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Development and Implementation of Sustainable Transportation Resilience Indicators
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Mark Abkowitz (PI)
Vanderbilt University
mark.abkowitz@vanderbilt.edu

Janey Camp
Vanderbilt University
janey.camp@vanderbilt.edu

Leslie Gillespie-Marthaler
Vanderbilt University
leslie.gillespie-marthaler@vanderbilt.edu

Madeline Allen
Vanderbilt University
madeline.c.allen@vanderbilt.edu

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PROJECT DESCRIPTION

Communities are complex systems subject to a variety of hazards that can result in significant disruption to critical functions. Community resilience assessment is gaining popularity as a means to help communities better prepare for, respond to, and recover from disruption. Sustainable resilience, a recently developed concept, requires communities to assess system-wide capability to maintain desired performance levels, while simultaneously evaluating impacts to resilience due to changes in hazards and vulnerability over extended periods of time.

In an earlier work, the authors developed a classification scheme to aid in identification, selection and application of community sustainable resilience indicators that can be tailored to a community's needs in operationalizing the assessment process (Gillespie-Marthaler et al., 2019b). These indicators were characterized according to whether they aligned with social, economic or environmental systems that are necessary for a community to achieve a sustainable resilience domain of survival, well-being, or full preparedness.

Of the critical infrastructure systems that support these systems and domains, transportation is arguably the most important. This is based on the premise that transportation is a means to an end, providing the mobility that enables a community to establish and maintain a social, economic and environmental fabric. Whether it involves an educational, medical, recreational, religious, work or other purpose, absent a safe and reliable transportation system, none of these activities can be satisfactorily pursued. Moreover, in times of crisis, transportation serves as a vital artery for enabling access to and egress from impacted areas.

The objective of this project was to establish and demonstrate a method for evaluating a community's transportation resilience, such that if deficiencies exist, attention can be focused on mitigating those concerns. For reasons described below, this approach was designed around the scenario of a river valley community exposed to the threat of a significant flood event, with the expectation that the methodology has the potential to be extended to assess community resilience to other natural and manmade hazards.

Dams and levees are the most prevalent flood protection infrastructure in the U.S., with over 90,000 dams in existence today, supplemented by a 100,000-mile levee network in which two-thirds of the nation's population live in a county with at least one levee (ASCE, 2017). These systems, however, can be vulnerable to overtopping and breach due to an extreme hydrologic event, which is cited as the primary cause of dam and levee failure in the U.S. Moreover, there is reason for heightened concern given that extreme hydrologic events are forecast to increase in both frequency and magnitude over the remainder of the century.

Complicating matters is the fact that a large percentage of the nation's flood protection infrastructure is considered to be in deteriorating condition. By 2030, more than one-half of existing dams will exceed 50 years in age, beyond their originally intended design basis (NRCS, 2003; Lane, 2008; ASCE, 2017). Many of these dams were originally constructed in rural areas for agricultural irrigation; however, since their construction, populations living near these dams have increased significantly (NRCS, 2003; NRC, 2012). Currently, 17% of existing dams are rated as having high-hazard potential (ASDSO, 2017; ASCE, 2017). The status of the nation's levee system is no different; a recent study concluded that 13% of the levee network is considered at a moderate, high, or very high level of risk (USACE, 2018).

The project selected Dyer County, Tennessee as being representative of a river valley community with genuine concerns regarding its resiliency to a significant flooding event. Dyer County is located along the Mississippi River in western Tennessee, bordered by Missouri and Arkansas to the west (see Figure 1). The main levee in Dyer County, Little Levee, is 20 miles long and protects 41 farm buildings and 30 homes – including roughly 80 residents (USACE, 2014). In 2010, Dyer County had a population of 37,463; almost one-half of the population lives in the City of Dyersburg, despite comprising only 3% of the area of the county, with the remainder of the county population widely dispersed (U.S. Census Bureau, retrieved 2019). Approximately 24% of the population is below age 18, and 17% is over age 65. For those under age 65, roughly 15% have a disability and 10% do not have health insurance. It is estimated that 17% of the population in Dyer County is considered below the poverty line.

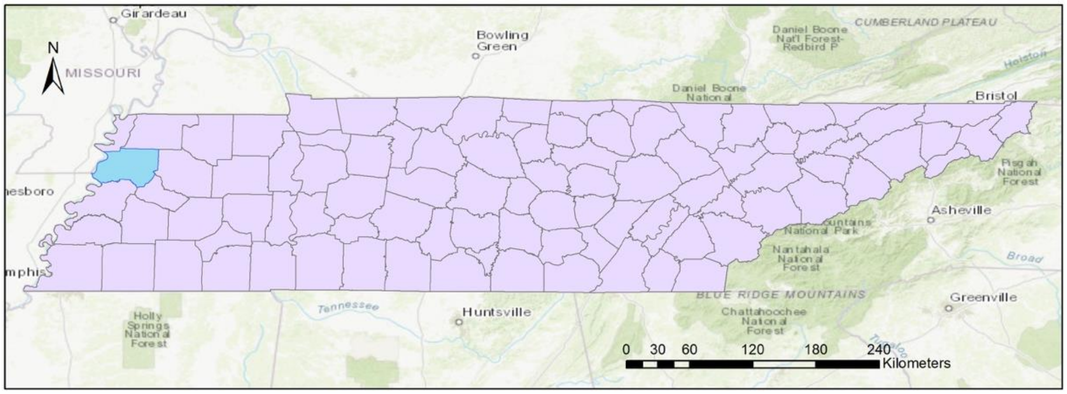

Figure 1. Tennessee county map (Dyer County highlighted)

Floods have devastated Dyer County on several occasions over the past century, including a few of note (Van West, 2018). The floods of 1927 occurred between January and May, when the Mississippi River floodplain spanned 80 miles wide in some places. Referred to as the Great Flood of 1927, it was one of the costliest natural disasters in U.S. history, prompting significant re-evaluation of flood mitigation and response that ultimately led to passage of the Flood Control Act of 1928 (NWS & NOAA, retrieved 2019). A decade later, the Mississippi River experienced another major flood, due to the saturated state of the ground from a particularly wet winter, followed by significant rain in late January (Coggins, 2018). January 24th, 1937 became known as "Black Sunday," as multiple large river systems reached critical levels. Roughly 75,000 homes were impacted, 250 people lost their lives, and 900 others were seriously injured.

More recently, in the Spring of 2011, the Ohio River, Mississippi River and many surrounding tributaries experienced severe flooding. Over one hundred counties and parishes were impacted, impacting over 43,000 people, more than 21,000 structures, and 1.2 million acres of agricultural land, with resulting damages of close to $2.8 billion (USACE, 2013). The volume of water flowing down the middle and lower parts of the Mississippi River was greater than that of the 1937 flood. The flood was a result of snow melt from an extraordinarily wet winter, combined with a two-week period of rainfall in which some tributary basins received 700% to 1,000% above normal values (U.S. Department of Commerce, NOAA, NWS, 2012). During this flood, Little Levee was breached in 24 locations due to overtopping and one controlled breach (USACE, 2014). A NASA satellite image taken of Dyer County in May 2011 is shown in Figure 2b, in comparison with a NASA satellite image of the same area on April 21, 2010 (Figure 2a), with the Dyer County boundary outlined in red (NASA, 2011).

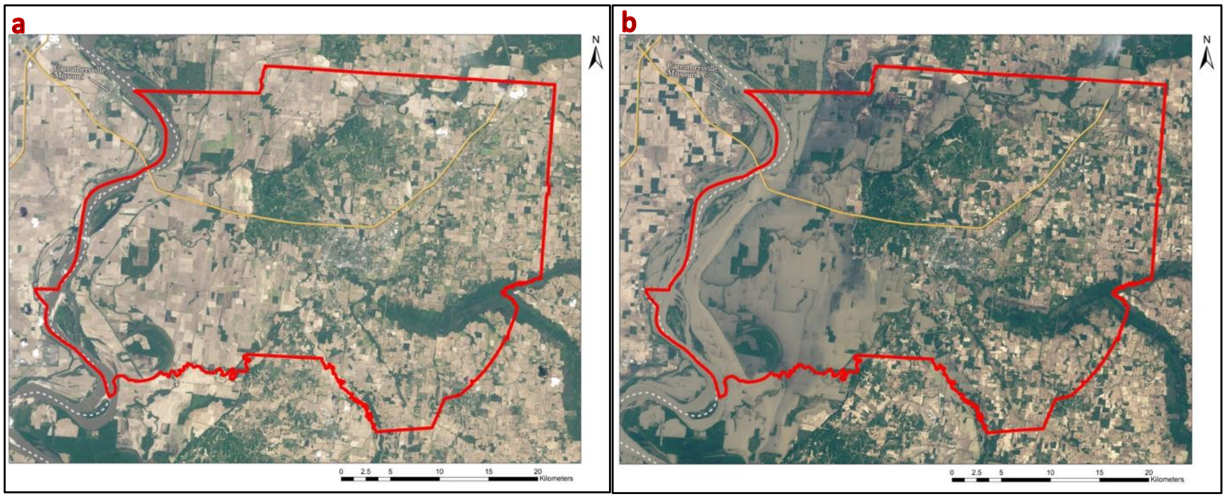

Figure 2. NASA Landsat 5 satellite imagery of 2011 Mississippi River flooding (NASA, 2011)

When considering future flood risk for Dyer County, it is important to not only account for these historical floods, but also to acknowledge the potential for these events to increase in frequency and magnitude due to the effects of climatic shifts in this region. Individual extreme precipitation events are projected to increase in severity based on several studies (EPA, 2016; Camp et al., 2016; Nelson et al., 2019; Gillespie-Marthaler et al., 2019a). In fact, precipitation during heavy rainstorms over roughly the last seventy years has increased by 27% in the southeast region of the U.S. Moreover, research conducted in this region suggests that our previous notion of a 100-year flood event[1] is no longer a sufficient benchmark to use when preparing for future scenarios (Nelson et al., 2019). These observations indicate an important need for more stringent flood prevention and emergency preparedness measures.

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[1] A 100-year flood event is a flood with a magnitude that has a 1 in 100 (or 1%) annual chance of occurring. This is an average recurrence interval and does *not* mean that a flood of this magnitude could only occur once in 100 years (USGS, retrieved 2019). This terminology is used throughout the rest of the paper when referring to a 100-year flood (1% annual recurrence interval), 500-year flood (0.2% annual recurrence interval), and 1,000-year flood (0.1% annual recurrence interval).

METHODOLOGICAL APPROACH

The nationally recommended tool for developing flood hazard mitigation plans in the U.S. is Hazus, a software tool developed by the Federal Emergency Management Agency (FEMA). The flood application within Hazus is defined as “an integrated system for identifying and quantifying flood risks [that] is intended to support communities in making informed decisions regarding land use and other issues in flood prone areas” (Scawthorn et al., 2006). With such reliance on Hazus to inform flood hazard mitigation planning, it is important to have confidence in the efficacy of the tool by benchmarking Hazus results with other information sources, with a willingness to adapt the methodology to enhance functionality where Hazus does not perform well.

The study methodology comprises three parts: 1) an initial flood loss assessment performed using Hazus for each scenario of interest, 2) a comparison of Hazus flood extent results, building damage estimates, and essential facility inventory with other sources of information, and 3) an assessment of the impacts of flood scenarios on Dyer County, augmenting Hazus functionality, as appropriate. Much of this research was conducted within the ArcGIS 10.5.1 platform (Esri, 2017), using the projected coordinate system: NAD 1983 2011 State Plane Tennessee FIPS 4100 Ft US.

Initial Flood Loss Assessment Using Hazus

In order to evaluate a range of potential flooding events, three flood scenarios, 100-, 500- and 1,000-year flood events, were selected based on potential future flood risk. Hazus Version 4.2 SP1 was used to produce respective flood depth grids and associated loss and damage estimates for Dyer County, utilizing steps outlined in the Hazus User Manual[2] (Department of Homeland Security & FEMA, 2013). The study region was defined as extending slightly beyond the county boundary to preserve river continuity. Topography was defined by importing 1 arc second USGS-produced Digital Elevation Models (DEMs) retrieved from the National Elevation Dataset (USGS, retrieved 2018). A stream network was generated, and a five square mile drainage area was chosen (i.e., rivers that have a drainage area of five square miles or larger were included), because the selection of a larger drainage area provided less detailed stream networks and a smaller drainage area was not continuous due to discrepancies between the scale of the analysis and the resolution of the DEMs.

Initially, a 100-year flood scenario was defined, with all stream reaches east of the Mississippi River and immediately to the west included. The Hazus hydrologic analysis was run for a 100-year flood event, resulting in delineation of the respective floodplain. Summary impact reports were exported as Excel files, and the geographic data was exported as shapefiles. This process was repeated for the 500- and 1,000-year flood scenarios.

Comparison of Hazus Flood Results

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[2] A user manual for Hazus 4.2 was released in August 2018. However, the Hazus portion of this research had already been completed using the previous user manual, which was the 2013 Hazus 2.1 User Manual.

The accuracy of Hazus flood extent boundaries was assessed through comparison with Flood Insurance Rate Maps (FIRMs), official maps developed by FEMA and used by the National Flood Insurance Program to determine insurance rates for buildings within different flood zones (FEMA, retrieved 2019 a,b). This included both visual comparisons within ArcGIS, as well as quantitative comparisons of the estimated flood inundation area. Additionally, Hazus flood extent boundaries were compared to the May 2011 flood. A preliminary flood extent map prepared by USGS (2011) was imported into ArcGIS, georeferenced using the outline of Dyer County, and then a shapefile was drawn manually. The comparative analysis showed that the 500-year FIRM flood extent was in close alignment with what was experienced in May 2011 and was therefore selected as the most reasonable flood extent to use for future flood mitigation planning.

Hazus building damage estimates were then compared to and augmented through the use of Microsoft Building Footprints (Microsoft, 2018). RStudio was used to isolate the building footprint data for Dyer County and export as a shapefile to use in ArcGIS (RStudio Team, 2015). To estimate the number of buildings affected by flooding, the building footprint polygons that intersected the flood extent polygon for each Hazus scenario (100-, 500-, and 1,000-year) as well as FIRM boundary (100- and 500-year extents) were selected and exported as shapefiles. In order to eliminate buildings that could represent less costly damages (such as sheds or garages) that would have likely been included in the Microsoft building footprint data, a threshold of 88.3 square meters (950 square feet) — the average size of a single-wide mobile home — was established (US Mobile Home Pros, retrieved 2019). Thus only buildings above this threshold that intersected the flood boundary were considered impacted. In order to compare these results with the damaged building results produced by Hazus, centroids were generated and displayed as dots for each of the polygons within the impacted Microsoft building footprints (Esri, retrieved 2019). These centroids could then be visually compared to a dot density map of Hazus' estimated damaged buildings, so that each map displayed one dot per damaged building.

Essential facilities (i.e., fire stations, police stations, medical centers)[3] are vital in the assessment of emergency response capability to flood hazards, so it was critical to use the most comprehensive dataset available. Hazus' essential facility inventory was compared to the Homeland Infrastructure Foundation-Level Data (HIFLD) (U.S. Department of Homeland Security, retrieved 2018). Three datasets representing the most up to date opensource data available for fire stations, police stations, and medical centers were evaluated (International Association of Fire Chiefs, 2019; Technigraphics Inc., 2009; Oak Ridge National Laboratory, 2018a).

Flood Impact Assessment

Among the key demographic factors that could impact response and recovery are vulnerable populations who may have difficulty due to limited means or mobility. According to Cutter et al (2000), these factors include: 1) population distribution, 2) both sides of the age spectrum – the

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[3] This definition of essential facilities can be modified to include other facilities of interest (e.g., shelters).

elderly and young, and 3) those who are considered economically disadvantaged. For the purpose of this study, these indicators were measured using data available at the census block level from the 2010 Census, as follows: 1) total population, 2) population over age 65 and under age 16, and 3) households earning less than $40,000 per year —slightly less than the most recent estimates of the median income for Dyer County, TN (U.S. Census Bureau, retrieved 2019). The locations of mobile home parks were also examined, as these communities face heightened flood risk due to structural vulnerabilities unique to these communities (ORNL, 2018b; TNECD, 2010). Areas of high vulnerability in Dyer County were identified via spatial analysis by visualizing the proximity of vulnerable populations to flood damage and emergency facilities.

To further assess the impact of flood inundation on transportation, two additional factors were examined: 1) road network disruption, and 2) accessibility to and from essential facilities. Using the Dyer County road network downloaded from TIGER/Line products (U.S. Census Bureau, 2012), the road network was clipped to the 500-year FIRM polygon, producing a shapefile consisting of all road segments that directly overlapped the flood impact area.

In order to assess essential facility accessibility, a portion of the methodology developed by Kermanshah and Derrible (2017) was adopted and modified. Specifically, ArcGIS Network Analyst was used to compute baseline service areas, defined as the area that can be reached within 16.1 km (10 miles) of an essential facility. The flood extent was then taken into account to determine which portions of the network could potentially be cut off, with the percent reduction in service area used as a quantitative measure of loss.

RESULTS/FINDINGS

Comparison of Hazus and FIRM Flood Extents

Figure 3 displays the estimated flood extents for 100-, 500- and 1,000-year events as produced by Hazus. Note that there are only subtle differences in these inundation areas, and the Mississippi River along the western border does not appear to be significantly flooded.

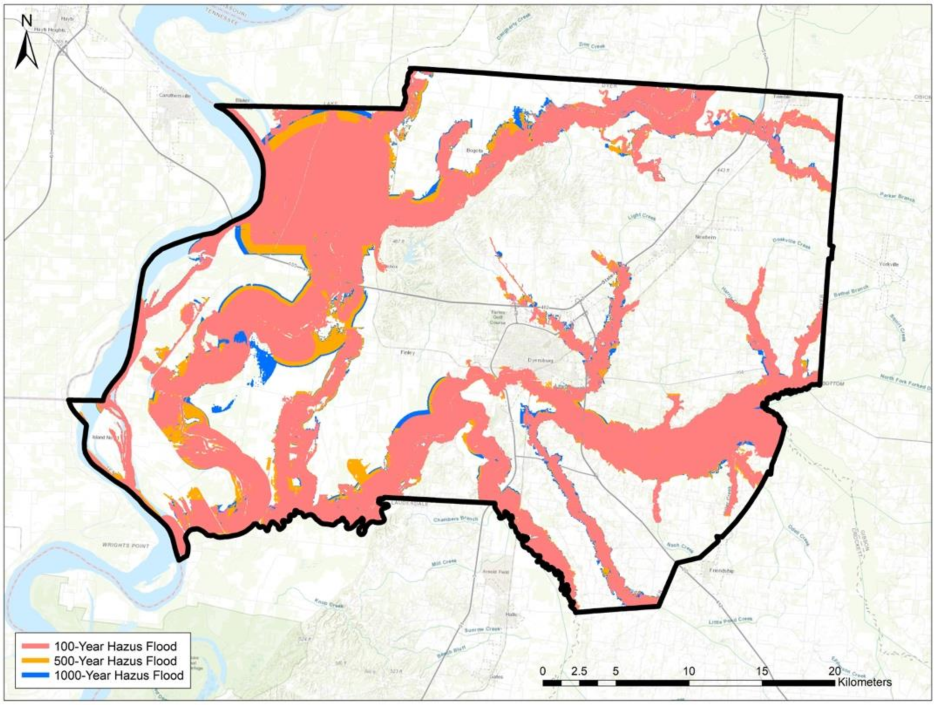


Figure 3. Comparison of 100-, 500-, and 1,000-year Hazus flood extents

Figure 4 displays the 100- and 500-year FIRM flood extents. These maps also have relatively similar boundaries, with the 500-year FIRM containing only 1.6% more area than the 100-year FIRM.

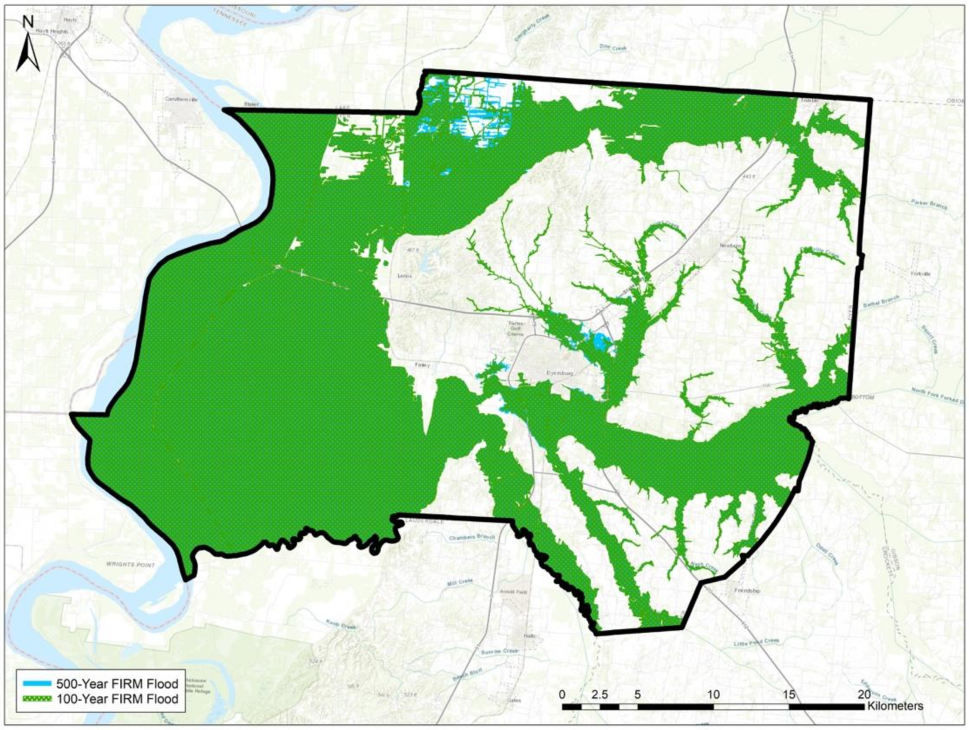


Figure 4. Comparison of 100-year and 500-year FIRM flood boundaries

The small discrepancies across the three Hazus flood extents, and between the 100- and 500-year FIRMs, respectively, suggest there may not be a sizeable difference in inundation area among the event scenarios. This could be due to: 1) the elevation of the region being such that increasing the amount of precipitation results in a flood with greater depth but not necessarily a larger area, or 2) the amount of overall precipitation in a 100-year flood and 500-year flood not being drastically different.

Unlike the comparisons shown in Figures 3 and 4, respectively, there are large discrepancies, as seen in Figure 5, when the flood extents from the two different sources are compared. The 100-year FIRM covers roughly 3.5 times more area than the 100-year Hazus extent (Figure 5a), and the 500-year FIRM covers close to 3.6 times more area than the 500-year Hazus extent (Figure 5b). One of the most notable differences is along the Mississippi River, the western border of Dyer County. For both Hazus flood extents, the Mississippi River flows mainly within its normal banks. However, the FIRM 100- and 500-year floods show the vast majority of the western portion of the county flooded. Additionally, most tributaries appear more flooded in the FIRM extents.

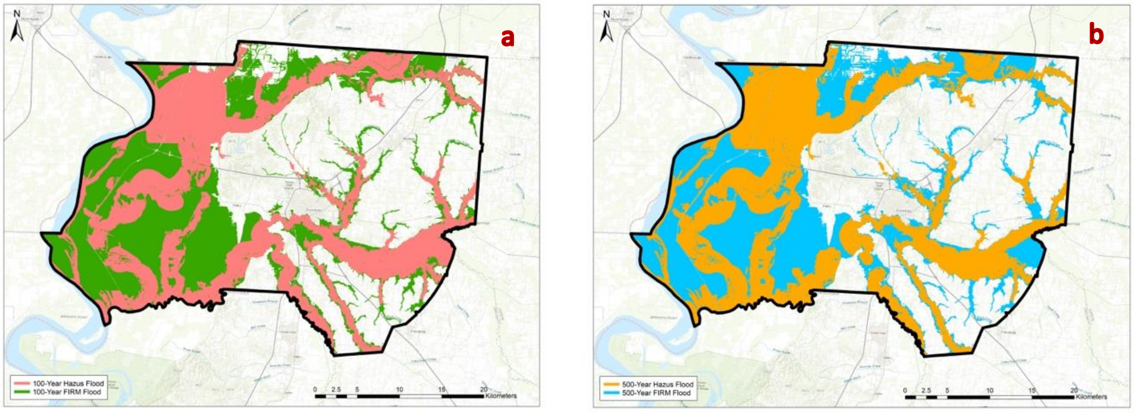


Figure 5. Comparison of Hazus and FIRM 100- and 500-year flood maps

In order to determine whether Hazus or FIRM flood extents would be more appropriate for additional analyses, the boundaries were compared to the historical flood that occurred in Dyer County in May 2011 (see Figure 6). It is evident that the 2011 flood extent aligns more closely with the 500-year FIRM map than to the 500-year Hazus extent (Figure 6b). It was therefore concluded that the FIRM-500 boundary is more representative of extreme flood events in this area. Moreover, in using Hazus, one may be significantly underestimating the 100-year and 500-year flood extents, respectively. A likely explanation can be found in the way Hazus predicts flood extent boundaries, particularly the fact that Hazus only accounts for precipitation that occurs *within* the defined study region. Since it is not possible to include the entire, or even a significant portion of, the Mississippi River watershed in the initial study region, Hazus is unable to account for precipitation occurring on the Mississippi River upstream of the study region.

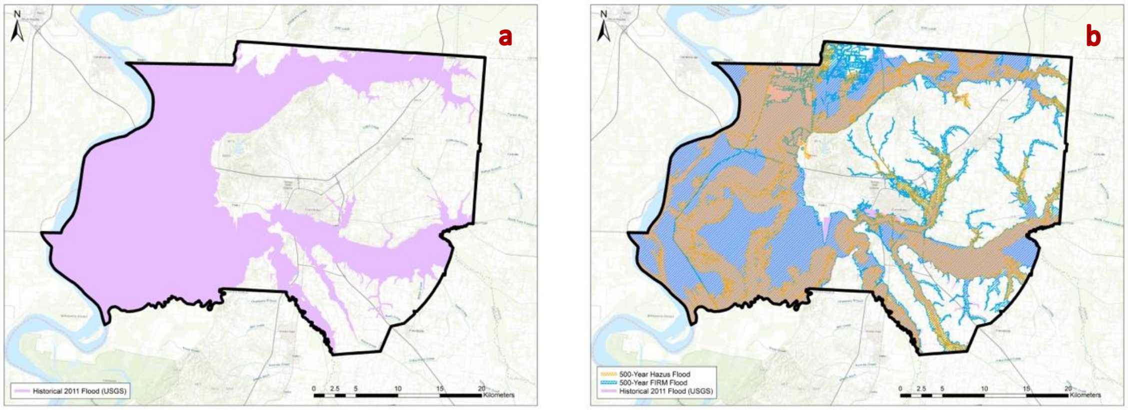


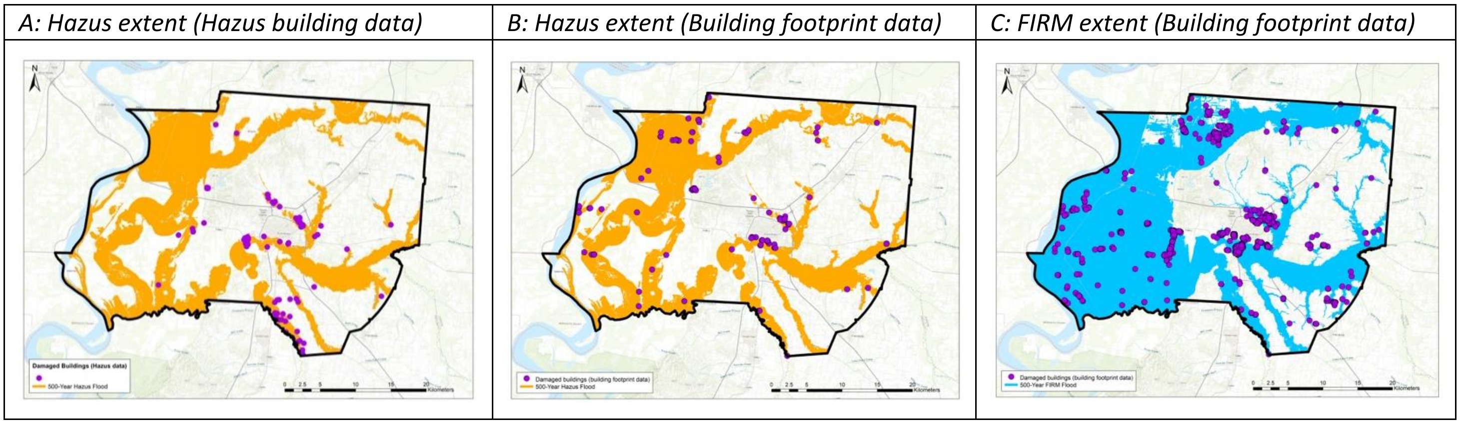
Figure 6. Comparison of 500-year FIRM and Hazus flood extents with actual 2011 flood

Comparison of Hazus Results and Microsoft Building Footprints

One key benefit to using Hazus is the built-in loss and damage functions for each building class and sub-class (e.g., a residential building with one floor and no basement), which account for the flood depth as it is calculated by Hazus using the DEMs. By contrast, FIRMs do not provide impact assessments. Consequently, even though the 500-year FIRM scenario is more representative of the inundation area, utilizing the Hazus impact assessment is a necessary starting point for performing a 500-year FIRM impact assessment.

Hazus estimates building damage based on assumptions made at the census block level (i.e., if 25% of a census block is inundated, 25% of the buildings of a certain type are considered damaged). The downside to using census-block level estimations is losing the accuracy of the actual building locations (i.e., it is possible that 25% of a census block could be inundated and no houses damaged, or vice-versa). In order to explore this potential bias, Microsoft building footprints were obtained for Dyer County and intersected with the flood inundation area.

The results of this process are displayed in Figure 7 and Table 1. Damaged building estimates from the 500-year flood is shown according to Hazus model output (column A), Microsoft building footprint analysis using Hazus 500-year flood boundary (column B), and Microsoft building footprint analysis using 500-year FIRM flood boundary (column C).


A: Hazus extent (Hazus building data)

B: Hazus extent (Building footprint data)

C: FIRM extent (Building footprint data)

Figure 7. Comparative Building Damage Estimates

Table 1. Affected Building Counts

Hazus 500-year flood boundary		**FIRM 500-year flood boundary**
Hazus results (# affected buildings)	Microsoft building footprint analysis results (# affected buildings)	Microsoft building footprint analysis results (# affected buildings)
75	128	1,194

There are visible differences in the number of affected buildings based on which flood model and building data are being used. The Microsoft building footprint results indicate a greater number of impacted buildings when compared to Hazus. For example, inspecting the damaged building estimates for just the 500-year Hazus flood extent, the Microsoft building footprint analysis results in the identification of roughly 70% more buildings impacted than initially estimated via Hazus for the same area of inundation.

Another difference is the extent to which the location of damaged buildings differs between the two analyses. The Hazus methodology (Figure 7, column A) shows the majority of the damaged buildings as clustered along a corridor in the south-southeast corner of the county, and in the center of the county. In comparison, the Microsoft building footprint analysis (Figure 7, column B) agrees that there is a cluster of damaged buildings in the center of the county; however, there is not a significant cluster in the south-southeast portion of the county, and rather the damaged buildings are more widely dispersed across the county.

Due to their flood extent differences, as expected the FIRM boundaries (Figure 7, column C) encompass significantly more buildings than do the Hazus flood extents. As shown in Table 1, the 500-year FIRM flood extent with the Microsoft building footprint analysis produces over 9 times more damaged buildings than the 500-year Hazus extent with the Microsoft building footprint analysis (Figure 7, column B), and almost 16 times more damaged buildings than the 500-year Hazus extent with Hazus' damaged building estimates (Figure 7, column A).

One caveat to consider when interpreting the Microsoft building footprint analysis is that the footprints were initially created using Microsoft's artificial intelligence methodology. As mentioned previously, it is not possible to identify a building's function from the footprint, and as a result it is not possible to assess the damage a specific building would sustain if flooded. Despite an attempt to exclude less critical buildings from the Microsoft footprints (only buildings with areas greater than the average size of a single-wide mobile home were included), there may still be many buildings that this threshold does not eliminate which could result in less serious damages (e.g., garages, sheds, or barns that do not house valuable assets). It is likely, however, that excluding dozens of additional building footprints from the figures shown in Figure 7, column C would still result in several times more impacted buildings identified than estimated from Hazus' calculations.

These findings suggest that in addition to potentially underestimating the flood extent, Hazus may also be incorrectly estimating the number and location of damaged buildings within a given boundary. This could have significant implications for hazard mitigation planning. If counties are preparing hazard mitigation plans based primarily from Hazus results, not only would resources be incorrectly allocated geographically, but there would likely be significantly more damage than estimated and thus more aid required. For this reason, supplementing Hazus results with the Microsoft building footprint analysis is highly recommended.

Hazus and HIFLD Essential Facilities Comparison

One key aspect of flood hazard resilience is the ability of emergency responders to reach affected populations, and for affected populations to seek help. In order to assess these considerations, it is important to use the most inclusive set of essential facility data available. In the following discussion, the Hazus essential facility dataset is compared with similar information contained in the Homeland Infrastructure Foundation-Level Data (HIFLD), maintained by the U.S. Department of Homeland Security.

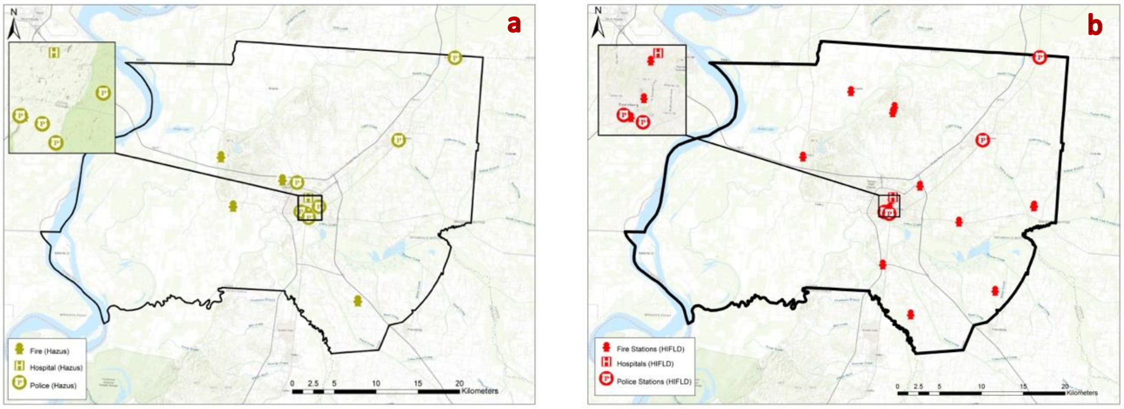


Figure 8. Comparison of Hazus and HIFLD essential facility data

The two maps in Figure 8 show Hazus and HIFLD essential facilities, respectively. Note the discrepancies in both the locations of police and fire stations. For police stations, the differences exist within the Dyersburg city limits, where the Hazus data displays five police facilities and the HIFLD dataset only two. However, on the City of Dyersburg's official website, only two police stations are reported – the two that are included in both datasets (DyersburgTN.gov, retrieved 2019).

A more significant concern is the discrepancy when examining the location of fire stations; Hazus and HIFLD depict 6 and 16 fire stations, respectively. The difference lies in the fact that the HIFLD dataset has recognized the existence of several volunteer fire departments located in Dyer County (Bruceville, Tigrett, East Dyer County, Millsfield, Bogota, Trimble, Fowlkes, and Yorkville), dispersed around the county such that response capability is substantially improved. As a result, it is recommended that the HIFLD dataset be used in analyzing resilience indicators associated with essential facilities.

Economic Impact

Though many limitations to Hazus have been raised, a beneficial output the software produces are flood depth grids, unlike FIRMs which are boundary polygons without associated depth measurements. These depth grids are subsequently used to estimate loss and damage based on the inundation depth of impacted structures. As this evaluation would be extremely tedious to conduct manually, Hazus provides the means by which base level damage and losses can be estimated, from which extrapolations could be possible to account for Hazus underestimates of the flood boundary and affected infrastructure.

Tables 2-4 provide conservative estimates of the loss and damage that may be expected in Dyer County for a flood event matching the Hazus 500-year flood boundary: 1) roughly $107 million in direct economic losses for buildings, 2) over $13 billion in direct economic losses for agriculture, and 3) around $10 million in direct economic losses for vehicles. Hazus also includes a methodology to estimate displaced people and those needing shelter, as shown in Table 5 for the 500-year Hazus flood extent.

Table 2. Hazus estimated direct economic building loss for a 500-year flood

Direct Economic Losses for Buildings (thousands of US dollars)								
Capital Stock Losses				Income Losses				
Building Loss	Contents Loss	Inventory Loss	Building Loss Ratio %	Relocation Loss	Capital Related Loss	Wage Losses	Rental Income Loss	**Total Loss**
$17,496	$24,684	$749	2.9	$7,688	$8,985	$44,777	$2,540	**$106,919**

Table 3. Hazus estimated direct economic agricultural loss for a 500-year flood

Direct Economic Loss for Agriculture Products (thousands of dollars)					
Crop	Crop Loss Day 0	Crop Loss Day 3	Crop Loss Day 7	Crop Loss Day 14	Max Total Loss
Corn	$0	$3,523,207	$4,697,609	$4,697,609	$4,697,609
Corn Silage	$0	$3,951,068	$5,268,090	$5,268,090	$5,268,090
Soybeans	$0	$220,472	$293,962	$293,962	$293,962
Wheat	$0	$2,656,415	$3,541,887	$3,541,887	$3,541,887
Total	$0	$10,351,161	$13,801,549	$13,801,549	**$13,801,549**

Table 4. Hazus estimated direct economic vehicle loss for a 500-year flood

Direct Economic Losses for Vehicles (dollars)			
Car	Light Truck	Heavy Truck	Total Loss
$6,223,842	$3,280,057	$576,224	$10,080,123

Table 5. Hazus displaced population & short-term shelter need estimates for a 500-year flood

# of Displaced People	# of People Needing Short-Term Shelter
1066	20

As noted earlier, Hazus likely underestimates the flood extent and number of damaged buildings for a 500-year flood in Dyer County. As such, these loss and damage results should be considered modest ballpark figures, with the expectation that a flood with an extent similar to the 500-year FIRM boundary would have a more significant economic impact. Further research could develop a methodology in which these damage and loss estimates could potentially be scaled using some factor, for example based on the difference between the number of damaged buildings calculated by Hazus for a 500-year flood and the number of buildings calculated through the Microsoft building footprint analysis for the 500-year FIRM.

Social Vulnerability Analysis

Figure 9 displays four maps, each depicting an indicator at the census block level of social vulnerability in Dyer County relative to a 500-year FIRM flood extent: a) total population, b) households earning less than $40,000 per year, c) population over age 65, and d) population under age 16. The locations of essential facilities also appear on each map. Figure 10 displays the location of mobile home parks in relation to a 500-year FIRM.

All of the respective indicators reveal similar pockets of potentially vulnerable populations in flood inundated areas, most notably situated in the southeastern and central-western portions of the county. As expected, given that one-half of the population of Dyer County lives in Dyersburg, clusters of vulnerable populations are located there. Although Dyersburg is not included in the flood boundary in most places, it is surrounded by inundation, which could impact evacuation routes as well as transportation to and from essential facilities, most notably Dyer’s one hospital. Additionally, all of the four mobile home parks are located within a kilometer of the 500-year FIRM flood boundary – one of which lies within the boundary – and those in the southern central portion of the county in particular may have difficulty evacuating or reaching the hospital in Dyersburg. Examining these potentially vulnerable areas is a critical component of emergency preparedness, as it allows for advance planning regarding how to best access and provide aid to the most at-risk county residents.

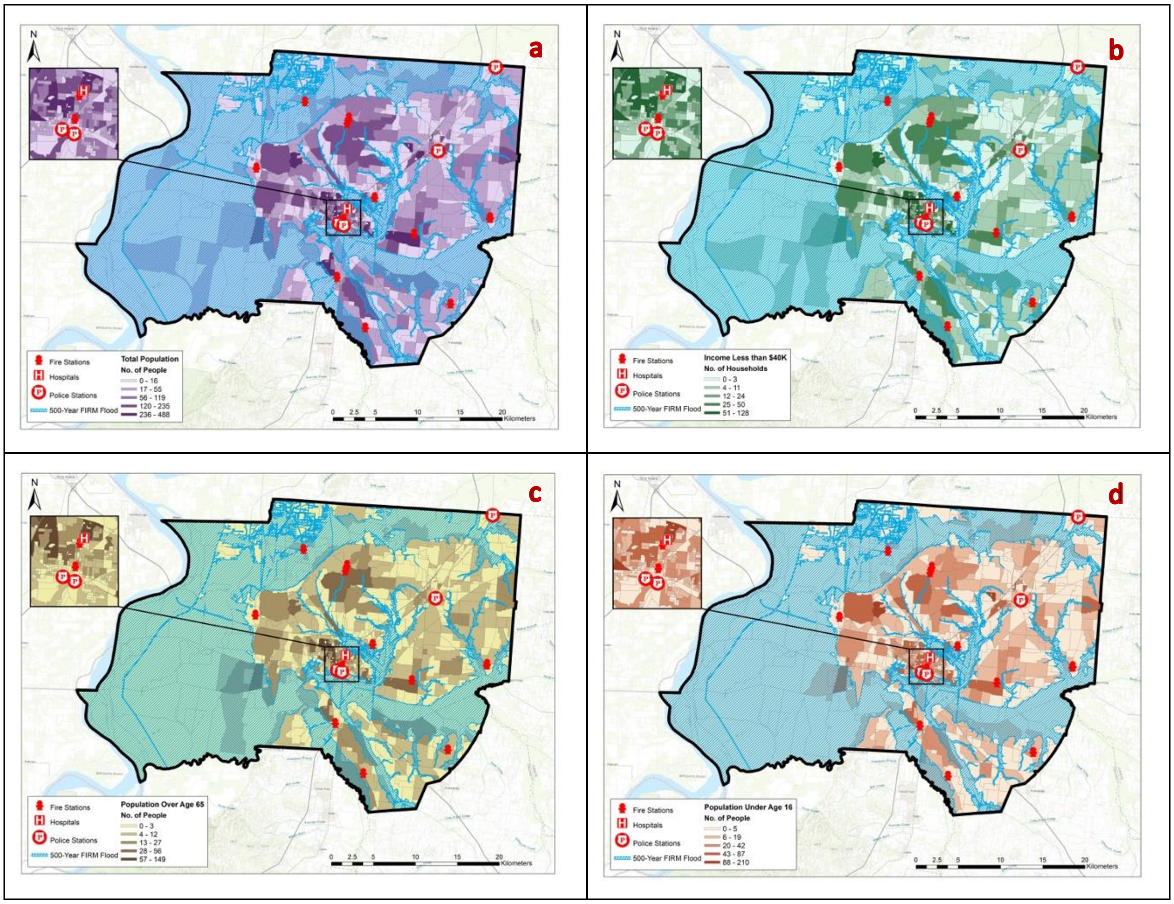


Figure 9. Social vulnerability - 500-year FIRM flood extent and HIFLD essential facilities

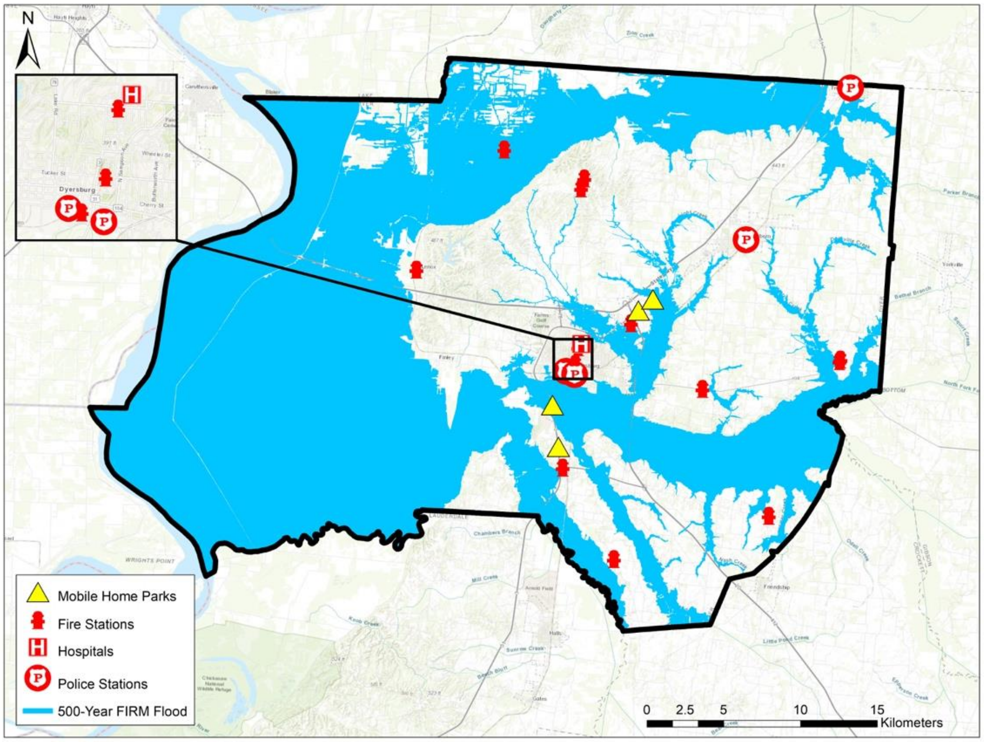


Figure 10. 500-year FIRM flood extent and mobile home park locations

Transportation Mobility Analysis

Figure 11 shows that 22% of the road network is directly inundated by the 500-year FIRM flood extent. This is supported by the results displayed in Table 6, which shows the length and percent affected for various road types in the county. Such disruption to the transportation system would dramatically affect local travel, and likely regional travel as well, impacting personal mobility and causing supply chain interruptions. This also underscores the aforementioned concerns regarding access to emergency response and evacuation routes.

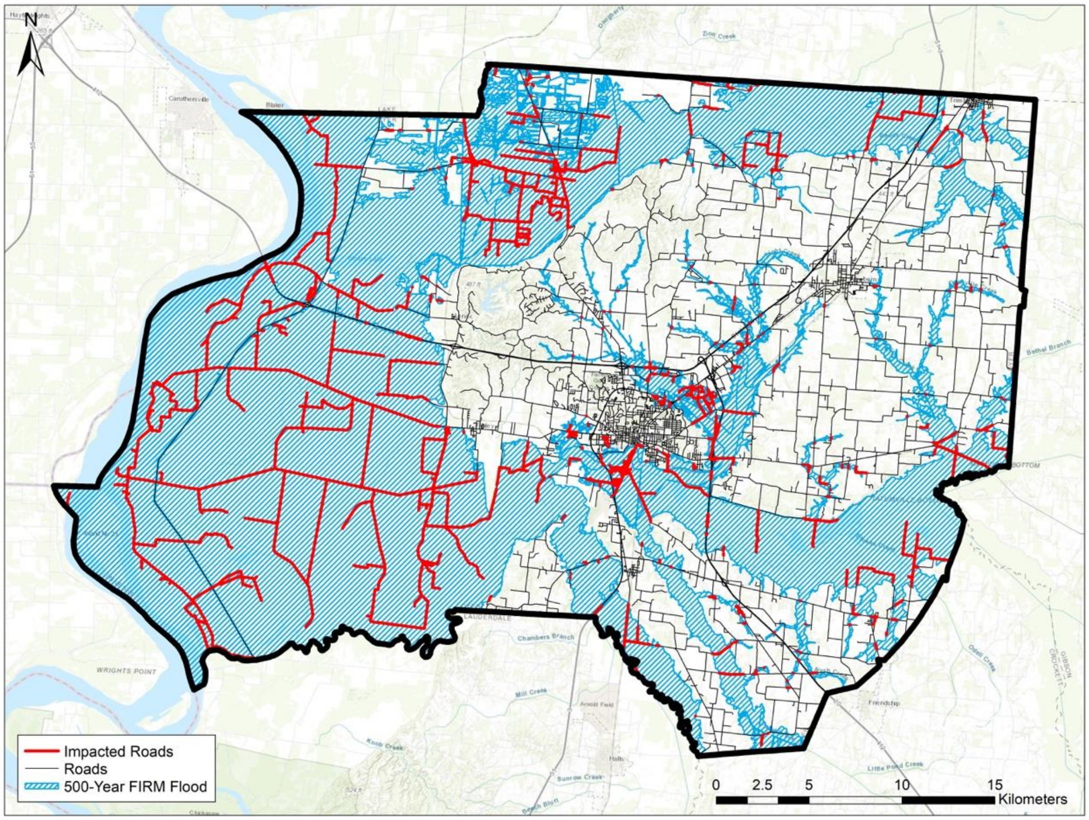


Figure 11. Road network affected by a 500-year FIRM extent flood

Table 6. Inundation by road type for 500-year FIRM flood

Road Type	Length (miles)	% Affected
County	4.8	10%
Interstate	3.3	11%
Common Name	196.4	23%
State Recognized	29.9	15%
U.S.	9.9	8%
Not Categorized	71.7	38%

Another perspective in assessing the impact of a 500-year FIRM on the transportation system is the extent to which the service area of the county is affected. Recall that this is defined as the area that can be reached within 16.1 km (10 miles) of an essential facility. As shown in Figure 12, when compared with the initial baseline service area (Figure 12a), the 500-year FIRM event results in a service area reduction of roughly 49% less (Figure 12b). Additionally, note that many essential facilities are located either within the inundated area or surrounded by inundation, diminishing their ability to provide assistance and potentially requiring help themselves. This has dramatic implications in terms of human health and safety.

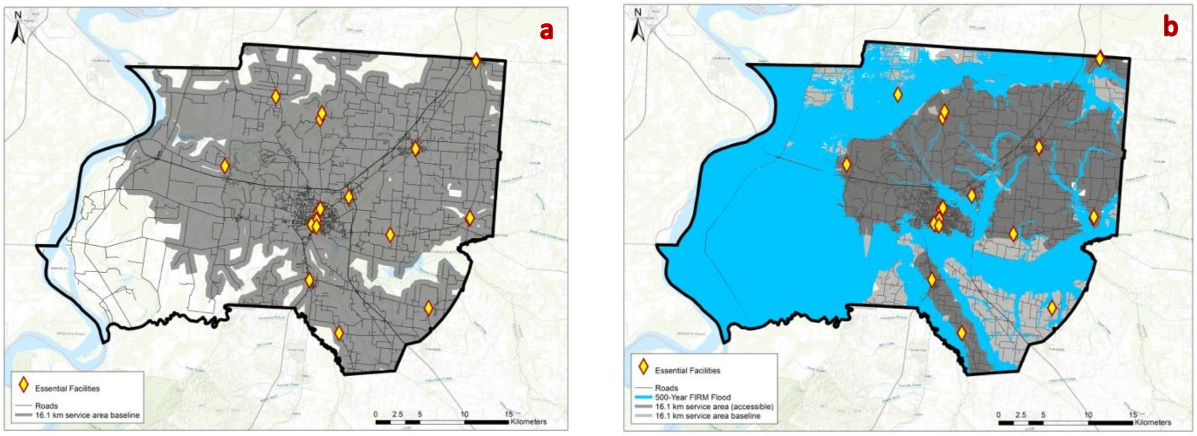


Figure 12. Baseline and 500-year FIRM service area analysis results

IMPACTS/BENEFITS OF IMPLEMENTATION

Using Dyer County as a use case, areas were identified where more vulnerable populations may be impacted by flooding. These locations should be the focus of future flood management planning, as well as communication with residents and business about heightened flood risk. Creating this informed dialogue within the community before the next major flood is vital to ensuring that people are aware of such risks and know the best protocols to follow in case of an emergency.

This research also demonstrated the potential for flooding to cause immense disruption of the transportation network, impacting personal mobility, supply chain continuity, and emergency response. Within this context, special emphasis was placed on the mobility needs of at-risk populations (e.g., impoverished, children and elderly). This additional consideration can enable communities to facilitate policy changes and activities to build resilience in the most vulnerable areas of their jurisdictions.

Beyond the knowledge gained in terms of flood management planning for Dyer County, important methodological considerations were discovered. It was observed that: 1) Hazus likely underestimates the flood extent boundaries for study regions along major rivers such as the Mississippi, and the 500-year FIRM is a more realistic boundary to use in preparing for a significant flood event in Dyer County, 2) Hazus may be incorrectly predicting the number and location of damaged buildings, and 3) Hazus essential facility inventory data underrepresents the accessibility and response capabilities of essential facilities.

These methodological findings have important implications given that Hazus is the nationally recommended tool for flood mitigation planning at the county level. For example, if Dyer County were to base its flood emergency response plans on the initial Hazus results (flood extents, damaged buildings, essential facility locations, and resulting loss and damage), they would be woefully underprepared for a flood of significant magnitude, more accurately represented by the 500-year FIRM.

There are several ways this pressing issue could be addressed. The methodology demonstrated in this study provides a starting point (i.e., comparing Hazus results with other sources to determine flood extent, affected buildings, and essential facilities; augmenting the assessment with social vulnerability and transportation mobility analyses to understand ability to evacuate or be reached by emergency responders). Yet, the Hazus damage and loss results are helpful in providing an initial perspective on the implications of a flood of the magnitude predicted by a Hazus flood extent, and could potentially be scaled to provide a more realistic estimate of the consequential impacts.

There is also a compelling need for further research, including improved tools and data availability. The creation of flood depth grids based on FIRM boundaries that could be used in Hazus would enable more accurate damage and loss estimates. Alternatively, the Hazus software hydrologic models could be improved to account for precipitation that does not occur within the study region, such that flooding in communities bordering large river systems with extensive watersheds can be more realistically portrayed, without compromising the intricacy of the stream network or requiring extensive computing power. Additionally, it is difficult to update the general building stock data within Hazus, as any modifications require detailed information (for example the number of stories and type of basement for each building). Since collecting such data for every building may not be feasible, Hazus damage loss curves could benefit from having more generalized settings which would allow the user to estimate loss and damage on more current building data.

Finally, this work was intended to create a methodology that can be replicated by other counties and regions who wish to evaluate their flood resilience and improve decisions regarding future flood management. Of the data and software described in the methodology, the only element that was not open source was ArcGIS 10.5.1, which requires a license to operate (Esri, 2017). Though the methodology was developed to be conducted in ArcGIS, much of it can be adapted to be performed in QGIS – an open source alternative. The transferability and scalability of this approach provides considerable value-added beyond the locale where the case study was implemented.

REFERENCES

American Society of Civil Engineers (ASCE). (2017). The 2017 Infrastructure Report Card: A comprehensive assessment of America's infrastructure.

Association of State Dam Safety Officials (ASDSO). (2017). The Cost of Rehabilitating Our Nation's Dams: A methodology, estimate &proposed funding mechanisms.

Camp, J., Whyte, D., Shaw, A. (2016). Technical Report: Freight Economic Vulnerabilities Due to Flooding Events. CFIRE 09-19. National Center for Freight & Infrastructure Research & Education, University of Wisconsin–Madison.

Coggins, A. R. (2018). Floods of 1937. Retrieved from https://tennesseeencyclopedia.net/entries/floods-of-1937/

Cutter, S. L., Mitchell, J. T., & Scott, M. S. (2000). Revealing the vulnerability of people and places: A case study of Georgetown County, South Carolina. *Annals of the Association of American Geographers*, *90*(4), 713–737. https://doi.org/10.1111/0004-5608.00219

Ding, A., White, J. F., Ullman, P. W., & Fashokun, A. O. (2008). Evaluation of HAZUS-MH Flood Model with Local Data and Other Program. *Natural Hazards Review*, *9*(1), 20–28. https://doi.org/10.1061/(ASCE)1527-6988(2008)9:1(20)

DyersburgTN.gov. (Retrieved 2019). City Directory. Retrieved from https://www.dyersburgtn.gov/city_directory/index.htm#police

Environmental Protection Agency (EPA). (2016). What Climate Change Means for Tennessee. EPA 430-F-16-044 (August, 2016). Retrieved from: https://19january2017snapshot.epa.gov/sites/production/files/2016-09/documents/climate-change-tn.pdf

Esri. (2017). ArcGIS Desktop 10.5.1.

Esri. (Retrieved 2019). How To: Locate polygon centroids and convert them to points in ArcView and ArcEditor. Retrieved from https://support.esri.com/en/technical-article/000009647

Federal Emergency Management Agency (FEMA). (2008). National Flood Hazard Layer: Dyer County, Tennessee [GeoDatabase]. Retrieved from https://www.floodmaps.fema.gov/NFHL/status.shtml

Federal Emergency Management Agency (FEMA). (2018). Hazus-MH Flood Model 4.2 SP1 [Software]. Retrieved from https://msc.fema.gov/portal/resources/hazus

Federal Emergency Management Agency (FEMA). (2012). Hazus-MH 2.1 Flood User Manual. Retrieved from https://www.fema.gov/media-library/assets/documents/24609

Federal Emergency Management Agency (FEMA). (Retrieved 2019a). Flood Insurance Rate Map (FIRM). Retrieved from https://www.fema.gov/flood-insurance-rate-map-firm

Federal Emergency Management Agency (FEMA). (Retrieved 2019b). The National Flood Insurance Program. Retrieved from https://www.fema.gov/national-flood-insurance-program

Gillespie-Marthaler, L., Baroud, H., Abkowitz, M. (2019a). Failure Mode Analysis and Implications for Sustainable Resilience of Flood Protection Infrastructure in the U.S. (in manuscript).

Gillespie-Marthaler, L., Nelson, K., Baroud, H., Abkowitz, M. (2019b). Selecting indicators for assessing community sustainable resilience. *Risk Analysis* (in print).

International Association of Fire Chiefs (IAFC). (2019). Fire Stations (2019 Partial Data Set) [Shapefile]. Retrieved from https://hifld-geoplatform.opendata.arcgis.com/datasets/fire-stations-2019-partial-data-set

Kermanshah, A., & Derrible, S. (2017). Robustness of road systems to extreme flooding: using elements of GIS, travel demand, and network science. *Natural Hazards*, *86*(1), 151–164. https://doi.org/10.1007/s11069-016-2678-1

Lane, N. (2008). Aging Infrastructure: Dam Safety, Washington: Congressional Research Service.

Microsoft. (2018). Computer generated building footprints for the United States [GeoJSON]. Retrieved from https://github.com/Microsoft/USBuildingFootprints

National Aeronautics and Space Administration (NASA). (2011). Landsat Satellite Images of Mississippi Flooding May 2011 Compared to April 2010. [Satellite Images]. Retrieved from https://svs.gsfc.nasa.gov/10773

National Research Council (NRC). (2012). Dam and levee safety and community resilience: a vision for future practice. National Academies Press. Washington, DC.

National Weather Service (NWS) & National Oceanic and Atmospheric Administration (NOAA). (Retrieved 2019). Mississippi River Flood History 1543-Present. Retrieved from https://www.weather.gov/lix/ms_flood_history

Nelson, K. S., Gillespie-Marthaler, L., Baroud, H., Abkowitz, M., & Kosson, D. S. (2019). An Integrated and Dynamic Framework for Assessing Sustainable Resilience in Complex Adaptive Systems. *Sustainable and Resilient Infrastructure,* DOI: 10.1080/23789689.2019.1578165.

National Resource Conservation Service (NRCS). (2003). Aging Dams. U.S. Department of Agriculture. Washington, DC.

Oak Ridge National Laboratory (ORNL). (2018a). Hospitals [Shapefile]. Retrieved from https://hifld-geoplatform.opendata.arcgis.com/datasets/hospitals

Oak Ridge National Laboratory (ORNL). (2018b). Mobile Home Parks [Shapefile]. Retrieved from https://hifld-geoplatform.opendata.arcgis.com/datasets/mobile-home-parks/data

RStudio Team. (2015). RStudio: Integrated Development for R. RStudio, Inc. Retrieved from http://www.rstudio.com/.

Scawthorn, C., Blais, N., Seligson, H., et al. (2006). HAZUS-MH Flood Loss Estimation Methodology: Overview and Flood Hazard Characterization. *Natural Hazards Review*, 7(2), 60-71. https://doi.org/10.1061/(ASCE)1527-6988(2006)7:2(60)

Technigraphics Inc. (2009). Local Law Enforcement Locations [Shapefile]. Retrieved from https://hifld-geoplatform.opendata.arcgis.com/datasets/local-law-enforcement-locations

Tennessee Department of Economic & Community Development (TNECD). (2010). Floodplain Management in Tennessee Quick Guide. Retrieved from https://02f0a56ef46d93f03c90-22ac5f107621879d5667e0d7ed595bdb.ssl.cf2.rackcdn.com/sites/2587/uploads/16747/NFIP_TN_Quick_Guide20170508-30578-b3dxnd.pdf

U.S. Army Corps of Engineers (USACE). (2018). Levee Portfolio Report. Levee Safety Program.

U.S. Army Corps of Engineers (USACE), Memphis District. (2014). Memphis District Tennessee Projects Dyer County Little Levee, TN. Retrieved from https://www.mvm.usace.army.mil/Portals/51/docs/missions/projects/Projects%20By%20State/Tennessee.pdf

U.S. Army Corps of Engineers (USACE), Mississippi Valley Division. (2013). MR&T 2011 Post Flood Report. Retrieved from https://www.mvd.usace.army.mil/Missions/Flood-Risk-Management/Regional-Flood-Risk-Management-Program/MR-T-Post-Flood-Report/

U.S. Census Bureau. (Retrieved 2019). QuickFacts: Dyersburg city, Tennessee; Dyer County, Tennessee; Tennessee; United States. Retrieved from https://www.census.gov/quickfacts/fact/table/dyersburgcitytennessee,dyercountytennessee,tn,US/AGE295217

U.S. Census Bureau. (2012). 2010 TIGER/Line Shapefiles [machine-readable data files]. Retrieved from https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html

U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS). (2012). Spring 2011 Middle & Lower Mississippi River Valley Floods. Retrieved from https://www.weather.gov/media/publications/assessments/MisssissippiRiverFloods12.pdf

U.S. Department of Homeland Security. (Retrieved 2018). Homeland Infrastructure Foundation-Level Data (HIFLD). [Dataset, Shapefile]

U.S. Department of Homeland Security, Federal Emergency Management Agency. (2013). Hazus®–MH User Manual. Retrieved from www.msc.fema.gov

U.S. Mobile Home Pros. (Retrieved 2019). Mobile Home Sizes and How To Choose The Best One For Your Family. Retrieved from https://www.mobilehomesell.com/mobile-home-sizes/.

United States Geological Survey (USGS). (Retrieved 2018). USGS_NED_1_n36w089_ArcGrid, USGS_NED_1_n36w090_ArcGrid, USGS_NED_1_n36w091_ArcGrid, USGS_NED_1_n37w089_ArcGrid, USGS_NED_1_n37w090_ArcGrid, USGS_NED_1_n37w091_ArcGrid [Digital Elevation Models]. Retrieved from https://www.usgs.gov/core-science-systems/ngp/tnm-delivery/gis-data-download?qt-science_support_page_related_con=0#qt-science_support_page_related_con

United States Geological Survey (USGS). (2011). Peak Flood Inundation – preliminary map [PDF]. Retrieved from https://water.usgs.gov/floods/events/2011/memphis/Dyer_Co_peaks_5_26_11_draft_disclaimer.pdf

United States Geological Survey (USGS). (Retrieved 2019). Floods and Recurrence Intervals. Retrieved from:https://www.usgs.gov/special-topic/water-science-school/science/floods-and-recurrence-intervals?qt-science_center_objects=0#qt-science_center_objects

Van West, C. (2018, March 01). Dyer County. Retrieved from https://tennesseeencyclopedia.net/entries/dyer-county/