area of land use change in the city over the 5 year study time period, if flash flooding risk changes at all due to land use change the amount of change in risk would be minimal.

Figures 7 and 8 (see Chapter 3) display the spatial distribution of different flash flooding risk categories, which were the result of the flash flood risk assessment. As seen in Figures 7 and 8, the spatial distributions of each of the flood risk categories are very similar. There seems to be a major divide in risk level across the study area. This divide runs north/south across the central portion of the study area. West of this divide, flood risks mostly range from very high to moderate. East of this divide, flash flood risk is much lower, ranging from risk levels from very low to moderate. This divide likely has a lot to do with the weighting scheme used to produce the flash flooding risk assessment (described in Chapter 2). In the weighting scheme, elevation accounts for nearly a quarter, 23.25%, of the overall weighting scheme, and thus has a large influence on the resulting risk output. Due to the study are having a much lower elevation to the west, close to the Wabash River, it was expected that areas with a greater flash flooding risk would be seen in the western section.

Table 3 shows the numerical results of the flash flooding risk assessment for each risk level for the years 2001 and 2006. The overall area of each risk level and total area for each year are shown along with the percentage of area accounted for by each modeled risk level. As water categories are not included in this analysis, and a change in some water areas to other land uses between the year 2001 and 2006 did take place, the overall area at risk actually increased by 2006. Since comparing area in 2001 versus area in 2006 would not account for this increase in examined area, the comparison to determine how changes in impermeability affects flash flooding risk should be based on the percentage of the overall study area in each risk category for each year. As seen, the percentage of area that falls within the very high risk category increases from 9.75% of the total area in 2001 to 10.19% of the total area in 2006. For high risk areas, 25.28% of the total area is high risk in 2001 and 24.11% of the total area was high risk in 2006. Collectively, the very high and high risk areas account for 35.03% of the total area in 2001 and 34.3% of the total area in 2006. The differences between the study years are relatively negligible due to the very few changes in land use between these years; 81,943,200 m^2 of developed land in 2001 versus 96,993,900 m^2 of developed land in 2006. Yet there was an overall increase in percent of area that is very high risk between 2001 and 2006. Since the only difference between the 2001 and 2006 risk assessments were the land use data, the rise in very high risk area is attributed to the increase in developed area during the 5 year study time period.

The second research question dealing with the flash flood risk assessment focused on determining which land use categories correlated to the highest flash flood risk level in the Terre Haute area. As stated in Chapter 1, Hypothesis 2 was that the majority of the highest flooding risk area, would be located in the developed areas of Terre Haute rather than the surrounding undeveloped areas. Figure 9 shows the very high flash flooding risk area for the year 2006, and displays 3 main areas which experience very high risk: the northern part of the study area, along the Wabash river in the central portion of the study area, and in the southern portion of the study area. In Figure 10, very high risk areas are broken up into their corresponding land use. This Figure shows that most of the very high risk areas that are close to the Wabash River are either wetlands, crop, or pasture land uses. The very high flash flooding risk areas that are not near the Wabash River are almost all developed or barren land use, with these categories being broken down in Table 3. Table 4 shows the area that each land use classification consists of for the very high risk category. Of note is that 55.36% of the very high risk area is in the developed or barren land use categories. The next closest land use is crop or pasture, with 29.12% of the very high risk area. These results are slightly biased because land use is used in the risk assessment. As seen in Table 2 (Chapter 2), land use is a variable used in developing the flash flood risk assessment for Terre Haute, accounting for 15.5% of the overall weighting scheme. Despite the fact that most of the risk assessment is based on the other variables beside land use, land use is incorporated in the risk assessment and thus the very high risk assessment area has an increased likelihood of residing in the very high risk land use category, which is developed or barren land in this study. Even though land use is used in the risk assessment, having it included is essential to the risk assessment since land use is a contributing factor for flash flooding. Hypothesis 2, which was that the majority of the highest flooding risk area would be located in the developed areas of Terre Haute rather than the surrounding undeveloped areas, is supported because according to the results of the flash flooding risk assessment, the majority of the very high risk area is developed rather than undeveloped.

Flash Flood Inundation Model

The second half of this study consisted of developing a flash flooding inundation model that would predict where flooding would occur in Terre Haute during typical and atypical storm events. This model served to address the following research questions:

1. What storm events will result in the largest amount of flooded area within Terre Haute?
2. Is the flash flood inundation model an accurate way to identify areas in which flash flooding does occur within Terre Haute?

Hypothesis 3 (Chapter 1), which is related to the first research question, was that high magnitude, low frequency storm events would result in a greater flooded area than low magnitude, high frequency storm events. In this study, high magnitude storms are 100 year storm events, and result in much greater precipitation and have a much lower likelihood of happening than low magnitude storms, 2 year storm events. Two storm magnitudes, 100 year and 2 year, were modeled at four different time spans, 15 minutes, 2 hour, 3 hour, and 6 hour, to create eight individual storm events.

After using the method described in Chapter 2 to iterate and reach a final volume within 95% of the total calculated runoff, shown in Table 5 (Chapter3), the resulting rasters were mapped, shown in Figures 11 through 18, and summarized in Table 5. Figures 11 through 14 are the 2 year storm magnitude at 15 minute, 2 hour, 3 hour, and 6 hour time intervals, respectively. The 2 year – 15 minute storm event shows no flooding outside of the initial sinks and their one interval expansion. This is because the calculated surface runoff volume for a weak storm such as this only allowed for the initial iteration of water to be added before it expanded past the calculated amount. The 2 year – 2 hour storm event is the next modeled storm. Table 5 shows that this storm took 28 iterations of various water amounts to get to within 99% of the calculated runoff volume. This resulted in 115 flooded patches across Terre Haute, which can be seen in Figure 12. It should be noted that flooded areas around the intersection of highway 41 and 63 all experienced growth from the 2 year – 15 minute model, with one location in particular experiencing a great amount of growth in flooded area.

The next storm event is the 2 year – 3 hour storm event. As seen in Table 5, it took 30 iterations of various water amounts to reach its termination. This model exceeded the 100% of the calculated surface runoff volume and this value was used because 29 iterations resulted in only approximately 91% of the runoff volume being added, and according to the methods proposed in Chapter 2 if this situation arose then the first iteration that exceeds 95% would be used. Overall there is not a great difference in the extent between this storm event and the 2 year – 2 hour storm event. The 2 year – 3 hour storm event also has 115 flooded patches and the only areas of noticeable growth, as seen in Figure 13, are in the bigger flooded areas seen in the previous storm event. The final 2 year storm event that was modeled was the 2 year – 6 hour storm event. Table 5 shows that it took 18 iterations of various water amounts to reach the 95% threshold. This resulted in 112 flooded patches with an overall flooded area of 1,039,500 m^2. There seems to be a threshold for flooded patches that exists between this storm event and the 2 year – 3 hour storm event. The decline in the number of patches seen in this storm event is due to patches becoming large enough that they are combining to form much larger flooded areas. As seen in Figure 14, there are three large noticeable flooded patches in the northern part of the study area. It is also of note that all of the flooded locations in the southern part of Terre Haute did not exhibit a great amount of change between the different time intervals for a storm of 2 year magnitude.

The other storm magnitude considered, the 100 year storm event, also produced significant flooding. The first 100 year storm event modeled was the 100 year - 15 minute storm. It took 13 model iterations for the model to finish, resulting in 114 flooded patches with an overall flooded area of 513,900 m^2. The flooded area of this storm is comparable to the 2 year – 3 hour storm event mentioned above. As seen in Figure 15, the main areas of flooding in this model are near the intersection of highway 41 and 63 with another larger patch east of the intersection of Maple and Lafayette Ave. This visual similarity is supported by the data shown in Table 5 (Chapter3). The total model determined flooded area for the 2 year – 3 hour storm event was 486,000 m^2, resulting in just a difference of 27,900 m^2 between this storm event and the 100 year – 15 minute storm. Due to the similarity in model derived flooded area, it was expected that the spatial extent of flooding for these two storm events would be similar.

The next storm event that was modeled is the 100 year – 2 hour storm event. It took 21 model iterations to reach the water volume threshold, which resulted in 86 flooded patches and an overall flooded area of 3,006,000 m^2. The decline in the number of patches indicates that the threshold for patch combination has already been exceeded and the number of patches should continue to decline for the subsequent models. As seen in Figure 16, in the northern section of Terre Haute, there are numerous large flooded patches. However, there still are not large flooded areas in the southern part of Terre Haute for this storm event. The 100 year – 3 hour storm event was the next storm modeled. It took 18 iterations to exceed the water volume threshold, which resulted in 76 flooded patches with a total flooded area of 5,278,500 m^2. As expected, the number of patches declined due to merging of patches as flooded area grew into each other. Figure 17 shows the spatial distribution of the flooded areas for this storm event. Patches in the northern part of Terre Haute grew to considerable size and merged into numerous mega patches in the 100 year – 3 hour event. Also this storm event results in flooded area growth in the southern part of Terre Haute for the first time, with three larger patches seen in the south/central area. The final storm event examined in this study is the 100 year – 6 hour storm event. It took 19 iterations to reach the water volume threshold and this resulted in 63 flooded patches with an overall flooded area of 7,159,500 m^2. This storm event resulted in the greatest modeled flooded area by far and this area is shown in Figure 18. The flooded areas in north Terre Haute continued to grow and fill in with this storm event. Also the three flooded areas in the southern/central portion of Terre Haute that exhibited growth during the 100 year – 3 hour storm event model continued to show growth, along with other smaller patches experiencing minimal growth.

Model results show that high magnitude, low frequency storm events result in greater flooded area than low magnitude, high frequency storm events. This result was expected since high magnitude storms, which consist of higher rainfall intensity, produce more precipitation than low magnitude storm events. Also, the longer the storm event is in duration, the more precipitation will be produced since precipitation will be falling and accumulating for a longer period of time. The shortest duration high magnitude storm event resulted in a flooded area that was greater than the third longest low magnitude storm event. Also, when examining the difference between the overall model-derived flooded areas of high and low magnitude storm events, the results were very different. The 100 year – 6 hour storm event resulted in 6,120,000 m^2 more flooded area than the 2 year – 6 hour storm event. This shows that during a high magnitude storm that is producing rainfall at a rapid rate, flash flooding should be more pronounced than during a lower magnitude storm. This significant increase in the flooded area derived from a high magnitude storm event compared to a low magnitude storm event supports hypothesis 3, that high magnitude, low frequency storm events would result in a greater flooded area than low magnitude, high frequency storm events. It should also be noted that the model supports the intuitive nature of this hypothesis, which indicates that the model does a reasonable job of determining flash flooding in Terre Haute. Further investigation into the accuracy of the model prediction is covered in the next paragraph.

The second research question in this section hoped to address whether an inundation model such as the one created is an accurate way of predicting flooded areas within Terre Haute.

Hypothesis 4 (Chapter 1) was that the inundation model would be a reasonable way of identifying areas prone to flash flooding, meaning that it would be able to identify areas but the exact extent may not be highly accurate. Figure 19 shows the location of the 26 selected validation sites based on area seen within the 100 year – 6 hour storm model. Of the 26 selected sites, 7 of them could not be reached due to inaccessibility or discovering they resided on private property/secure locations. These locations were not validated and not included in the table of results, Table 6. Figures 19 through 23 show the observed field flooded areas for the April 3rd, 2014 storm and the model predicted flooded areas for the closest modeled storm equivalent, the 2 hour – 15 minute storm event. Of the 19 validation locations that were observed, only 2 or 10.5% of the locations did not experience any flooding. On the one hand, model results indicate that the model does a decent job of predicting whether or not flooding will occur at a particular location. Prediction of flooded areas, on the other hand, is a different story.

As seen in Figures 20 through 24, the observed flooded locations are much smaller in area than their model predicted counterparts. Table 6 shows the comparison for each validation location between the field observed areas and the predicted model areas. There is only one validation location, 25, that has a reasonably low error percentage, calculated as the percent error between the observed and modeled values, at 4.5%. Another validation location of interest was site 21. The flood model predicted that flooding would occur in an area between a residential apartment complex and residential housing. Field observations confirmed this location as a flooding area, as seen in Figure 25. This location is a drainage area that has been installed to serve as a catchment for surface runoff from the nearby homes. Upon further investigation as to how the model predicted this flooding location so accurately, it was discovered that the DEM shows this manmade drainage feature. This makes it worth noting that the flash flood model used in this study is dependent on the quality of the DEM and accuracy could be heavily skewed due to inaccuracies in a DEM. The rest of the field observation locations exhibit a high amount of error, ranging from 70.5% to an astounding 23,192.6% error. For example, site 18 had a model calculated flood area of 900 m^2 but an observed flooded area of only 3.863885374 m^2. Given that the model did so poorly in predicting the extent of flooding for the validation locations base on the field observations, it is not recommended that a model such as this be used to accurately predict the extent of flooding.

Model Limitations

However, there are limitations to this study that could be addressed before completely discounting the approach as they could increase the validity of the model's flooded area predictive capabilities. The first limitation deals with the spatial extent of the model. The spatial extent of the data used in the model was 30 by 30 meters, based on the coarsest resolution data used in this study, even though the DEM data is a much finer 1.5 by 1.5 meter resolution. This resulted in each 30 by 30 meter pixel either being classified as all flooded or not flooded at all by the model. With data of increased spatial resolution the model would be able to predict flooded areas with much finer detail and may more accurately capture the true extent of flooding, rather than basing predictions on relatively coarse 30 by 30 meter pixels.

Another limitation of the approach presented here arises in the surface runoff calculation. In order to accurately calculate the surface runoff for each storm event, it must be known how much water the storm/sewer system for Terre Haute can handle. Unfortunately, the Terre Haute Wastewater Utility was not able to provide an exact runoff capacity for which the storm/sewer drainage network was rated. The Utility could provide a yearly capacity that their wastewater processing plant can handle, along with a daily gallon-average that passes through the

Figure 25. Validation sites 18 (left), 21 (center), and 25 (right).

wastewater plant, calculated for 2012. Using this information, the amount of water that moves through the storm/sewer system for each storm event can be calculated, but more detailed information on the ratings and capacity of the drainage and water treatment system would make a significant difference in the accuracy of surface runoff volume calculations. Due to a number of factors, the surface runoff volume calculations used in this study may have substantially underestimated surface runoff, and more accurate volumes could significantly change the outcome of flood predictions.

A further refinement to the model would involve incorporating more storm events so that the storm event that most accurately corresponds to the actual storm providing validation data could be used. The storm event used in field validation in this study, which took place on April 3rd, 2014 resulted in precipitation amounts that were close to the 2 year – 15 minute modeled storm, but lasted much longer than the 15 minute period considered by the model. Having more storms modeled to compare with validation data may show that the model is more accurate in predicting flooded area than this study has shown, although other complications with the approach, described above, make this unlikely.

The selection of starting points within the model could also contribute to skewed modeled results. The model started adding water in sinks that were within the very high risk areas derived from the flash flood risk assessment. Because the model took water that fell across all of Terre Haute and only added it to the very high risk areas, this probably resulted in flooding areas that were much greater in the modeled results that observed during an actual storm.

Finally, multiple validation teams are needed to collect the validation data. Collection of the validation started at 11 am on April 3rd and lasted until 6 pm the same day. With only one validation team collecting data, the optimal flood time may have been missed and the recorded observations were not accurate due to the optimal flooded time not having yet occurred or having already passed. Additional validation teams would ensure that more accurate validation data is collected, which could have resulted in greater observed flood areas in some locations that would put it more in line with the modeled results.

Conclusions

Overall, this study has provided some insight on different aspects of flash flooding in Terre Haute, Indiana. First, the flash flood risk assessment shows that a change in impermeability and developed area will increase the evaluated very high risk area. The risk assessment also addressed which land use categories are the most susceptible to flash flooding in Terre Haute. According to the risk assessment, a majority of the very high risk area was located in locations where the land use was developed or barren.

The inundation model also provided some valuable insight on flash flooding in Terre Haute, IN. The flash flooding inundation model, which incorporated aspects of the flash flood risk assessment, precipitation data, and drainage infrastructure, supported the hypothesis that high magnitude, low frequency storm events have a greater flooded area than low magnitude, high frequency storm events. Secondly, validation data collected from a storm in Terre Haute indicates that an inundation models such as this based on current data can predict where flooding may occur, but does a poor job at accurately estimating the spatial extent of flooding.

Further studies could aim to further refine the flood inundation model. Obtaining or creating finer resolution data on variables included in this study would allow for the raster pixel resolution to be finer. This finer resolution would allow the inundation model to iterate and expand in smaller, more natural ways. Also, further validation needs to be carried out to further refine the model with hopes that it could produce accurate spatial estimations of flash flooding for varying storms in the future.

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APPENDIX A: EXAMPLE OF INUNDATION MODEL PYTHON CODE

```
# Import system modules for hard-coupling with ArcGIS, create geoprocessing link,
# acquire licenses, and load the necessary toolboxes
import sys, os, arcpy, time, numpy
from arcpy.sa import *
arcpy.CheckOutExtension("Spatial")

# Local variables
arcpy.env.workspace = "S:\Zach\Thesis\Inundation_Model\Python_Testing2"
output = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\"
arcpy.env.overwriteOutput = "True"
print "workspaces set " + arcpy.env.workspace + " and " + output
Surface_runoff = 563038048534 #total calculated surface runoff
print "Surface runoff set"

#Bring in starting wet cells raster
Beginning = "S:\Zach\Thesis\Inundation_Model\\sink_dem_inc2"
print Beginning + " loaded"
DEM = "S:\Zach\Thesis\Inundation_Model\\th_demx1000in"
print "DEM loaded"
```

```
iteration = 0
total_flood_vol = 0.00
vol_ratio = total_flood_vol/Surface_runoff

while vol_ratio < 0.2:
    iteration = iteration + 1
    #Add "x" amount of water to all wet cells in feet
    x = int(1000)
    output_wateradd = Raster(Beginning) + x
    output_wateradd.save(output + "flood_wadd.img")
    flood_wadd = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_wadd.img"
    print "flooded raster created"

    #Create table of attribute values
        #or might be able to do this:
    arr2 = arcpy.RasterToNumPyArray(flood_wadd)
    unique = numpy.unique(arr2)
    print "unique values determined"
    unique2 = unique[1:]
    print "unique null excluded"
    exlist = unique.tolist()
    print "list created"
```

```
#Expand all wet cells by 1 cell in all 8 neighboring directions (flood_expand)

output_expand = Expand(flood_wadd, 1, exlist)

output_expand.save(output + "flood_expand.img")

flood_expand = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_expand.img"

print"flood cells expanded"


###Subtract flood_expand cells by original DEM (flood_diff)

output_diff = Raster(flood_expand) - Raster(DEM)

output_diff.save(output + "flood_diff.img")

flood_diff = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_diff.img"

print "flood_diff calculated"


###Set null to any value <= 0 in the flood diff raster (flood_depth)

outSetNull = SetNull(flood_diff, flood_diff, "VALUE < 0")

outSetNull.save(output + "flood_depth.img")

flood_depth = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_depth.img"


###extract by mask to isolate wet cells in flood_expand (flood_final)

output_con = Con(flood_depth, flood_expand, "", "VALUE > 0")

output_con.save(output + "flood_final" + str(iteration) + ".img")

flood_final = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_final" +
str(iteration) + ".img"
```

```
###multiply flood depth by cell dimensions in inches (30 meters X 30 meters originally)
(flood_vol)

output_depth = Raster(flood_depth) / 1000

output_depth.save(output + "flood_depth_in.img")

flood_depth_in = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_depth_in.img"

output_vol = Raster(flood_depth_in) * 1395000

output_vol.save(output + "flood_vol.img")

flood_vol = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_vol.img"

print "Flood volue per cell calculated"


###add all flood_vol (tot_flood_vol)

##    #To determine total flooded volume

floodvol_null = SetNull(flood_vol, 1, "VALUE < 0")

floodvol_null.save(output + "flood_area.img")

flood_area = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_area.img"

print "Flood area created"

ZonalStatisticsAsTable (flood_area, "VALUE", flood_vol, "zonaltable.dbf", "", "SUM")

print "Total calculated flooded volume"


###total_flood_vol/Surface_runoff (vol_ratio)

values = set()

rows =
arcpy.SearchCursor("S:\Zach\Thesis\Inundation_Model\Python_Testing2\\zonaltable.dbf")

for row in rows:
```

```
        values.add(row.getValue("SUM"))
    water_list = list(values)
    total_flood_vol = water_list[0]
    vol_ratio = total_flood_vol/Surface_runoff
    Beginning = flood_final
else:
    it_inch = iteration
    print "Done with inch additions"


while vol_ratio < 0.25:
    iteration = iteration + 1
    #Add "x" amount of water to all wet cells in feet
    x = int(100)
    output_wateradd = Raster(Beginning) + x
    output_wateradd.save(output + "flood_wadd.img")
    flood_wadd = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_wadd.img"
    print "flooded raster created"


    #Create table of attribute values
        #or might be able to do this:
    arr2 = arcpy.RasterToNumPyArray(flood_wadd)
    unique = numpy.unique(arr2)
    print "unique values determined"
```

```
unique2 = unique[1:]

print "unique null excluded"

exlist = unique.tolist()

print "list created"


#Expand all wet cells by 1 cell in all 8 neighboring directions (flood_expand)

output_expand = Expand(flood_wadd, 1, exlist)

output_expand.save(output + "flood_expand.img")

flood_expand = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_expand.img"

print"flood cells expanded"


###Subtract flood_expand cells by original DEM (flood_diff)

output_diff = Raster(flood_expand) - Raster(DEM)

output_diff.save(output + "flood_diff.img")

flood_diff = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_diff.img"

print "flood_diff calculated"


###Set null to any value <= 0 in the flood diff raster (flood_depth)

outSetNull = SetNull(flood_diff, flood_diff, "VALUE < 0")

outSetNull.save(output + "flood_depth.img")

flood_depth = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_depth.img"


###extract by mask to isolate wet cells in flood_expand (flood_final)
```

```
    output_con = Con(flood_depth, flood_expand, "", "VALUE > 0")

    output_con.save(output + "flood_final" + str(iteration) + ".img")

    flood_final = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_final" +
str(iteration) + ".img"


    ###multiply flood depth by cell dimensions in feet (30 meters X 30 meters originally)
(flood_vol)

    output_depth = Raster(flood_depth) / 1000

    output_depth.save(output + "flood_depth_in.img")

    flood_depth_in = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_depth_in.img"

    output_vol = Raster(flood_depth_in) * 1395000

    output_vol.save(output + "flood_vol.img")

    flood_vol = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_vol.img"

    print "Flood volue per cell calculated"


    ###add all flood_vol (tot_flood_vol)

    ##    #To determine total flooded volume

    floodvol_null = SetNull(flood_vol, 1, "VALUE < 0")

    floodvol_null.save(output + "flood_area.img")

    flood_area = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_area.img"

    print "Flood area created"

    ZonalStatisticsAsTable (flood_area, "VALUE", flood_vol, "zonaltable.dbf", "", "SUM")

    print "Total calculated flooded volume"
```

```
    ###total_flood_vol/Surface_runoff (vol_ratio)
    values = set()
    rows =
arcpy.SearchCursor("S:\Zach\Thesis\Inundation_Model\Python_Testing2\\zonaltable.dbf")
    for row in rows:
        values.add(row.getValue("SUM"))
    water_list = list(values)
    total_flood_vol = water_list[0]
    vol_ratio = total_flood_vol/Surface_runoff
    Beginning = flood_final
else:
    it_10inch = iteration
    print "Done with tenth of an inch additions"


while vol_ratio < 0.3:
    iteration = iteration + 1
    #Add "x" amount of water to all wet cells in feet
    x = int(10)
    output_wateradd = Raster(Beginning) + x
    output_wateradd.save(output + "flood_wadd.img")
    flood_wadd = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_wadd.img"
    print "flooded raster created"


    #Create table of attribute values
```

```
    #or might be able to do this:
arr2 = arcpy.RasterToNumPyArray(flood_wadd)
unique = numpy.unique(arr2)
print "unique values determined"
unique2 = unique[1:]
print "unique null excluded"
exlist = unique.tolist()
print "list created"

#Expand all wet cells by 1 cell in all 8 neighboring directions (flood_expand)
output_expand = Expand(flood_wadd, 1, exlist)
output_expand.save(output + "flood_expand.img")
flood_expand = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_expand.img"
print"flood cells expanded"

###Subtract flood_expand cells by original DEM (flood_diff)
output_diff = Raster(flood_expand) - Raster(DEM)
output_diff.save(output + "flood_diff.img")
flood_diff = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_diff.img"
print "flood_diff calculated"

###Set null to any value <= 0 in the flood diff raster (flood_depth)
outSetNull = SetNull(flood_diff, flood_diff, "VALUE < 0")
```

```
    outSetNull.save(output + "flood_depth.img")

    flood_depth = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_depth.img"



    ###extract by mask to isolate wet cells in flood_expand (flood_final)

    output_con = Con(flood_depth, flood_expand, "", "VALUE > 0")

    output_con.save(output + "flood_final" + str(iteration) + ".img")

    flood_final = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_final" +
str(iteration) + ".img"



    ###multiply flood depth by cell dimensions in feet (30 meters X 30 meters originally)
(flood_vol)

    output_depth = Raster(flood_depth) / 1000

    output_depth.save(output + "flood_depth_in.img")

    flood_depth_in = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_depth_in.img"

    output_vol = Raster(flood_depth_in) * 1395000

    output_vol.save(output + "flood_vol.img")

    flood_vol = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_vol.img"

    print "Flood volue per cell calculated"



    ###add all flood_vol (tot_flood_vol)

    ##    #To determine total flooded volume

    floodvol_null = SetNull(flood_vol, 1, "VALUE < 0")

    floodvol_null.save(output + "flood_area.img")

    flood_area = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_area.img"
```

```
    print "Flood area created"
    ZonalStatisticsAsTable (flood_area, "VALUE", flood_vol, "zonaltable.dbf", "", "SUM")
    print "Total calculated flooded volume"


    ###total_flood_vol/Surface_runoff (vol_ratio)
    values = set()
    rows =
arcpy.SearchCursor("S:\Zach\Thesis\Inundation_Model\Python_Testing2\\zonaltable.dbf")
    for row in rows:
        values.add(row.getValue("SUM"))
    water_list = list(values)
    total_flood_vol = water_list[0]
    vol_ratio = total_flood_vol/Surface_runoff
    Beginning = flood_final
else:
    it_100inch = iteration
    print "Done with hundredth of an inch additions"


while vol_ratio < 0.95:
    iteration = iteration + 1
    #Add "x" amount of water to all wet cells in feet
    x = int(1)
    output_wateradd = Raster(Beginning) + x
```

```
output_wateradd.save(output + "flood_wadd.img")
flood_wadd = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_wadd.img"
print "flooded raster created"


#Create table of attribute values
    #or might be able to do this:
arr2 = arcpy.RasterToNumPyArray(flood_wadd)
unique = numpy.unique(arr2)
print "unique values determined"
unique2 = unique[1:]
print "unique null excluded"
exlist = unique.tolist()
print "list created"


#Expand all wet cells by 1 cell in all 8 neighboring directions (flood_expand)
output_expand = Expand(flood_wadd, 1, exlist)
output_expand.save(output + "flood_expand.img")
flood_expand = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_expand.img"
print"flood cells expanded"


###Subtract flood_expand cells by original DEM (flood_diff)
output_diff = Raster(flood_expand) - Raster(DEM)
output_diff.save(output + "flood_diff.img")
```

```
flood_diff = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_diff.img"

print "flood_diff calculated"


###Set null to any value <= 0 in the flood diff raster (flood_depth)

outSetNull = SetNull(flood_diff, flood_diff, "VALUE < 0")

outSetNull.save(output + "flood_depth.img")

flood_depth = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_depth.img"


###extract by mask to isolate wet cells in flood_expand (flood_final)

output_con = Con(flood_depth, flood_expand, "", "VALUE > 0")

output_con.save(output + "flood_final" + str(iteration) + ".img")

flood_final = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_final" +
str(iteration) + ".img"


###multiply flood depth by cell dimensions in feet (30 meters X 30 meters originally)
(flood_vol)

output_depth = Raster(flood_depth) / 1000

output_depth.save(output + "flood_depth_in.img")

flood_depth_in = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_depth_in.img"

output_vol = Raster(flood_depth_in) * 1395000

output_vol.save(output + "flood_vol.img")

flood_vol = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_vol.img"

print "Flood volue per cell calculated"
```

```
    ###add all flood_vol (tot_flood_vol)
    ##    #To determine total flooded volume
    floodvol_null = SetNull(flood_vol, 1, "VALUE < 0")
    floodvol_null.save(output + "flood_area.img")
    flood_area = "S:\Zach\Thesis\Inundation_Model\Python_Testing2\\flood_area.img"
    print "Flood area created"
    ZonalStatisticsAsTable (flood_area, "VALUE", flood_vol, "zonaltable.dbf", "", "SUM")
    print "Total calculated flooded volume"


    ###total_flood_vol/Surface_runoff (vol_ratio)
    values = set()
    rows =
arcpy.SearchCursor("S:\Zach\Thesis\Inundation_Model\Python_Testing2\\zonaltable.dbf")
    for row in rows:
        values.add(row.getValue("SUM"))
    water_list = list(values)
    total_flood_vol = water_list[0]
    vol_ratio = total_flood_vol/Surface_runoff
    Beginning = flood_final
else:
    it_1000inch = iteration
    print "Done with thousandth of an inch additions"


print "FLOOD EXPANSION COMPLETE!!"
```

```
print "Iterations: " + str(iteration)
print "Inch Iterations: " + str(it_inch)
print "Tenth Inch Iterations: " + str(it_10inch - it_inch)
print "Hundredth Inch Iterations: " + str(it_100inch - it_10inch)
print "Thousandth Inch Iterations: " + str(it_1000inch - it_100inch)
print "Final Volume: " + str(total_flood_vol)
print "Volume Ratio: " + str(vol_ratio)
```