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Minnesota River Basin Flood Mapping and Impact Assessment

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Minnesota River Basin Flood Mapping and Impact Assessment

By

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Abstract

South Central Minnesota has experienced frequent flooding in the past because of the relatively flat topography, low elevation, and large amounts of snow melt in the spring. When these events happen, there is a large economic impact and potential health hazards to residents of the area. Having up-to-date flood zone maps can help residents be better prepared for emergency situations. Using Geographic Information Science (GIS), flood zone maps can be updated frequently in a more time efficient and inexpensive manner.

Using a 30-meter digital elevation model (DEM) Compound Topographic Index (CTI) and Stream Power Index (SPI) layers were calculated for the all of South Central Minnesota for this study. These two indices combined were used to identify areas that would be more prone to flooding. 30-meter, 10-meter, and 3-meter resolution DEMs were used to create CTI and SPI layers for analysis in the Seven Mile Creek Watershed. They were used to not only find areas prone to flooding but also to find how the resolution of the DEM affects the outcomes of the indices.

Also, flood levels were created for the city of Mankato, MN using a DEM cell selection process. These flood levels were used to identify land and buildings that could be inundated in the event of flood water breaching the levee. The costs of such damages were also calculated using parcel shapefiles and lidar-derived building footprints.

The role of the DEM was also examined during the creation of these flood levels. Using 30-meter, 10-meter, and 1-meter resolution DEMs, the differences in the total extent of each flood stage and the predicted financial impacts were examined.

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Chapter 1: Introduction & Literature Review

1.1 Background & Objectives

Water is a 400 billion dollar global industry trailing only electricity and oil. Learning how to better predict, prepare, and control water movement and water crises including floods and droughts is an economic and health necessity that must be addressed more over the coming years. Floodplain mapping is an important piece of this puzzle.

South Central Minnesota has experienced flooding frequently in the past because of the relatively flat topography, low elevation, and large amounts of snow melt in the spring. When these events happen, there is a large economic impact and potential health hazards to residents of the area. Having up-to-date flood zone maps can help residents be better prepared for emergency situations.

Much of Mankato, Minnesota has been protected from major flooding by the levee that was constructed in 1985. This does not mean however that this structure will remain perfect. On September 26, 2010 for example, old water pipes broke under the ground near the levee causing the soil to collapse down (See Figure 1.1). Soon after, surrounding neighborhoods had to be warned that an evacuation could be possible (Linehan, 2010). In

Figure 1.1: Mankato Levee Damage September 2010 (Linehan, 2010)

the case of a breach of the levee when the water is high, citizens should be aware if their property could be affected. The city should also be aware of the possible costs of damages that could happen from an event and prepare themselves for the emergency scenario.

The following objectives will be addressed during this study:

1. Compound Topographic Index (CTI) and Stream Power Index (SPI) were calculated for South Central Minnesota using a 30-meter resolution DEM to determine areas prone to flooding.
2. CTI and SPI were calculated for the Seven Mile Creek Watershed using 30-meter, 10-meter, and 3-meter resolution DEMs to find how the resolution of the DEM affects the total area output for the respective indices.
3. In the city of Mankato, MN, using a DEM cell selection process, flood levels were created using 30-meter, 10-meter, and 1-meter resolution DEMs. This was done to delineate areas in the city that would be affected by rising water in the Minnesota River.
4. The role of the DEM scaling problem in the analysis of floodzone mapping is examined as well.
5. Land parcels and structures intersecting each flood stage for the three DEMs were selected and analyzed to calculate the total financial impact each DEM is predicting for the city.

CTI (also known at Topographic Wetness Index) is used to determine areas of water catchment and possible sites of water pooling and heavy soil saturation. SPI is used to highlight areas with large catchments and steep slope values which make water flow at high rates of speed. CTI and SPI are believed to be strong indicators of areas that could be prone to flooding.

CTI and SPI layers were created using ESRI's Geographic Information System (GIS) software ArcMap. These layers will be examined for the whole of South Central Minnesota using a 30-meter resolution DEM. What specific areas are highlighted when using these indexes? Also, CTI and SPI were calculated using 3-meter, 10-meter, and 30-meter resolution DEMs for the Seven Mile Creek Watershed in Nicollet County. What role does DEM resolution play in the calculation of these indexes?

Digital elevation models (DEMs) of varying resolution are available to aid in the derivation of hydrological modeling outputs. These outputs, however, can vary greatly depending upon the spatial scale of the DEM used in the model. Spatial scale includes two aspects: resolution and extent. While resolution refers to the smallest geographic unit of analysis for the model, extent defines the total geographic area to which the model is applied. Better knowledge of the scaling problem can help users understand the role of DEM error in their study. 30-meter, 10-meter, and high resolution (1-meter) LIDAR-based DEMs are used and compared in this study.

Additionally, parcel data was collected for the city of Mankato. A geographic information system (GIS) was constructed to estimate the impacts and damages at various flood stages based on county assessment values. How much does the resolution of the DEM change the total extent of the flood stages? How many more parcels and how much does the total cost of damages change with resolution? Lastly, using a first-return lidar-based 1 foot resolution digital surface model (DSM), 3-dimensional building footprints will be created to aid in the visualization and analysis of how much each individual parcel will be affected. Is a specific parcel completely inundated or partially inundated with flood water?

1.2 Why is flood mapping important?

Land near rivers and streams have always been sought after property because of its fertile soil, transportation abilities, and aesthetically pleasing views. However, as communities have developed around these areas, so has the potential for widespread economic impact when these bodies of water rise. Since there is not an agency in charge of collecting flood loss statistics, only estimates are available such as those compiled by the National Weather Service (See Figure 1.2). Every year, billions of dollars in losses are estimated due to flooding in the United States.

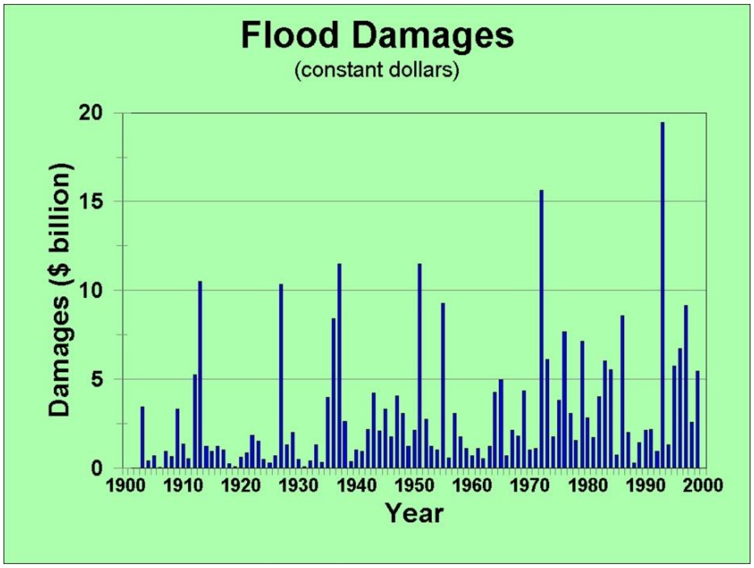


Figure 1.2: Graphical display of flood damage estimates (National Weather Service, 2010)

Flooding can affect communities in many ways. In areas that rely heavily on agriculture, such as southern Minnesota, there is loss of crops and livestock, damage to fences, pasture land, and farm buildings. All areas can be affected by damage to infrastructure (See Figure 1.3), buildings, and disruptions to local utilities and services such as power, gas, emergency services, and drinking water. Potential revenue is lost for businesses in these areas as well.

Figure 1.3: US Highway 169 south of St. Peter, Minnesota after Minnesota River flooding in fall 2010 (Unknown, 2010)

Flooding has the potential for some obvious health hazards such as those related to drowning and tainted water supplies. Over one hundred lives are lost every year in the US due to flooding. According to United States Geological Survey (2006), more than half of all fatalities during floods are auto related and usually involve the driver misjudging the depth and velocity of flowing water while driving. Also, there is great mental stress for families who are experiencing losses to their homes, income, and freedom. When flooding occurs and financial claims and liabilities are determined, accurate and timely maps can ease the stress that is common during these times of uncertainty.

Historically, private flood insurance has been too expensive to purchase because of the high risk involved in underwriting these types of policies for insurance companies (Holladay and Schwartz, 2010). The Federal Insurance and Mitigation Administration (FIMA) manages the National Flood Insurance Program (NFIP) that was enacted by Congress in 1968 (updated with more strict requirements in the 1973 and again in the 1990's). The program requires people and businesses who build within flood zones to purchase insurance offered through the program at more affordable rates. The program has steadily grown over the past three decades to over a one billion dollar investment with millions of policies in place (See Table 1.1). The areas required to obtain this insurance are determined by whether the property is located in a FEMA 100-year flood zone area (discussed in further detail in section 1.2). This being said, accurate flood maps are a necessity for people to know whether or not they fall into this zone.

Table 1.1: Growth of the National Flood Insurance Program (Harrison et al., 2001)

	1980	1990	1998
Policies in Force	2,058,601	2,415,883	4,117,936
Flood Loss Claims	47,983	21,176	75,663
Loss Dollars Paid ($)	219,449,804	186,324,840	569,572,510
Policy Revenue ($)	155,271,780	655,460,565	1,599,231132
Total Coverage ($)	93,963,333,000	210,005,953,000	482,576,897,000
Average Policy Coverage ($)	45,644	86,927	117,189
Cost per $1,000 of Coverage ($)	1.65	3.12	3.31

1.3 Who is mapping current and potential flood events?

1.3.1 FEMA

The Federal Emergency Management Agency (FEMA) has the responsibility to provide nationwide flood maps to communities and is in the process of updating these maps from paper to digital format while at the same time improving their accuracy through the Flood Map Modernization Program. In order to determine the flooding risk a community faces, a Flood Insurance Study is conducted on the area. The Flood Insurance Study compiles information including area rainfall, statistical river flow data, topographic surveys, and hydrologic/hydraulic analysis. FEMA then creates maps showing the level of risk an area faces. For example, some maps show 100-year flood risk (a flood that has a 1% probability of happening in a given year). These maps are used to not only implement emergency response plans but also to protect local and regional economies through flood protection zoning, improved water infrastructure, and home and business insurance in the case of damaging floods.

1.3.1.1 Flood Map Modernization Program

The potential for flood damage is always changing since the earth's surface and weather conditions are always changing. Land development, natural erosion, agriculture, and many other factors can cause changes in flood hazard damage and the frequency of floods. Technologies for flood mapping are evolving. Increased accuracy in GPS units and higher power computers used to improve modeling and GIS has changed the way flood maps are produced and maintained. Communities that have access to and understanding of these improving technologies are demanding more accurate and timely maps as well (Federal Emergency Management Agency, 2010).

1.4 How is a floodplain map created?

Flood zone mapping consists of several elements, each of which can vary depending upon the chosen study site and available resources. Ground point elevation data, a water flow simulation model, and an output are needed for any flood zone study. Each of these factors are briefly discussed below. Scale, cost, and land-cover are just a few factors to consider when creating these maps.

1.4.1 What are DEMs?

Digital elevation models (DEMs) are raster based GIS layers used to represent elevation data distributed over a surface. Based on a grid system, the squares used to visualize DEMs are available in different sizes or spatial resolutions. DEMs are used in flood mapping to identify and determine the slope, size, length, direction, velocity, and depth of water drainage features and floods. The accuracy of the DEM has a direct influence on the outcome of flood mapping as less accurate DEMs will omit certain features and/or over emphasize the influence of others.

DEMs were traditionally derived through surveying methods. These methods included using teams of people on the ground to collect ground point measurement information about an area. While this is extremely accurate, it can be financially costly and time consuming. As computer technology has improved over the last couple decades, so have the possibilities for automating the surveying process with the use of remotely sensed data combined with GIS.

1.4.1.1 USGS Nationwide DEMs

GIS and remote sensing data have improved quality, lower prices, and easier accessibility than ever before, making it a great option for digital flood mapping. Currently, the United States Geological Survey (USGS) is the largest provider of DEMs in the United States. The five types of DEMs available through the USGS have different:

1. Sampling intervals
2. Geographic reference systems
3. Areas of coverage
4. Accuracy

Of the four differences listed, they are most commonly recognized by their sampling distance. The NED data is available at resolutions of 1 arc-second (about 30 meters), 1/3 arc-second (about 10 meters) nationwide, and 1/9 arc-second (about 3 meters) in some parts of the US. Please reference Figure 1.4 to see the current 2011 availability of this data.

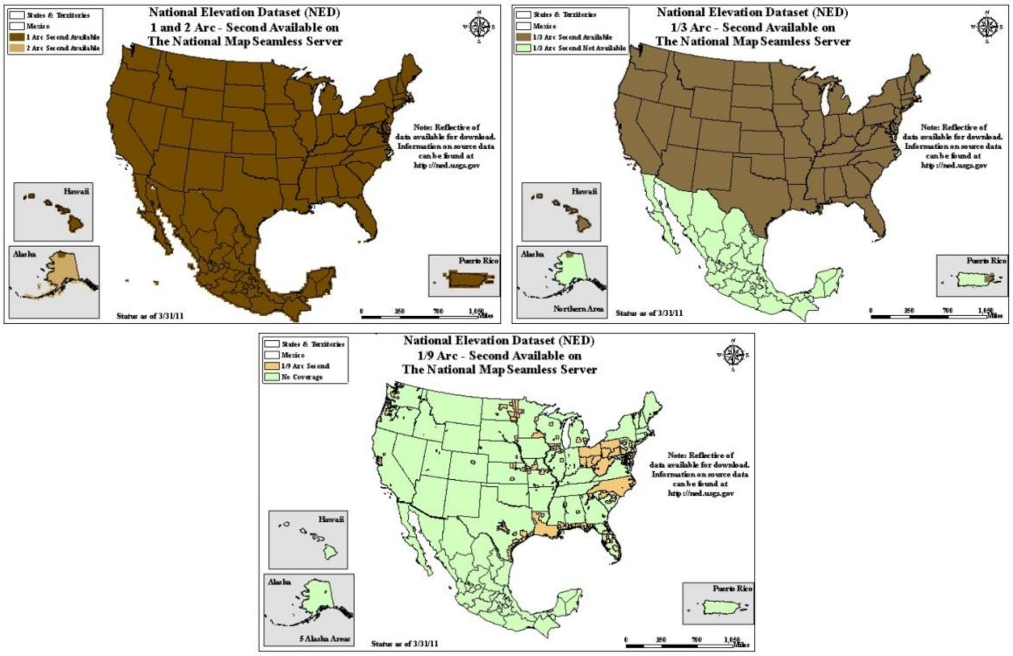


Figure 1.4 NED DEM Nationwide Availability (Gesch et al., 2002)

These DEMs have been developed in a number of ways from a number of available reference materials including manual profiling from photogrammetric stereomodels; stereomodel digitizing of contours; digitizing topographic map contour plates; converting hypsographic and hydrographic tagged vector files; and performing autocorrelation via automated photogrammetric systems. Although vector-based DEMs are available, including triangulated irregular networks (TINs), raster-based formats are the most common.

According to Maune (2007), NED DEM sources are as follows:

- High-resolution data, typically derived from lidar or digital photogrammetry, and often with edited water bodies. If collected at a ground sample distance no coarser than 5 meters, such data may also be offered within the NED at a resolution of 1/9th arc-second.
- Moderate-resolution data, other than that compiled from cartographic contours. These data may also be derived from lidar or digital photogrammetry, or less often by Interferometric Synthetic Aperture Radar IFSAR. A typical ground sample distance is 10 meters, though it is commonly called “1/3 arc-second data”.
- 10-meter DEM’s derived from cartographic contours and mapped hydrography. Most often, such data are produced by or for the USGS as a standard elevation product, and they currently account for the bulk of the NED.
- 30-meter cartographically derived DEM’s. Similar in most respects to their 10-meter counterparts, though usually of lower overall quality.
- 30-meter photogrammetrically derived DEM’s. These are the oldest DEM’s in the 7.5-minute series. These data were derived directly from stereo photography, either by a human operator or by an early form of electronic image correlation. They are badly marred by production artifacts that are addressed to the greatest practical extent by digital filtering within the NED production process.

1.4.1.1.1 NED Accuracy

Three types of errors are considered by the USGS when dealing with the vertical accuracy of DEMs: blunders, systematic errors, and random errors. Blunders are extreme vertical errors that must be removed before the data can be used. Systematic errors are found throughout the DEM. These can be predicted to exist and their effect can be planned for. Examples could be trees, buildings, and shadows in aerial photos that may affect the stereo analysis process. When blunders followed by systematic errors have been removed, random errors remain. (US Department of Interior, 1998)

Systematic and random errors are used to determine the Root Mean Square Error (RMSE) of DEMs. The following equation is used to calculate this number:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (X_i - Y_i)^2}{N}}$$

where Xi = interpolated DEM elevation of a test point
Yi = true elevation of a test point
N = number of test points

The N value, or number of test points, is required to equal at least 28 for each DEM including 20 points located along the interior of the image along with 8 points along the edge.

It should be noted that FEMA's flood maps require a 2-foot contour accuracy (root mean square error of 0.61ft) in flat areas and 4-foot contour accuracy (1.22ft root mean square error) in hilly areas. The NED have a root mean square error of 7.68ft. This means national elevation datasets currently available through the USGS do not meet the standards set by FEMA in their national mapping program (Committee on Floodplain Mapping Technologies, 2007).

Also, raster-based DEMs grid cell format is not as useful in areas of low relief because the elevation change between cells used to calculate slope can be less than the allowed 1-meter or 1-foot posting. DEM cell depressions or 'pits' are cells that do not have neighboring cells with lower elevations to calculate water drainage. There are multiple methods that can be used to fill these depressions including increasing the cells' elevation to its lowest point of overflow (Jenson and Domingue, 1988). Higher resolution

DEMs developed with data such as Light Detecting and Ranging (lidar) can help with this problem as well.

1.4.1.2 Lidar Derived DEMs

Another way DEMs are developed is through the use of lidar data. Lidar is an active form of remote sensing that can be deployed both on the ground and from an aerial platform. It is considered an active form of remote sensing because it does not record radiation naturally emitted by objects such as how infrared scanners operate. Instead, it emits short bursts of electromagnetic radiation (EMR) waves (usually in the visible or near infrared spectrum 500-1064 nanometers) that bounce off the surface of an object and return to a laser scanner which measures the speed, repetition rate, scan angle, scan rate, scan pattern, wavelength, pulse width, and frequency of the return waves (See Figure 1.5).

Specification	Typical Value
Wavelength	1.064m
Pulse Repetition Rate	10-150 kHz (150 kHz max)
Pulse Energy	100s J
Pulse Width	10ns
Beam Divergence	0.25-2 milliradian
Scan Angle (full angle)	40 (75 degree max)
Scan Rate	25-90 Hz
Scan Pattern	Zig-zag, parallel, elliptical, sinusoidal
GPS Frequency	1-2 times per second
INS Frequency	50-200 times per second max
Operating Altitude	80-3,000m (6,000 m max)
Footprint	0.25-2m (from 1,000m)
Multiple Elecation Capture	1 through 5
Grid Spacing Vertical RMSEz	0.3-2m
Vertical RMSEz	10+ cm
Horizontal RMSEr	15-100cm
Post-Processing Software	Proprietary
Price (standard)	\$850,000-\$1,500,000 Us\$
Price (custom)	\$1,000,000-\$2,000,000 US\$
Delivery (standard)	20-26 weeks

Figure 1.5: Characteristics of a typical commercial lidar system (Maune, 2007)

Often times, there are multiple reflections from one beam. This happens as part of the laser beam hits the surface of a building, tree, or any other solid object and reflects back while part of the beam continues to the ground where it is reflected back as well. The part of the beam that is reflected first is called the “first-return” while the portion that backscatters off the earth is called the “second-return”. Multiple returns from the beams are what allows lidar to give ground obstacle heights and 3-D views of the earth.

The location of the laser when it emitted the EMR waves must be considered in order to get an accurate measurement of the return as well. Aerial platforms accomplish this with the use of global positioning satellites (GPS) - that will provide the location and elevation of the aircraft as it emitts the laser, the equipment's mounting and calibration parameters (the angles and position the equipment is mounted in the aircraft), and an inertial navigation system (INS) (the yaw, pitch, and roll of the aircraft). Inputting the point data and laser equipment location data into lidar software creates a point cloud. When the point cloud is processed using filtering, sorting, and projecting, an image is created showing the target in two and three dimensions (Maune, 2007) (See Figure 1.6).

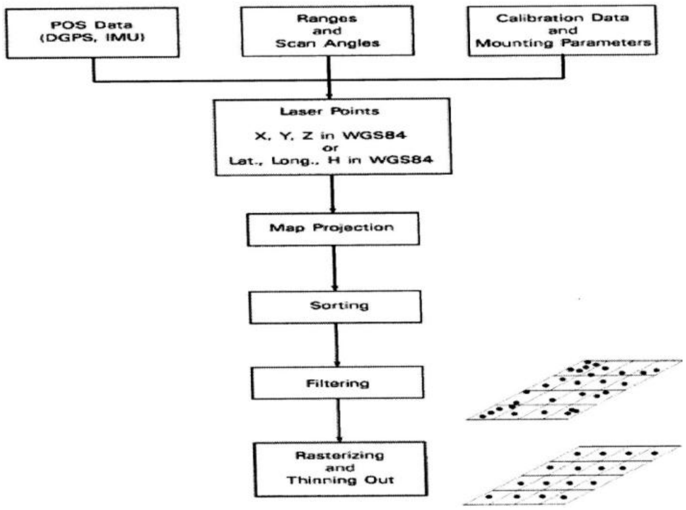


Figure 1.6: Typical data processing chain (Maune, 2007)

According to Campbell (2007), a typical lidar project includes:

1. A digital surface model (DSM) representing the first surface intercepted by the lidar pulse
2. A bare-earth digital elevation mode (DEM) representing the terrain surface after removal of vegetation or structures
3. A canopy layer representing the height of the canopy above the terrain surface

After the points have been filtered and processed, they must be converted into feature (vector) or grid (raster) files. Raster files are the most advantageous conversion because they offer cell-by-cell editing options. Before deciding exactly how to rasterize the data, the user must consider how many points were gathered, the size of the study site, the desired end-user format, and the resolution required for the study. Processing millions or sometimes billions of lidar data points can be time consuming and can require a lot of computing power. Carefully considering these factors can help expedite processing.

Through the use of lidar extensions such as ArcMap's or ERDAS Imagine's Lidar Analyst Toolbar, bare earth DEMs can be derived from raster images by completing building, tree, and forest extractions. This bare image can then be used by any industry requiring high resolution DEMs. After these steps, the lidar imagery can be combined with other types of data such Landsat images or aerial photographs to give a better understanding of what is populating the canopy or ground cover to improve ground cover classifications.

Lidar has been proven to be a more effective and affordable option for DEM creation in watershed analysis than other forms of photogrammetry and remote sensing such as aerial stereophotos (Kunapo, 2005; Kunapo et al., 2009). Furthermore, lower quality DEMs have been proven to lead to significant changes in erosion simulations (Zhang et al., 2009) and higher slope calculation errors (Luzio et al., 2005). While lidar experiences mapping difficulties of its own including differentiating between the beach and water line (Yates et al., 2008), it has proven to be an accurate and efficient tool in this field.

NASA’s Experimental Advanced Airborne Research Lidar (EAARL) has been mapping coastal areas’ marine habitats since 2001 using its unique Lidar system that has achieved sub-meter accuracy (See Figure 1.7). This data has been applied throughout Florida’s marine sanctuaries (Brock et al., 2006; Zawanda and Brock, 2009), national parks, and even the Platte River in Nebraska (Kinzel et al., 2007) for the conservation of coral reefs and other habitats.

NASA EAARL System Specifications	
Total system weight:	250 lbs.
Maximum power requirement:	28 VDC at 24 amps
Nominal surveying altitude:	300 m AGL
Raster scan rate:	97 knots (50 m/s)
Laser sample per raster:	25 rasters/second
Swath width at 300 m altitude:	240 m
Sample spacing:	Swath center = 2 x 2 m Swath edges = 2 x 4 m
Area surveyed per hour: (300 m altitude, 50 m/s)	43 km2 per hour
Nominal power required:	400 Watts
Illuminated laser spot diameter on the surface:	20 cm
Nominal ranging accuracy:	3 - 5 cm
Nominal horizontal positioning accuracy:	< 1 m
Digitizer temporal resolution:	1 nanosecond (13.9 cm in air, 11.3 cm in water)
Minimum water depth:	30 cm
Maximum measurable water depth:	26 m

Figure 1.7: NASA'a EAARL Specifications (United States Geological Survey, 2009)

1.4.1.2.1 1-meter Resolution DEM

In 2005, Blue Earth County, MN contracted Optimal Geomatics Inc. to collect lidar elevation data points for the entire county. The data were collected using an aircraft. The flight lines for this data collection operated at 1836 meters (6023.6 feet) above ground level (AGL). Blue Earth County's intent was to provide an elevation model with a high enough resolution to create 2-foot contour lines for use in various projects county-wide. The lidar data points were processed using ArcMap to create a 1-meter resolution DEM.

1.4.1.2.2 Lidar Accuracy

The lidar data collected by Optimal Geomatics Inc. was designed to have ≤ 15 centimeters Root Mean Square Error (RMSE). To determine if this level of accuracy was maintained, ground points were collected and compared to the lidar points. This RMSE error is the amount of error calculated for the lidar points, not the DEM they create. 920 ground samples were taken by Optimal Geomatics Inc. to calculate the RMSE error. RTK (Real-Time Kinematic) GPS techniques were used to collect this data. (Optimal Geomatics Inc., 2005)

According to the lidar metadata, although no testing was done to determine the horizontal accuracy of the points, it was decided to not allow points to exceed a 0.92 meters (3.01 feet) accuracy threshold. By considering the vertical accuracy tested on this data, it was determined that this standard of horizontal accuracy was met or exceeded. This level of accuracy was decided by taking 1/2000th of the flight height. As previously stated, the flight height was 6023.6 feet.

1.4.2 Flood Mapping Models

1.4.2.1 HEC-RAS

The US Army Corps of Engineers' Hydrologic Engineering Center (HEC) headquarters in Davis, California, and their many nation-wide field offices, house the experts in charge of surface and groundwater hydrology, river hydraulics and sediment transport, hydrologic statistics and risk analysis, reservoir system analysis, planning analysis, real-time water control management and a number of other closely associated technical subjects. The HEC develops general and site-specific water models that are used in-house but they are also available to the public.

Many models are available for flood plain mapping. The HEC-River Analysis System (HEC-RAS) can be used as a steady-state and unsteady flow model. This model is accepted by industry professionals and FEMA. The model consists of cross sections taken along the river perpendicular to the path of the river or stream, flow gauge data, and topographic information such as roughness coefficients. Higher resolution DEMs require more cross sections as the river will be shown in more detail and can have more changes in direction to its shape.

While the HEC-RAS can be very accurate at modeling water flow for use in flood mapping, it requires considerable resources including time, money, a team of surveyors, GIS specialists, and hydrological engineers to collect and process ground data. Working toward a more efficient flood mapping model using GIS could help expedite the creation and updating of DEMs and other variables required in calculations.

1.4.2.2 Compound Topographic Index & Stream Power Index

Topographic Indexes may prove to be a faster and less expensive way to highlight areas prone to flooding. Although, in the past, many factors have been considered during the derivation of topographic indexes including soil types, vegetation cover, and climate (Kirkby, 1987), the actual relief of the land has been the dominant factor considered. Relief is a determining factor of how fast water will travel and where it will collect (Vogt et al., 2003). CTI and SPI will highlight areas prone to both fast moving water and pooling of water (Murphy et al., 2009).

CTI layers are created by dividing a slope raster by a flow accumulation (catchment) raster. SPI requires the same input layers but rather than dividing the flow accumulation layer by the slope layer, the two layers are multiplied. These two values combined highlight areas that are more prone to flooding than those highlighted by only one of the two indices.

The use of topographic indexes such as CTI and SPI have been determined to be much less accurate when using DEMs with relatively low resolutions (30m and 10m) when compared to high resolution DEMs (3m). However, computing power has proven to be a limiting factor when dealing with high resolution DEMs for these calculations (Vaze et al., 2010).

Chapter 2: Study Site

2.1 South Central Minnesota

This study would consider “South Central Minnesota” to be composed of 13 counties including Blue Earth, Brown, Faribault, Freeborn, Le Sueur, Martin, Nicollet, Rice, Scott, Sibley, Steele, Waseca, and Watonwan (See Figure 2.1). South Central Minnesota is mainly an area of low relief but does contain some high sloped areas along the river bank. The river valley that contains the Minnesota River is quite large do to the presence of the glacial River Warren that traveled through the area approximately 12,000 years ago.

Various factors affect the chances of flooding in South Central Minnesota. In recent years, heavy rainfall in the fall combined with an early freeze and very snowy winters have contributed to widespread flooding, specifically in the Minnesota River and Blue Earth River. This has led to large economic impact in the area totaling in the millions of dollars. In fall 2010, an eleven mile stretch of US Highway 169 was closed for over a week due to the flooding (See Figure 2.2). Other buildings, homes, and infrastructure including bridges were damaged during the flooding as well (See Figure 2.3).

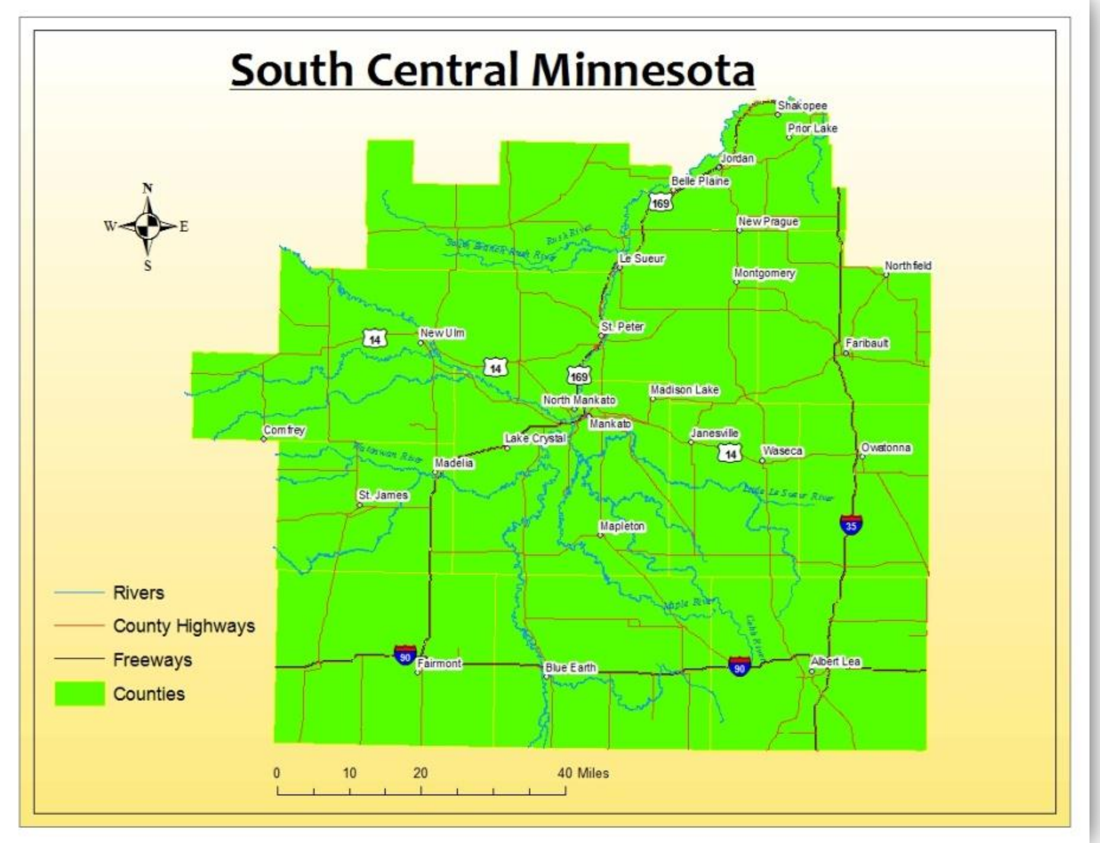


Figure 2.1: South Central Minnesota Study Site

Figure 2.2: Highway 169 north of Mankato, MN after flooding in October 2010 (Unknown, 2010)

Figure 2.3: Bridge damage from Southern Minnesota flooding in October 2010 (Unknown, 2010)

2.2 Mankato, Minnesota

Located in South Central Minnesota in Blue Earth County, the city of Mankato has a population of just over 36,000 living within its limits. It does however have a contiguous population of near 50,000. It is a major regional center hosting various forms of retail and manufacturing industry. Post-secondary education institutions in Mankato include Bethany Lutheran College; Minnesota State University, Mankato; Rasmussen Business College; and South Central College in North Mankato. These factors combine to give Mankato its' population base.

Physically, the city of Mankato is defined mainly by the convergence of the Minnesota River and the Blue Earth River. The steep slope along the river bank was also a result of the glacial river Warren. Outside of the river valley area in Mankato, the relief is generally mild. The elevation is approximately 1000ft Above Sea Level (See Figure 2.4).

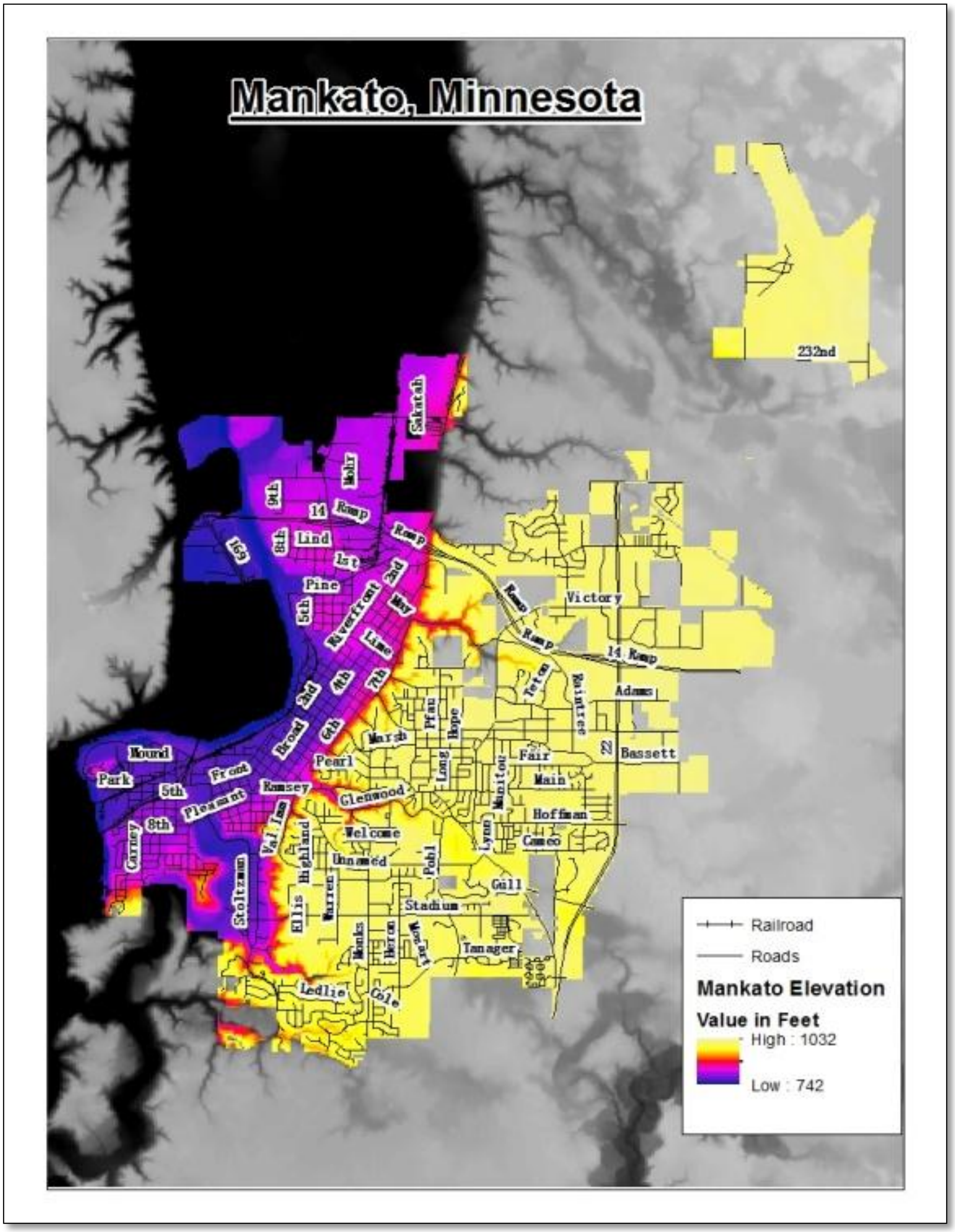


Figure 2.4: Mankato, MN

2.3 Seven Mile Creek Watershed

The Seven Mile Creek Watershed is located between St. Peter and Mankato (See Figure 2.5). It is approximately 23,551 acres (36.8 square miles). Although the majority of the watershed has been developed for agriculture and has relatively little relief, some portions, especially along the watershed's namesake creek has large relief with tree cover. Efforts have been under way to slow the high erosion rates in the creek caused by an increase in agricultural tiling. A county park is also located in the watershed with hiking, mountain biking, and horse riding trails.

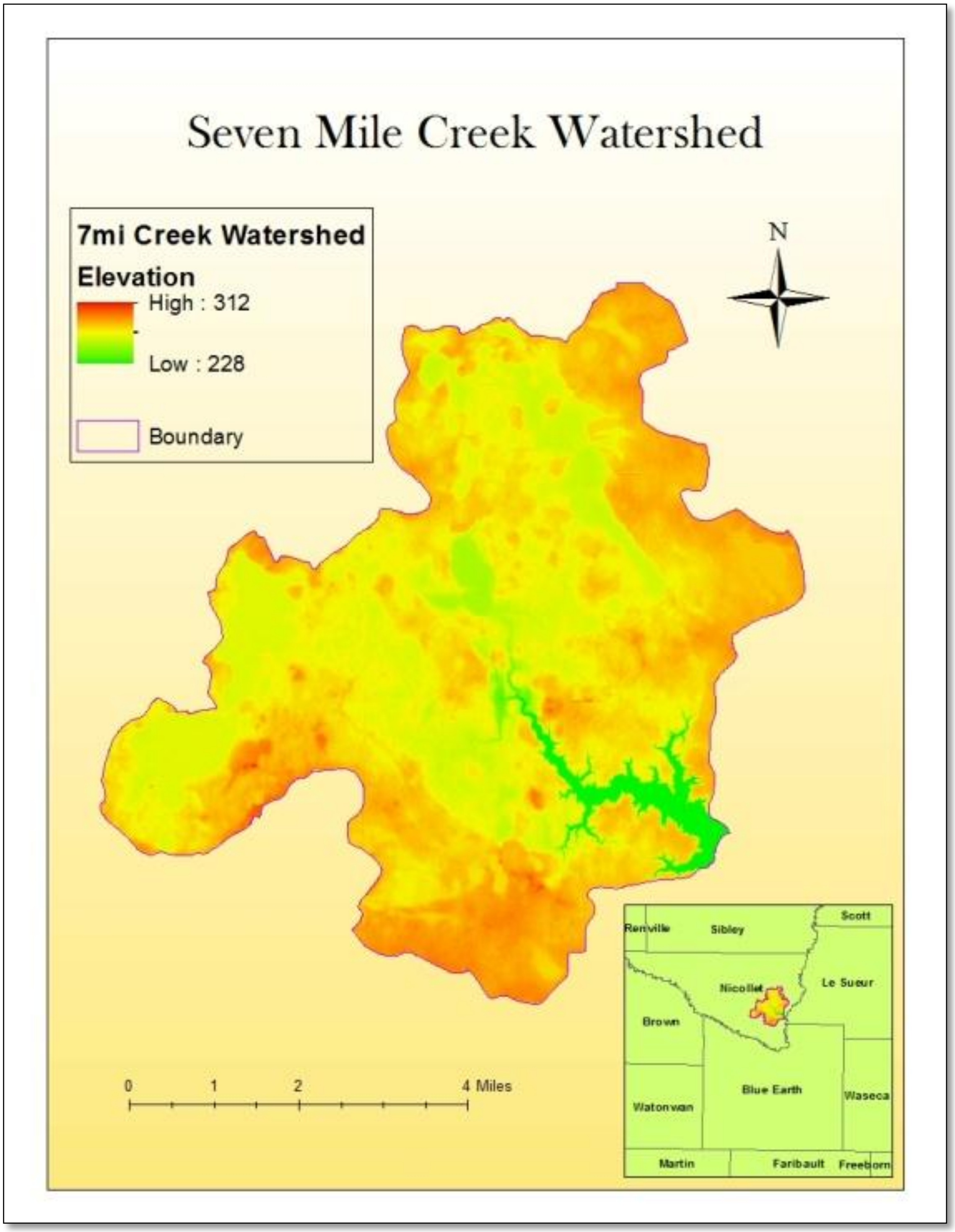


Figure 2.5: Seven Mile Creek Watershed Study Site

Chapter 3: Methodology

3.1 Datasets & Preprocessing

3.1.1 Shapefiles

The Minnesota Department of Natural Resources maintains various shapefiles for the state of Minnesota including files ranging from simple boundaries to DEMs and aerial photos. This study used South Central Minnesota counties, state of Minnesota, watersheds, and city of Mankato shapefiles. They were downloaded free of charge from the DNR Data Deli website (http://deli.dnr.state.mn.us/).

The city of Mankato created and donated road shapefiles to be used for network analysis. Parcel data is created, maintained, and updated by the Blue Earth County GIS department. This data set was purchased and contains both the parcel shapefile and attribute information along with legal descriptions and appraisal values for the land. A separate appraisal value for structures located on the property is also included.

3.1.2 DEMs

For this study, 30-meter and 10-meter resolution DEMs were downloaded from the USGS Seamless Server (http://seamless.usgs.gov/). The 3-meter resolution DEM was downloaded from MN Department of Natural Resources website (http://deli.dnr.state.mn.us/). The 1-meter resolution DEM was created by processing lidar data received from Blue Earth County.

3.1.3 DEM Preprocessing

Once all the DEMs were downloaded or created, they were clipped to fit the study site using the study site shapefiles and the Spatial Analyst's 'Extract by Mask' function in ArcMap. Furthermore, as previously stated, raster based DEMs can contain some errors such as 'pits' or 'sinks'. To correct this error each DEM was preprocessed using the Spatial Analyst's Hydrology tool 'Fill'. The 'Fill' process was only completed for those DEMs used in the CTI and SPI analysis. The Flow Accumulation layers used in the CTI and SPI must have flow connectivity and therefore filled DEMs were required.

3.2 Compound Topographic Index (CTI) and Stream Power Index (SPI)

3.2.1 South Central Minnesota CTI and SPI

The Compound Topographic Index (CTI) and Stream Power Index (SPI) use two different variables in their calculations: slope and flow accumulation. Slope measures the angle of relief in a digital elevation model (DEM) cell when compared to its neighboring cells. Slope can be represented in degree or percentage. Flow accumulation (also known as catchment) is also derived from the DEM but shows areas that would have a concentrated flow of water based on their lower elevation when compared to its neighboring cells. Slope and flow accumulation were created using 30-meter resolution DEMs.

Using ArcMap's Spatial Analyst extension, slope was calculated (See Figure 3.1). Next, a flow direction raster (a raster of flow direction from each cell to its steepest downslope neighbor) was created to be used as an input for the second variable, flow accumulation (See Figure 3.2).

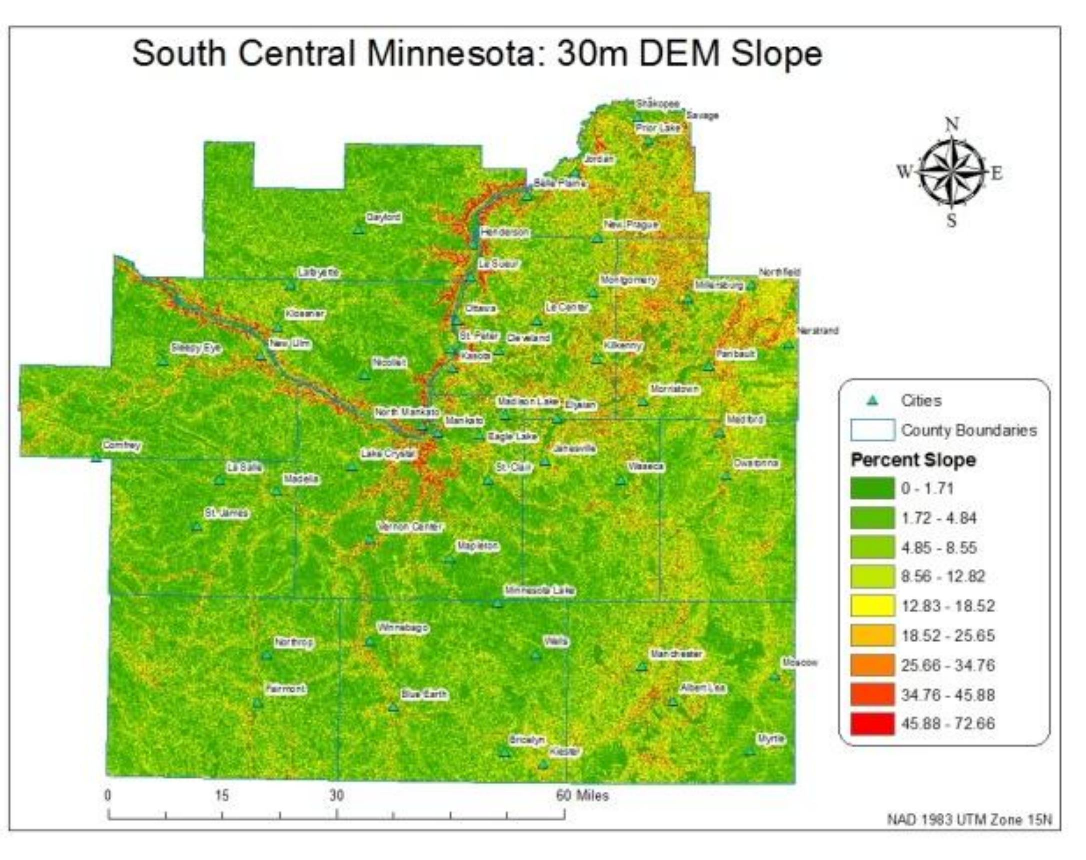


Figure 3.1: South Central Minnesota Slope

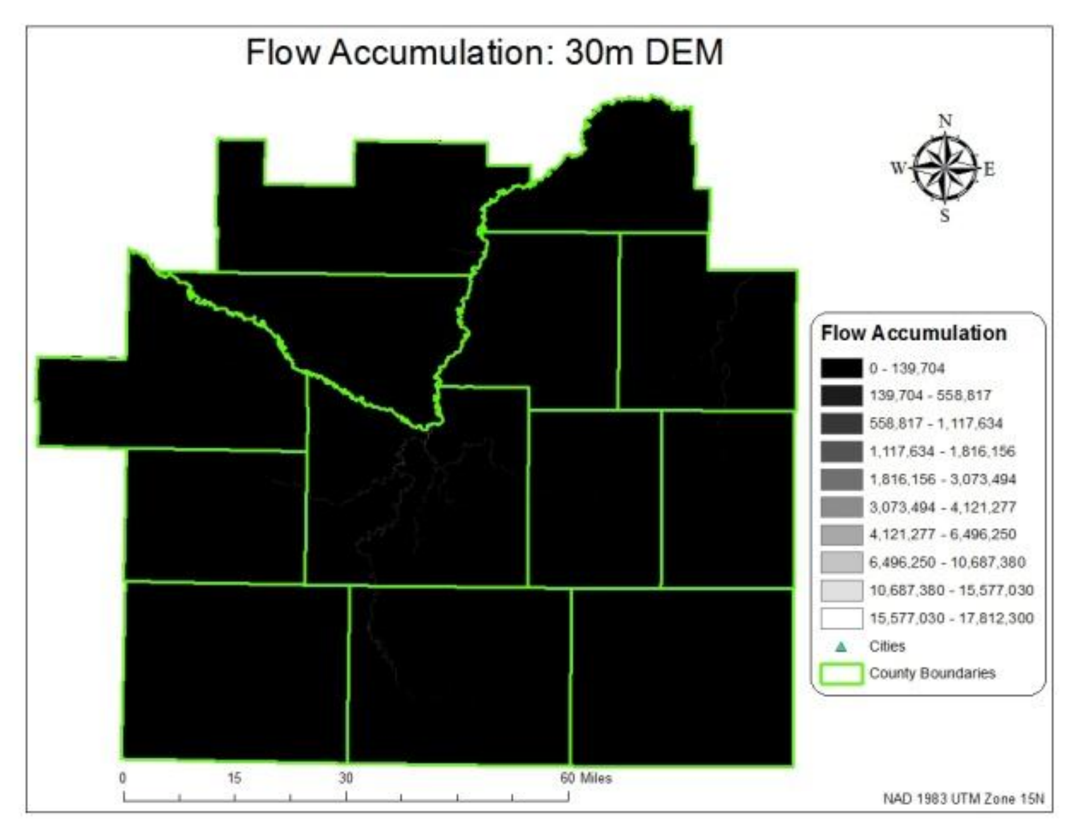


Figure 3.2: South Central Minnesota Flow Accumulation

Once the slope and flow accumulation layers were created, Spatial Analyst's raster calculator tool was used to create the following formulas.

Compound Topographic Index (See Figure 3.3):

CTI= LN((FlowAccumulation + 0.001) / (([Slope / 100) + 0.001)).

Stream Power Index (See Figure 3.4):

SPI= LN(([FlowAccumulation] + 0.001) X (([Slope / 100) + 0.001)).

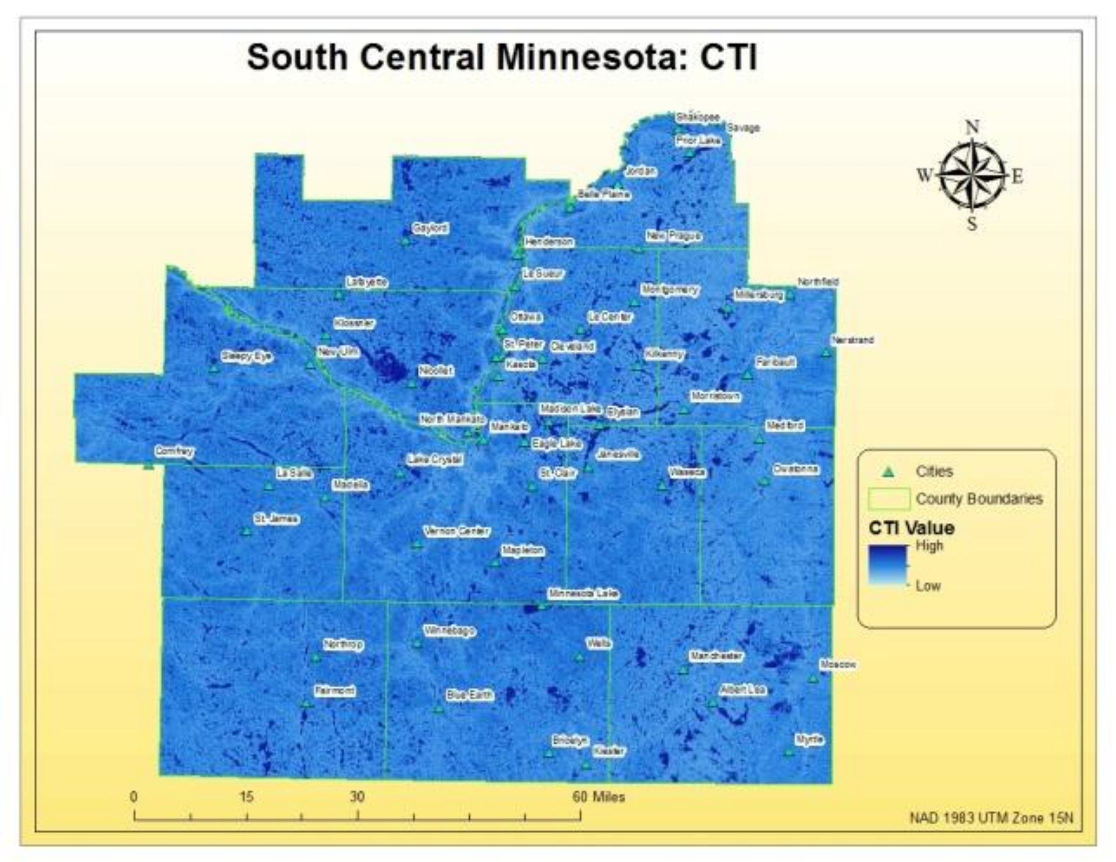


Figure 3.3: South Central Minnesota CTI

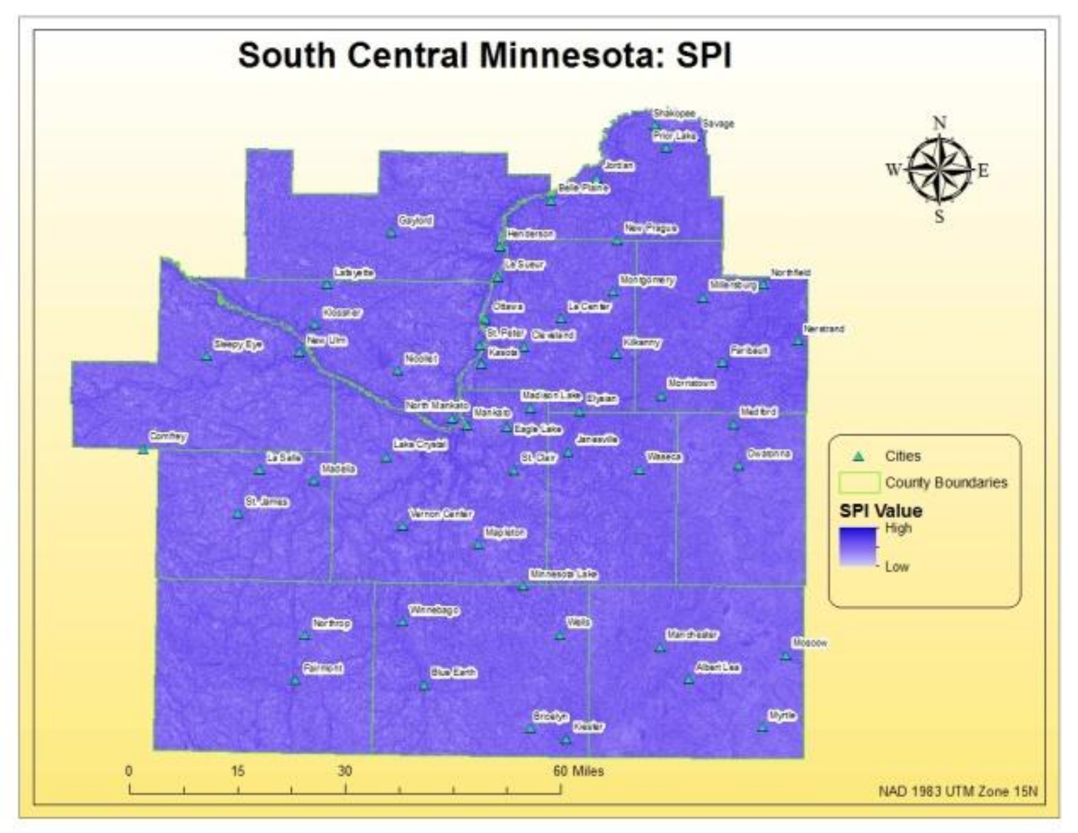


Figure 3.4: South Central Minnesota SPI

High values from these two layers were compared to shapefiles showing rivers and streams, lakes, and wetlands. These layers were downloaded from the MNDNR data deli.

Next, they were reclassified to show the top 90th percentile for CTI (See Figure 3.5) and 95th percentile for SPI (See Figure 3.6).

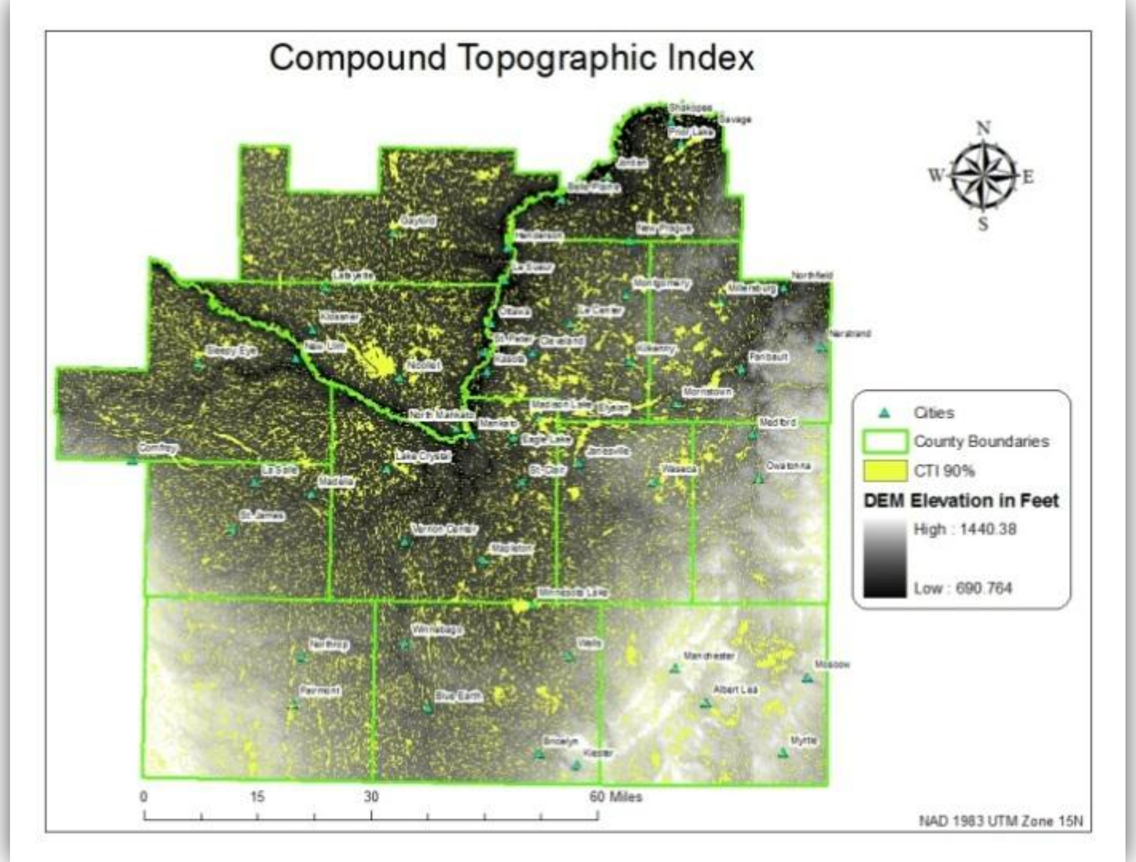


Figure 3.5: South Central Minnesota CTI Reclassified

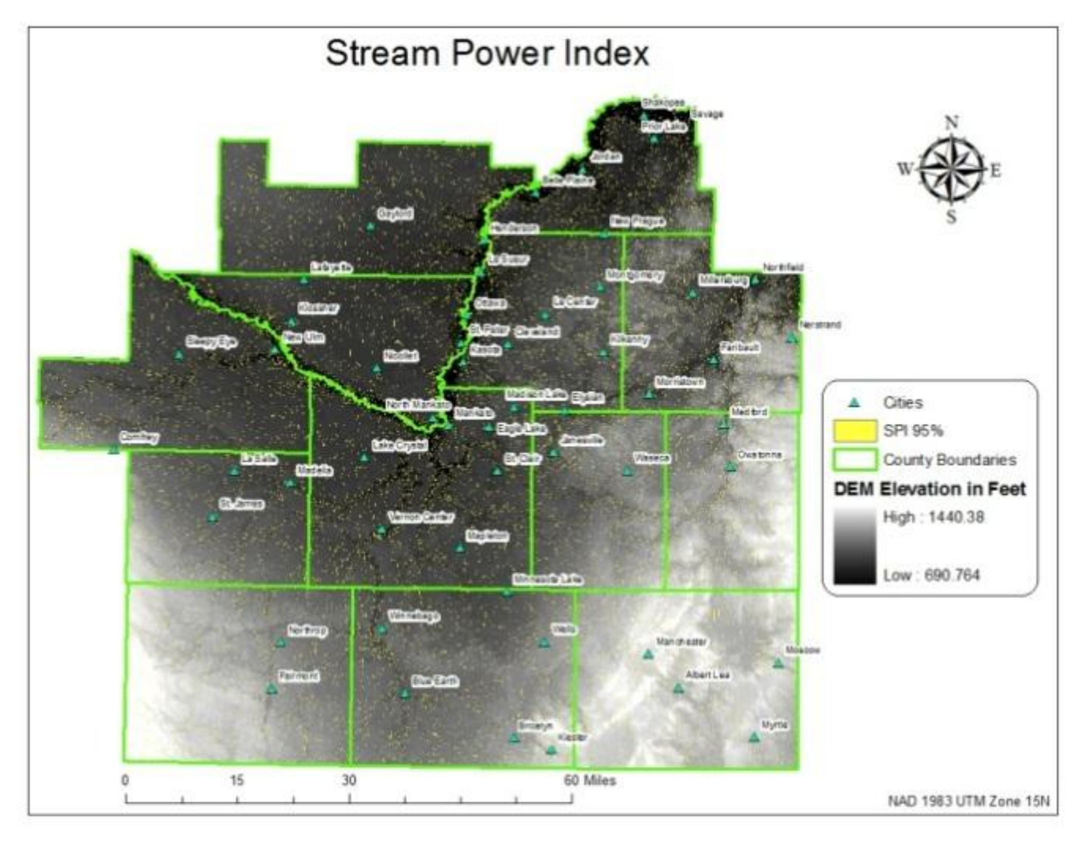


Figure 3.6: South Central Minnesota SPI Reclassified

To find a strong indicator of both CTI and SPI values, these two raster layers were converted to polygons using the Raster to Polygon tool in ArcMap then merged together (See Figure 3.7).

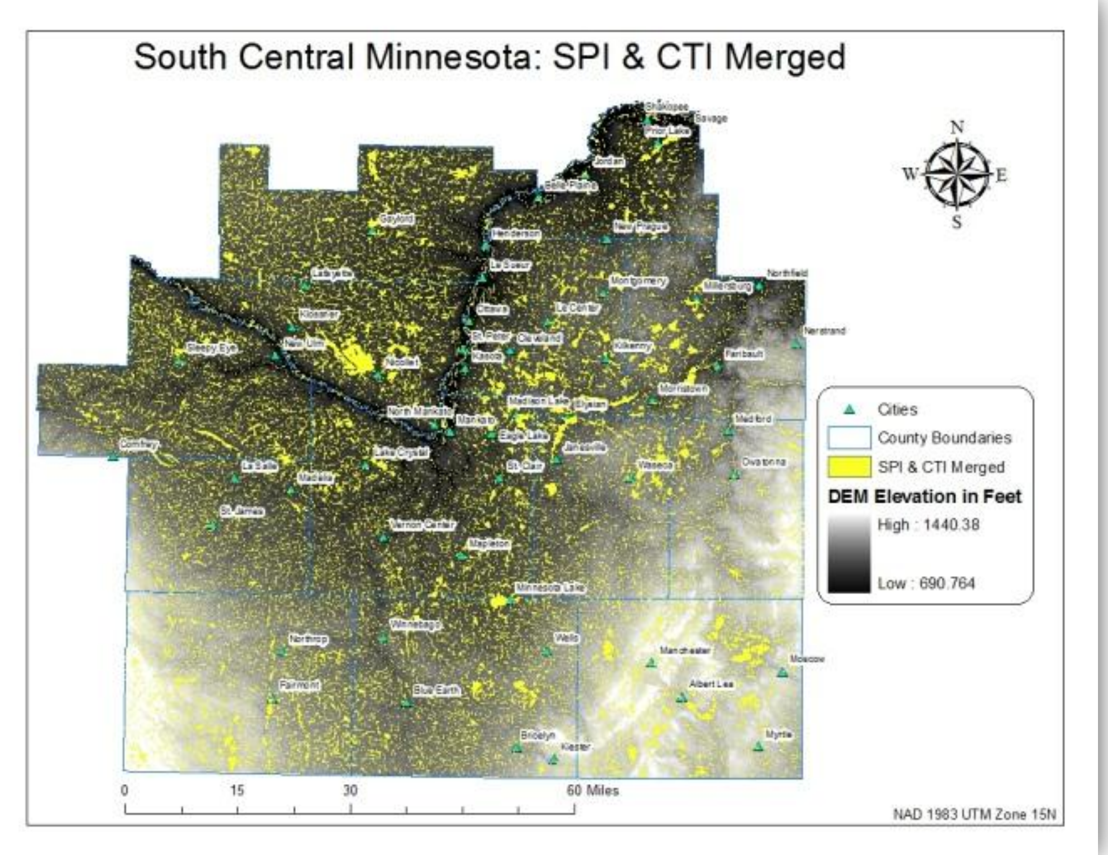


Figure 3.7: South Central Minnesota CTI & SPI Merged

3.2.2 Seven Mile Creek Watershed CTI & SPI

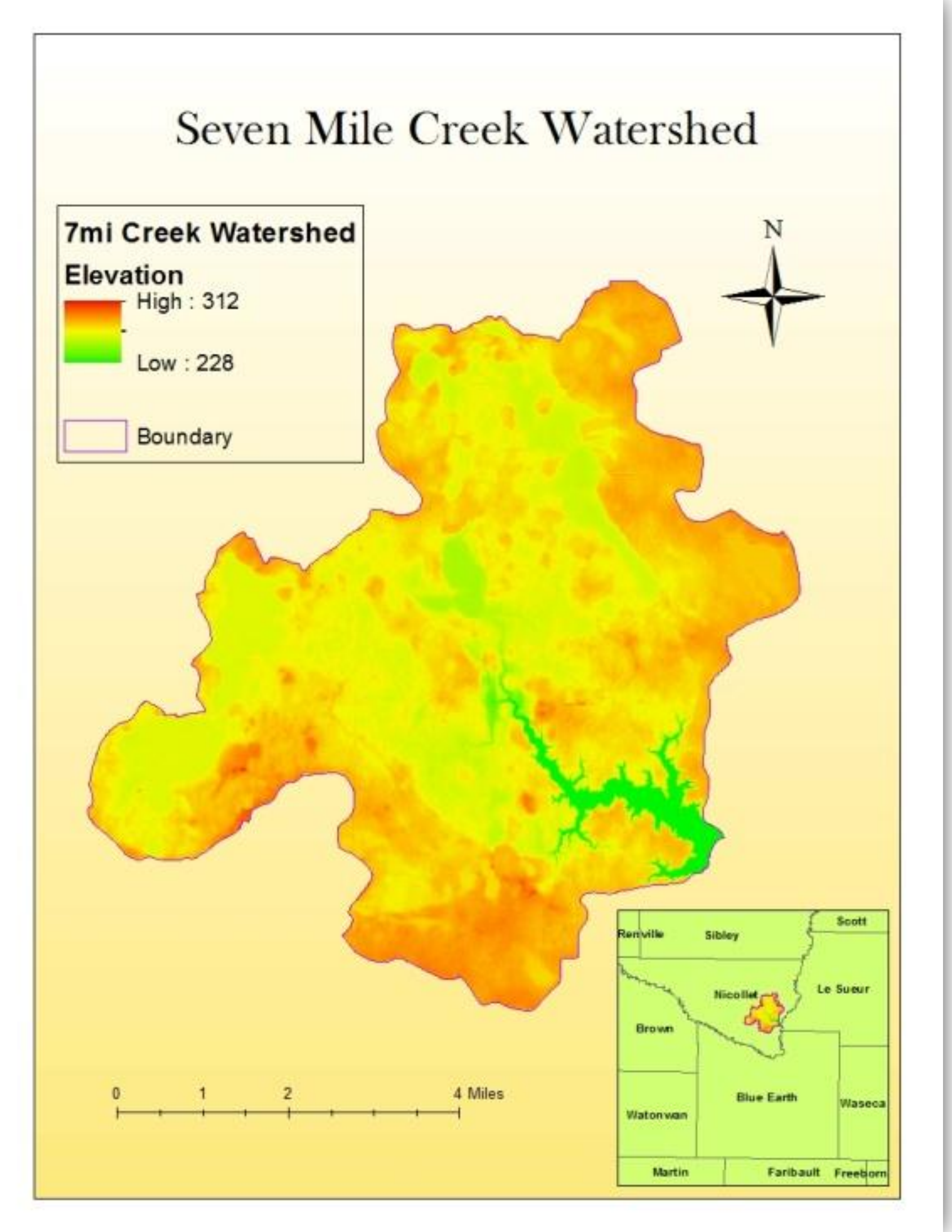


Figure 3.8: Seven Mile Creek Watershed

Seven Mile Creek Watershed has a large amount of research interest surrounding it because of its' relatively small size and the large amount of land use change it has experienced in the last twenty years. It has become an excellent location to see and measure changes implemented over time. The methods used to create the CTI and SPI layers were identical to those performed for the whole of South Central Minnesota. Flow Accumultation and Slope files were created and manipulated using the Raster Calculator. Also, the CTI data was reclassified to the upper 90th percentile while the SPI was reclassified to the 95th percentile. With this smaller study site however, CTI and SPI were calculated using 30-meter, 10-meter, and 3-meter resolution DEMs rather than only the 30-meter resolution DEM.

3.3 Lidar DEM Creation

The lidar points used in this study came in X, Y, Z format. Before using them in ArcMap, they were converted to feature files using the 3D Analyst extension's 'From File' - 'ASCII 3D to Feature Class' tool. This not only converted them to Multipoints but also projected them. The next step towards processing lidar points into a DEM involves building a geodatabase.

First, there are three types of geodatabases that are defined by their size and the number of people who can view and edit them.

1. Personal Geodatabase- one editor, one viewer, small storage size
2. File Geodatabase- one editor, multiple viewers, 1 terabyte of storage
3. Enterprise Geodatabase- multiple editors, multiple viewers, large storage

Since this study deals with large datasets including large terrains and masspoint files with one editor, a File Geodatabase was used. Within the geodatabase a feature dataset was created. The feature classes included in my ‘Lidar’ Feature Dataset were the lidar masspoint files, breaklines, and hard clip files to be used in the derivation of my lidar DEM. While I did not have to build topology or domains for these files, I was able to build a terrain dataset which is only possible in a geodatabase.

3.3.1 Lidar Terrain Dataset

The terrain dataset model (See Figure 3.9) was easy to build because of the Terrain Wizard option. Simple selections were made such as the files to be included (masspoint, breaklines, and a hard clip file), the point spacing, and the point thinning method. The default pyramid building options were used. Breaklines provide the edge for which the points will be interpolated from. They are often used to represent roads, bodies of water, and possibly large structures. This makes the edges of features in the image more distinct while improving visualizing as well as in the raster creation process. The ‘Clip’ tool simply clips the data so points are not interpolated to other points across or outside of the area of interest. The point spacing was determined by looking at the metadata and a value of 5 was chosen.

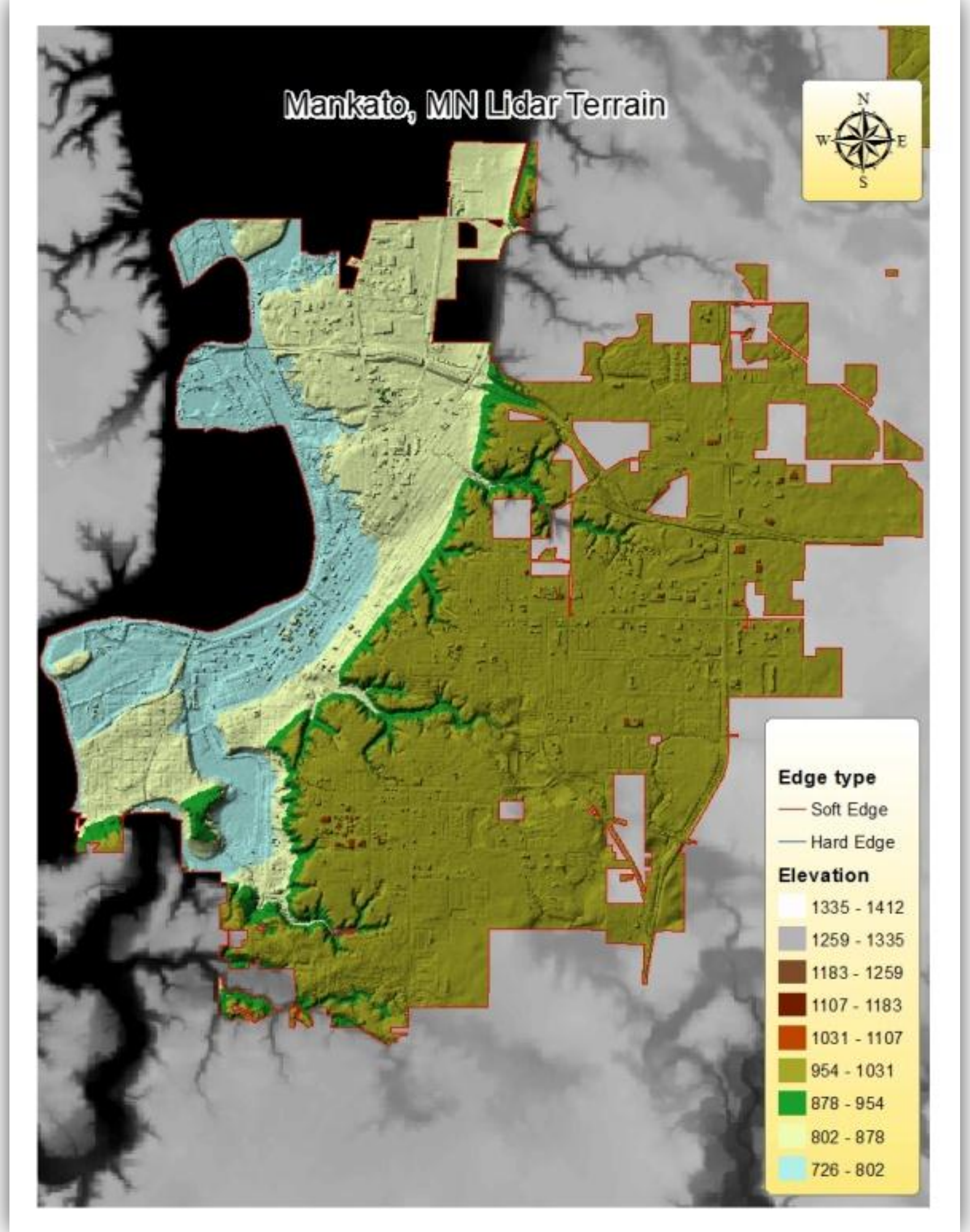


Figure 3.9: Mankato, MN Terrain Dataset

Once the terrain dataset was complete, it was converted to a raster using the 3D Analyst extension’s ‘From Terrain’ - ‘Terrain to Raster’ tool. The output data type was float while the method was linear. Since the data is projected in Blue Earth County Coordinates projections based on feet, a 3.28 sampling distance was chosen so that the DEM would have 1 meter resolution (See Figure 3.10).

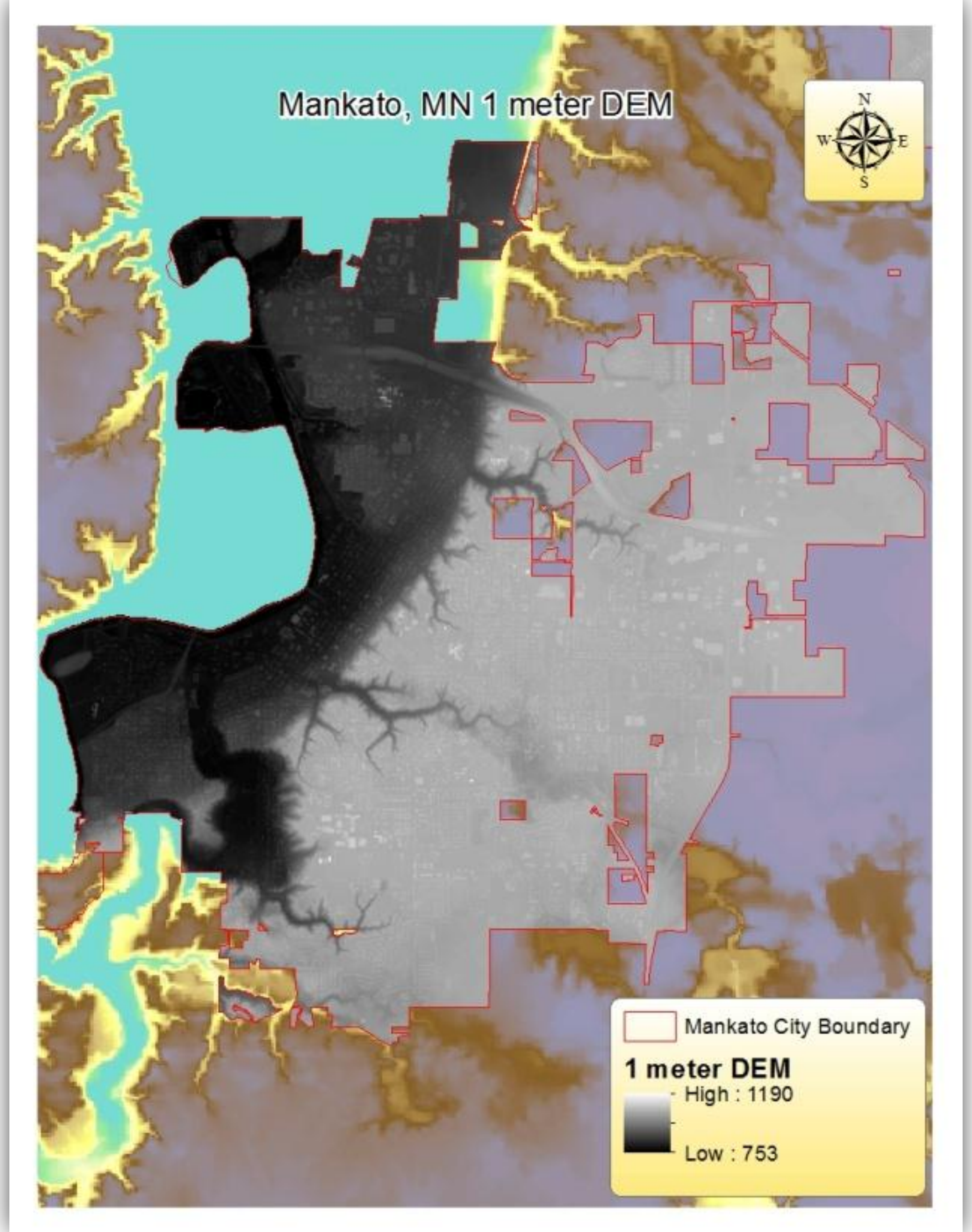


Figure 3.10: Mankato, MN 1-meter Resolution DEM

3.4 Flood Level Creation

In the city of Mankato, 30-meter, 10-meter, and 1-meter resolution DEMs were analyzed for their effects on floodzone shapefile creation. According to the National Weather Service, the base level for determining flood stages on the Minnesota River in Mankato is a height of 747.92 feet above sea level (National Weather Service, 2011). They also categorize flood stages as seen in Table 3.1:

Table 3.1 Flood Categories (In Feet)

Major Flood Stage:	30
Moderate Flood Stage:	25
Flood Stage:	22
Action Stage:	15

Based on this information, cells were selected in each DEM with elevation values of 762.92 ft, 769.92 ft, 772.92 ft, and 777.92 ft representing the 15, 22, 25, and 30 foot flood stages. This was done using ArcMap's 'Spatial Analyst'-'Math-Less than Equal to' tool. The selected raster cells were exported as shapefiles to show the respective flood levels (See Figures 3.11-3.22). A new attribute column was added to each shapefile. Using the 'Calculate Geometry' tool, the square acres for each flood stage were calculated. This helped determine the extent of each stage and the difference between each was easily calculated doing simple subtraction in Microsoft Excel.

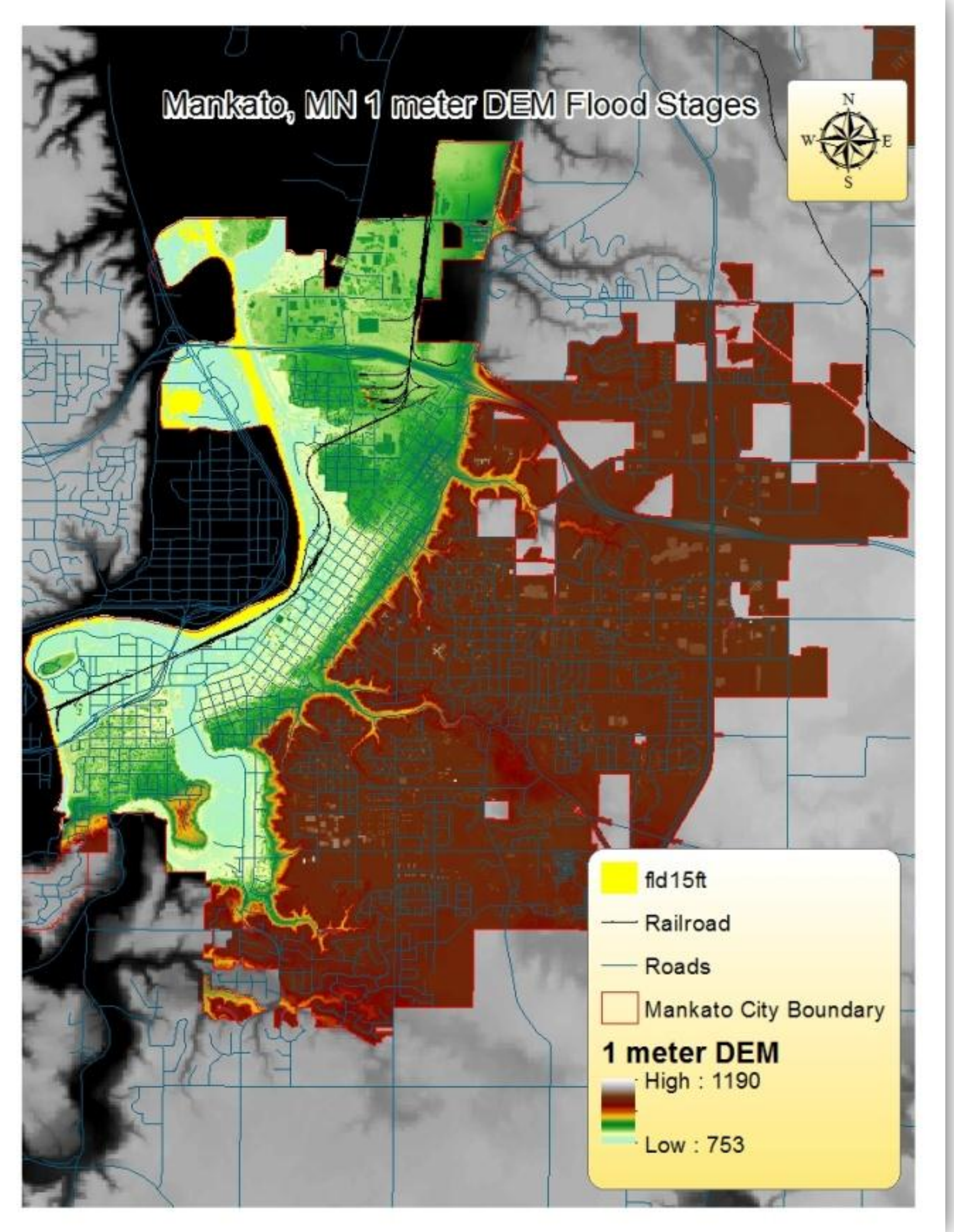


Figure 3.11: 1-meter DEM 15ft Flood Stage

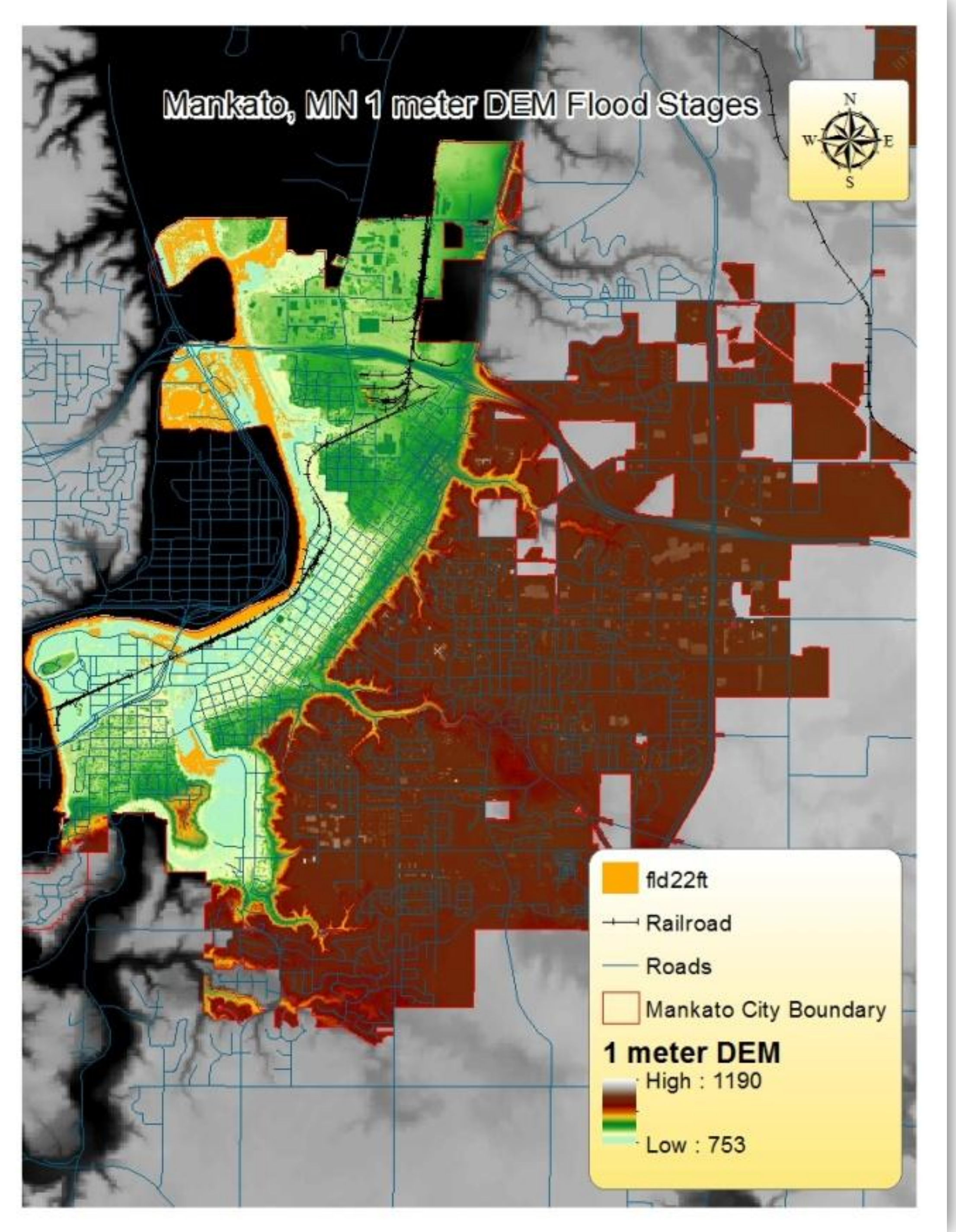


Figure 3.12: 1-meter DEM 22ft Flood Stage

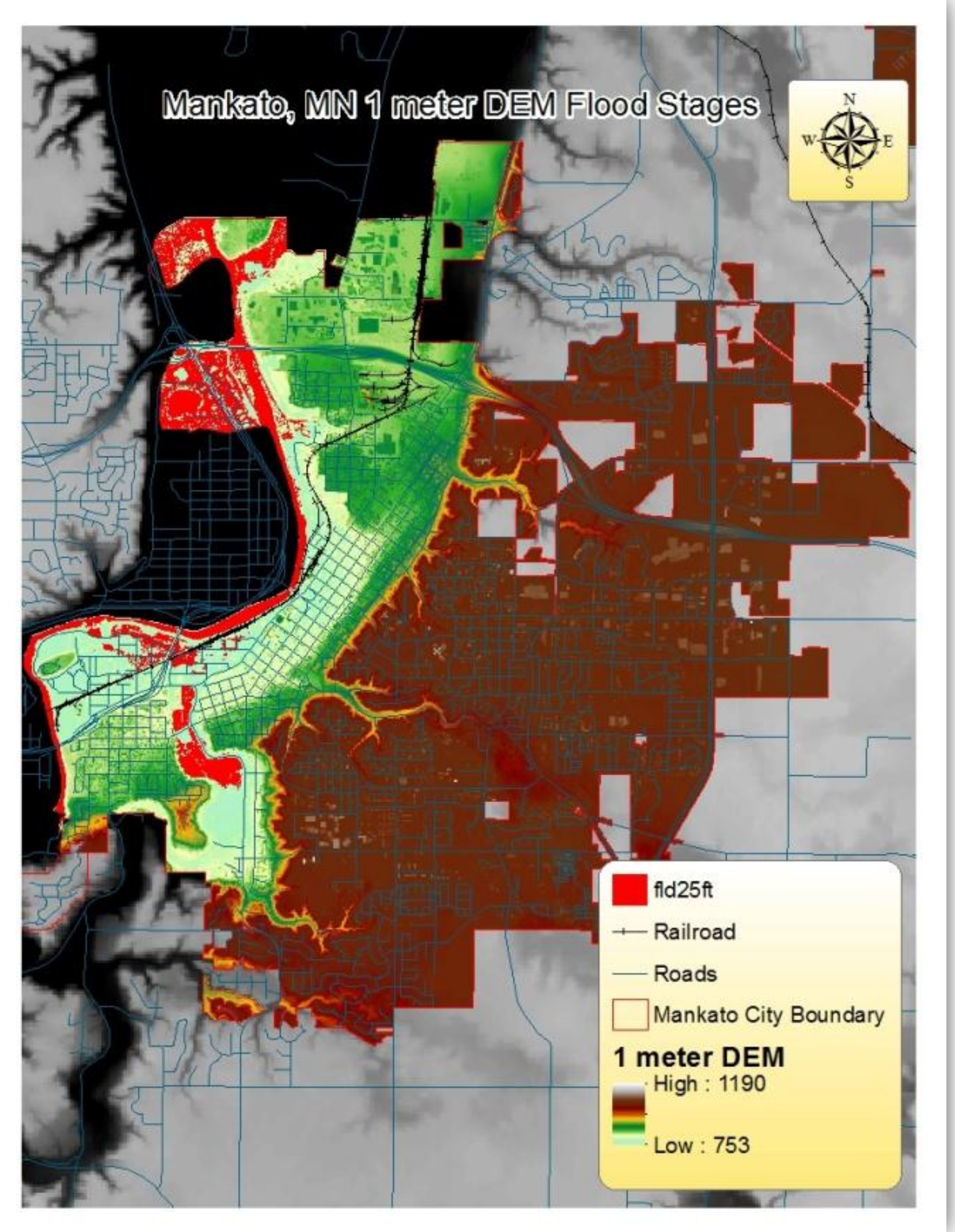


Figure 3.13: 1-meter DEM 25ft Flood Stage

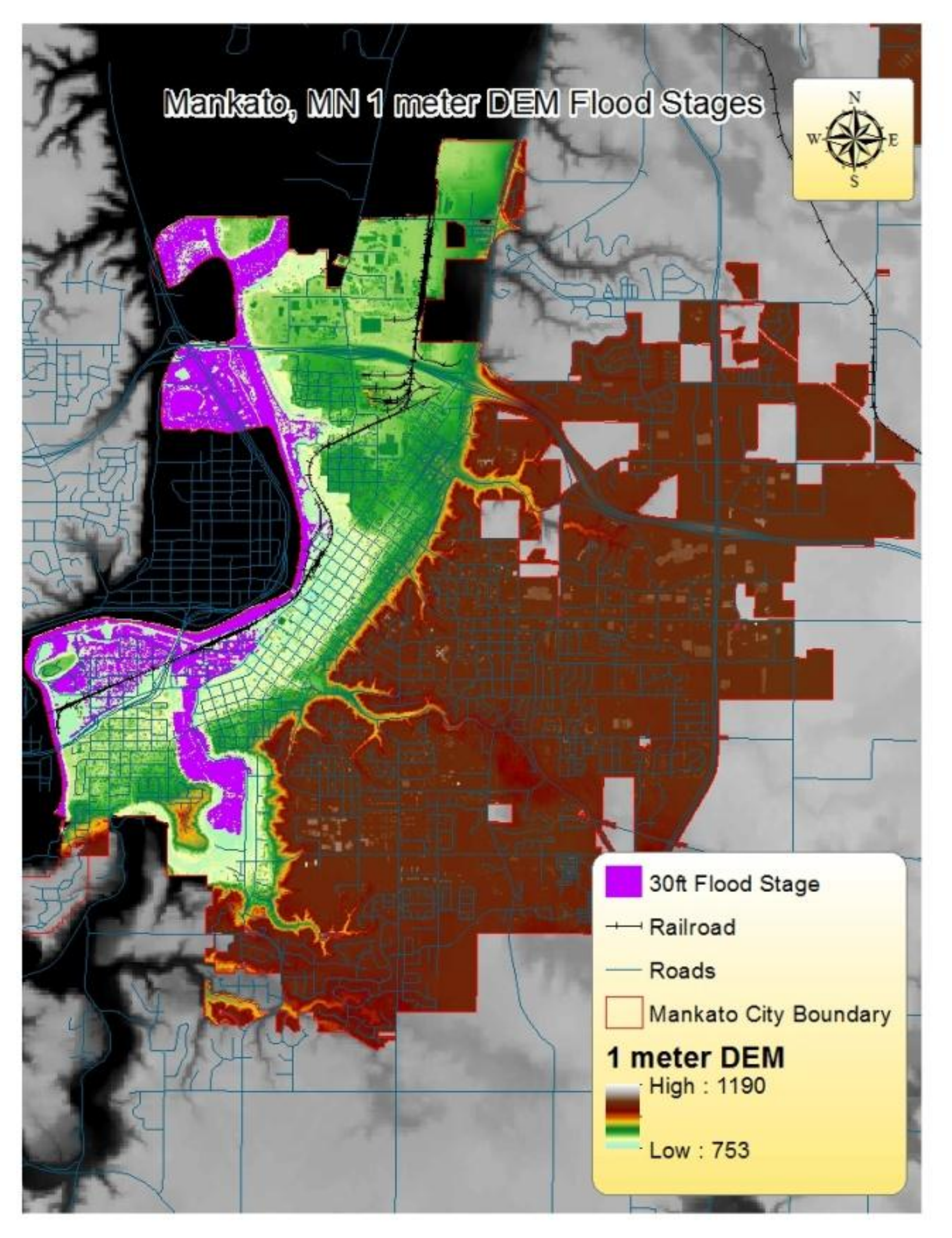


Figure 3.14: 1-meter DEM 30ft Flood Stage

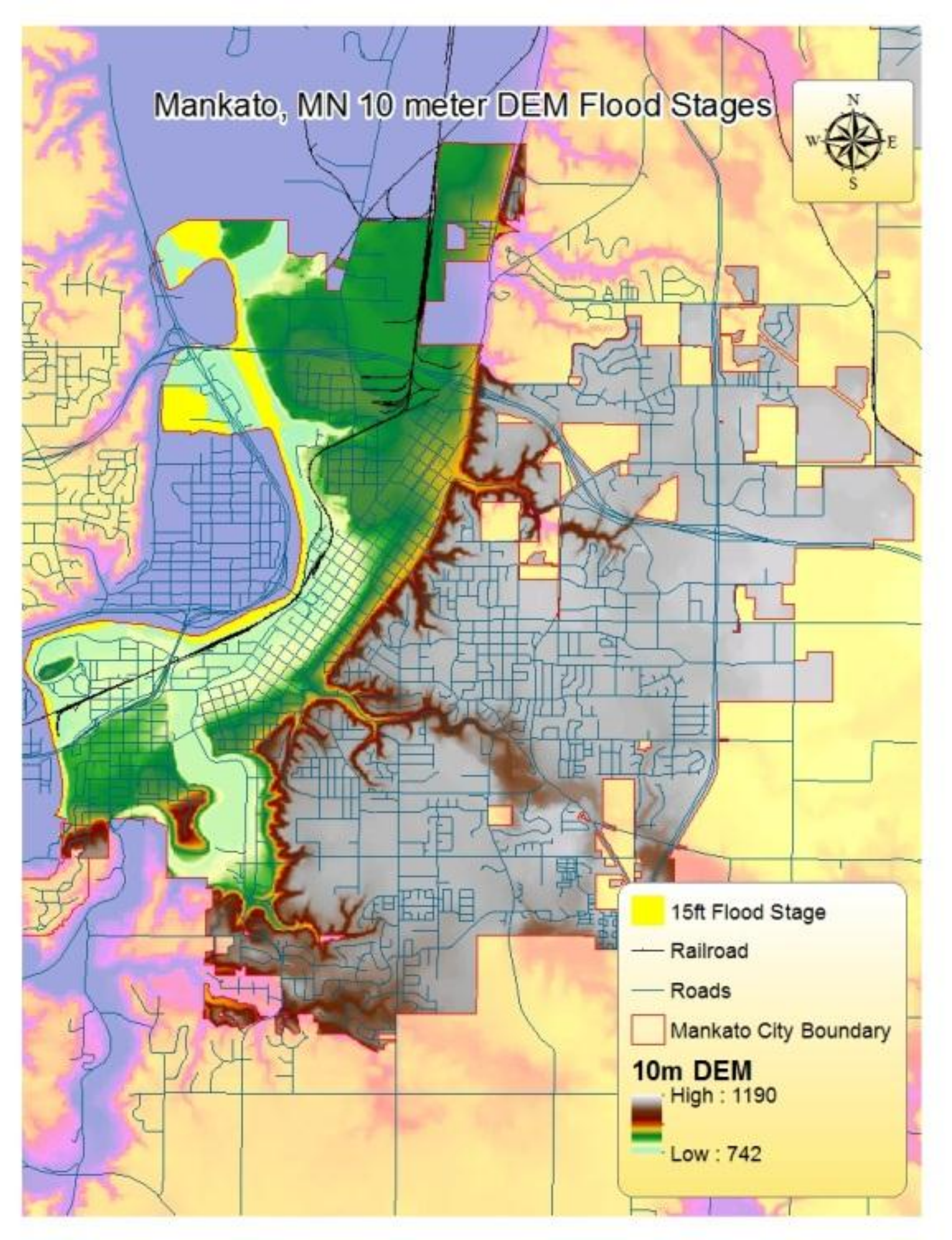


Figure 3.15: 10-meter DEM 15ft Flood Stage

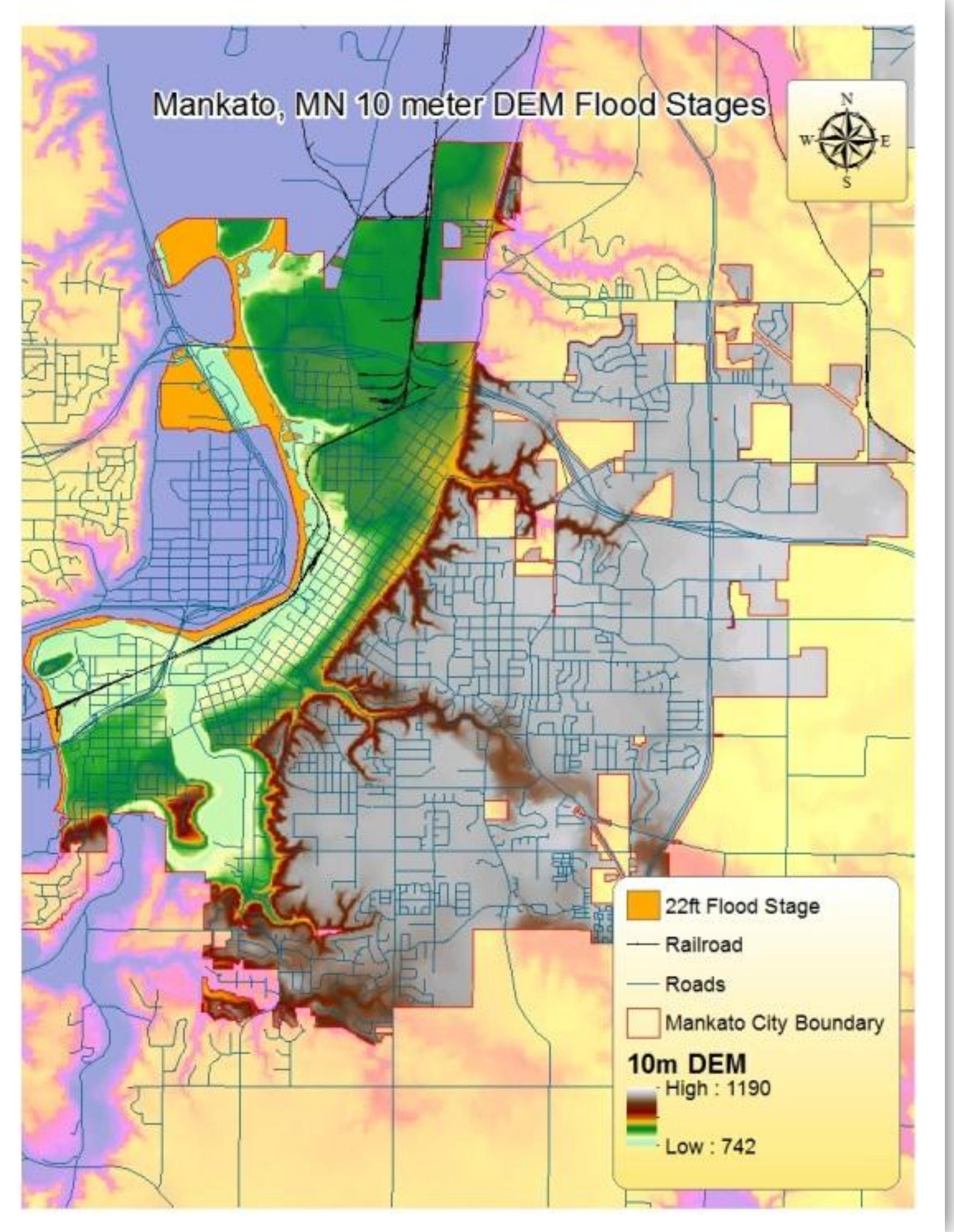


Figure 3.16: 10-meter DEM 22ft Flood Stage

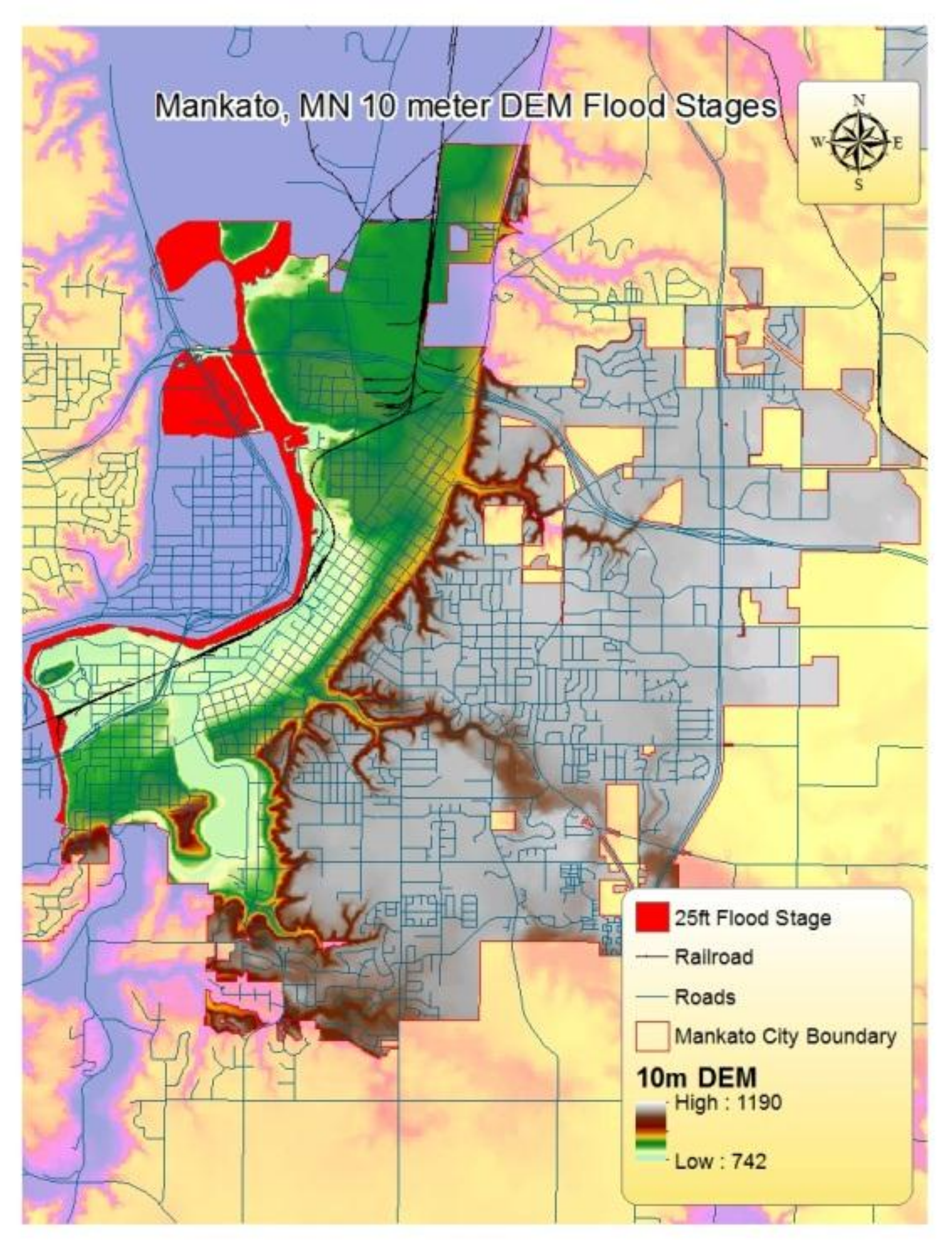


Figure 3.17: 10-meter DEM 25ft Flood Stage

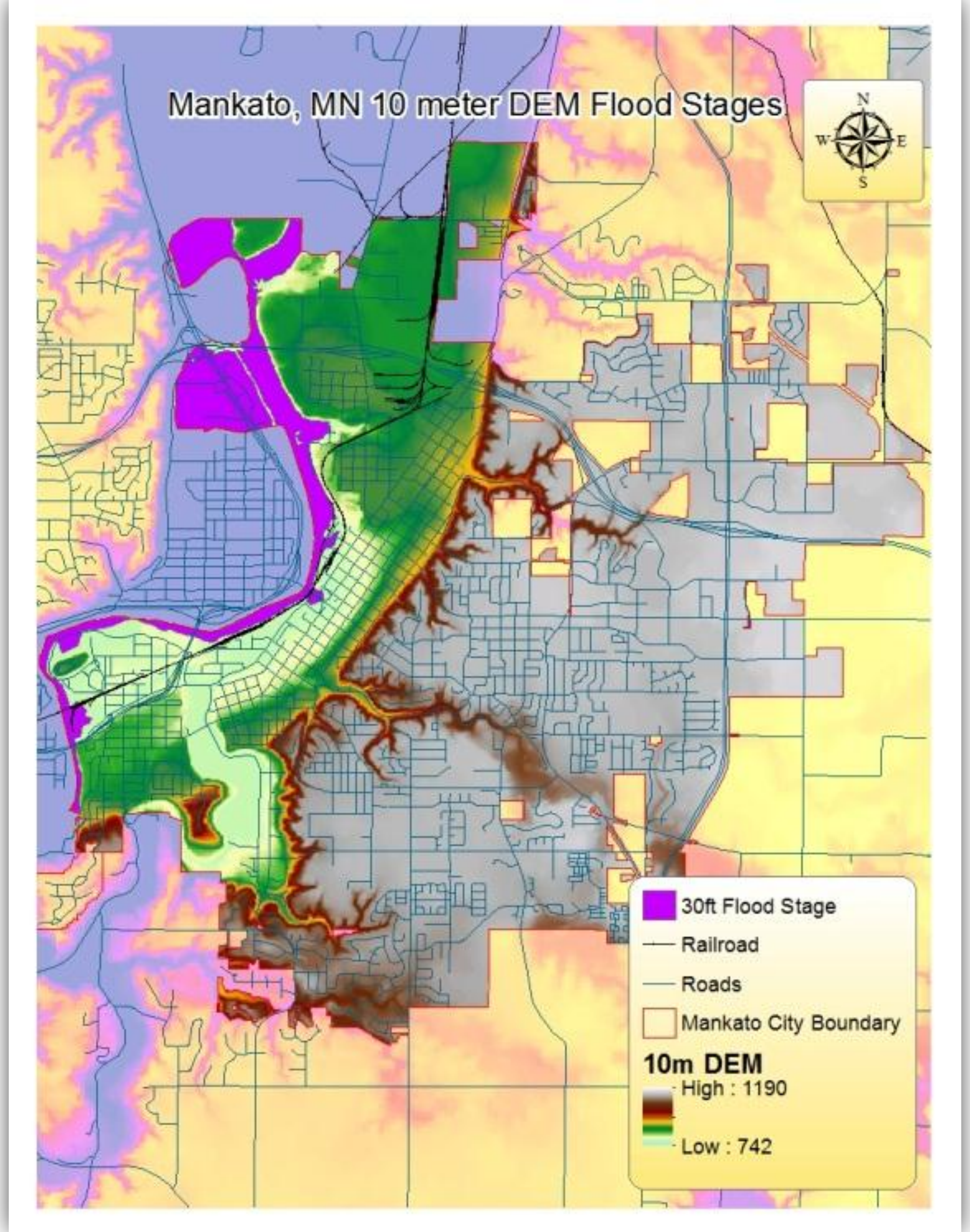


Figure 3.18: 10-meter DEM 30ft Flood Stage

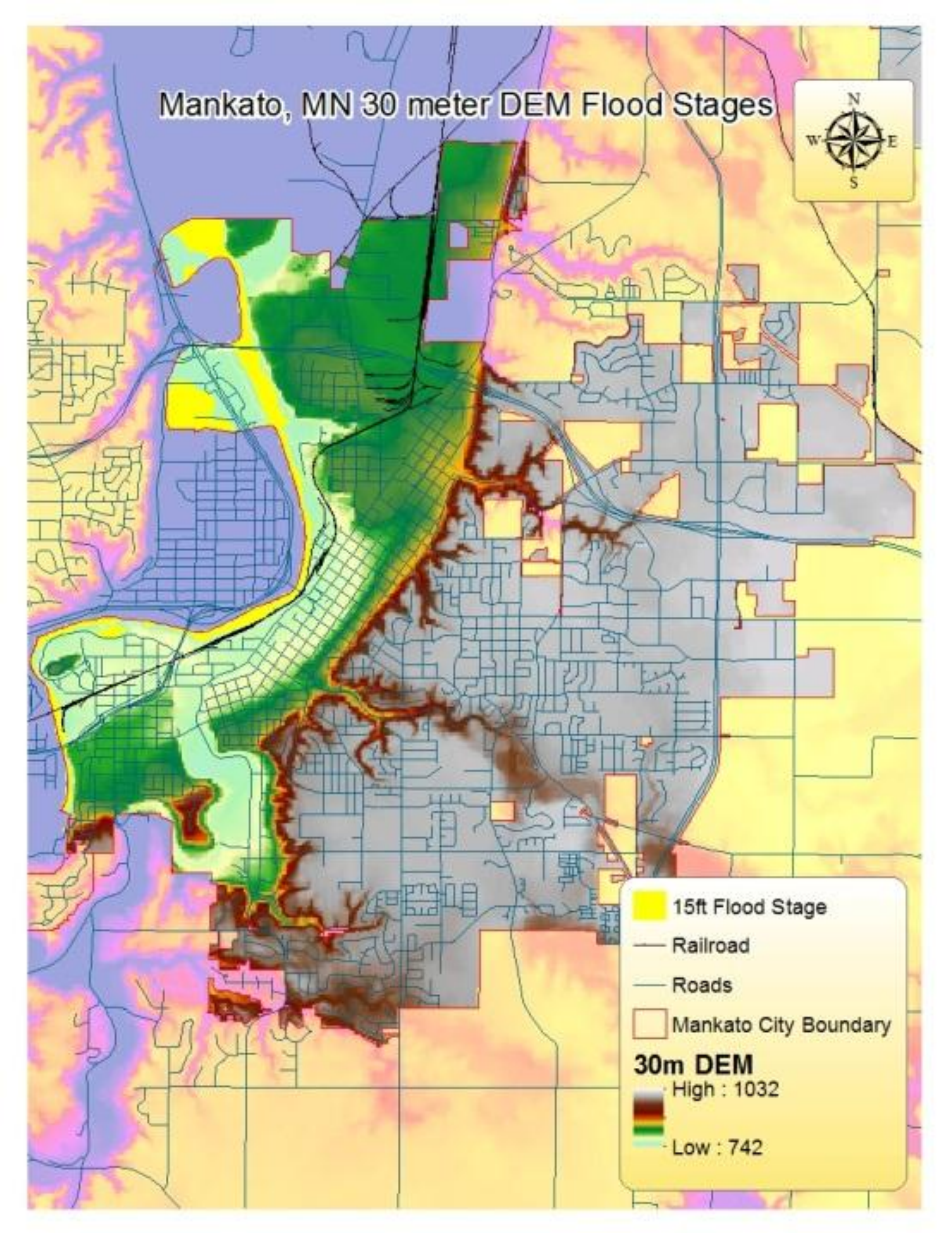


Figure 3.19: 30-meter DEM 15ft flood stage

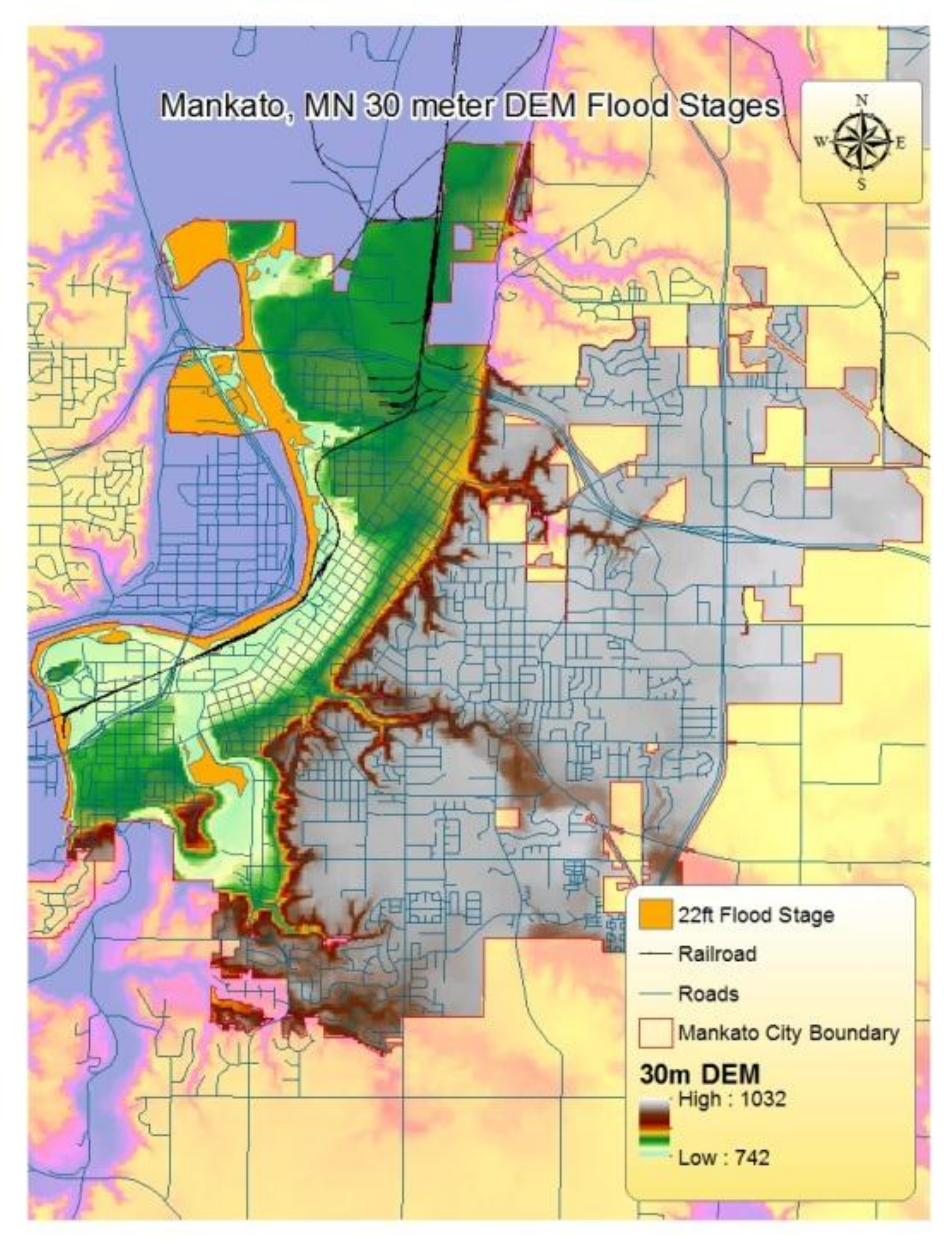


Figure 3.20: 30-meter DEM 22ft flood stage

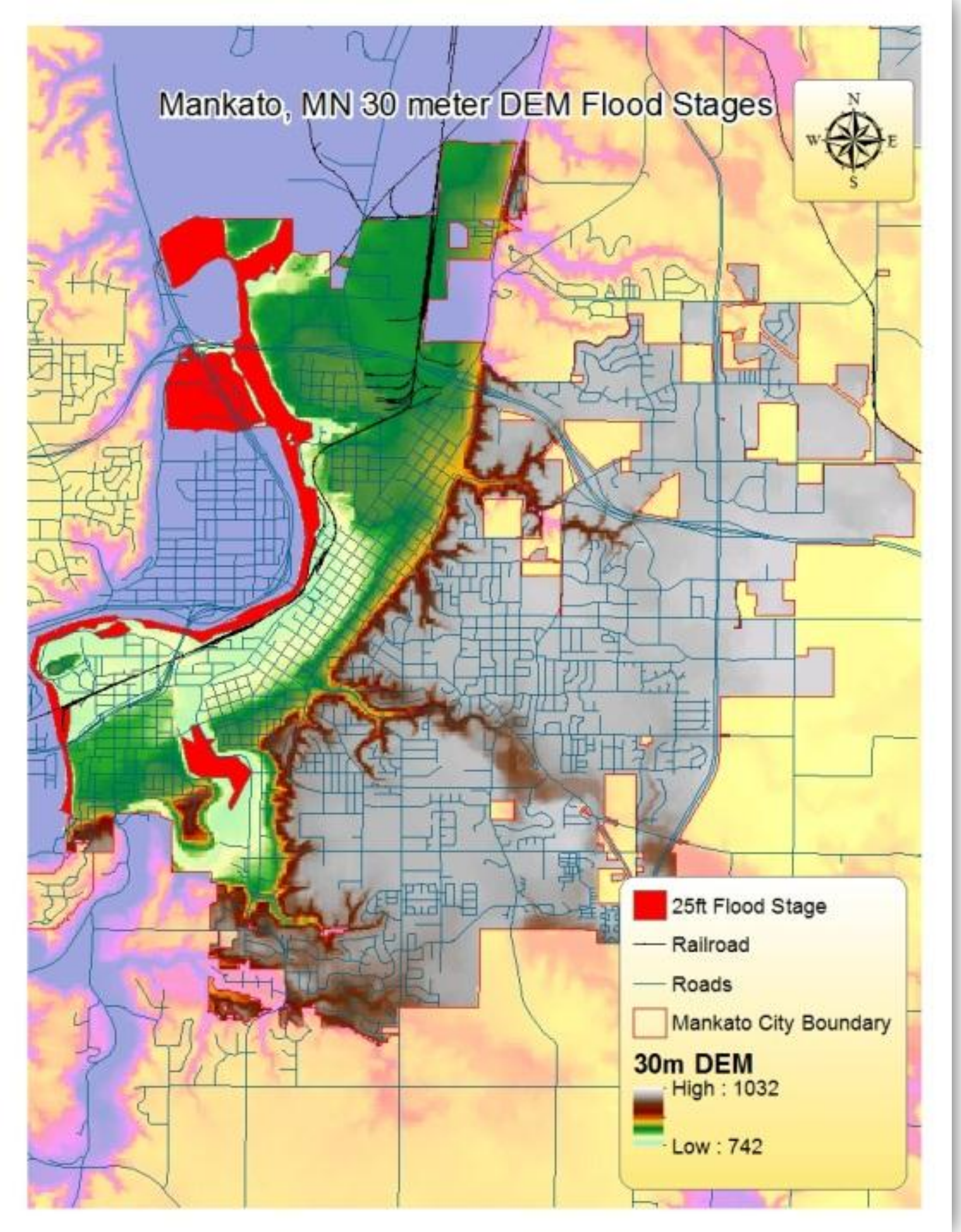


Figure 3.21: 30-meter DEM 25ft flood stage

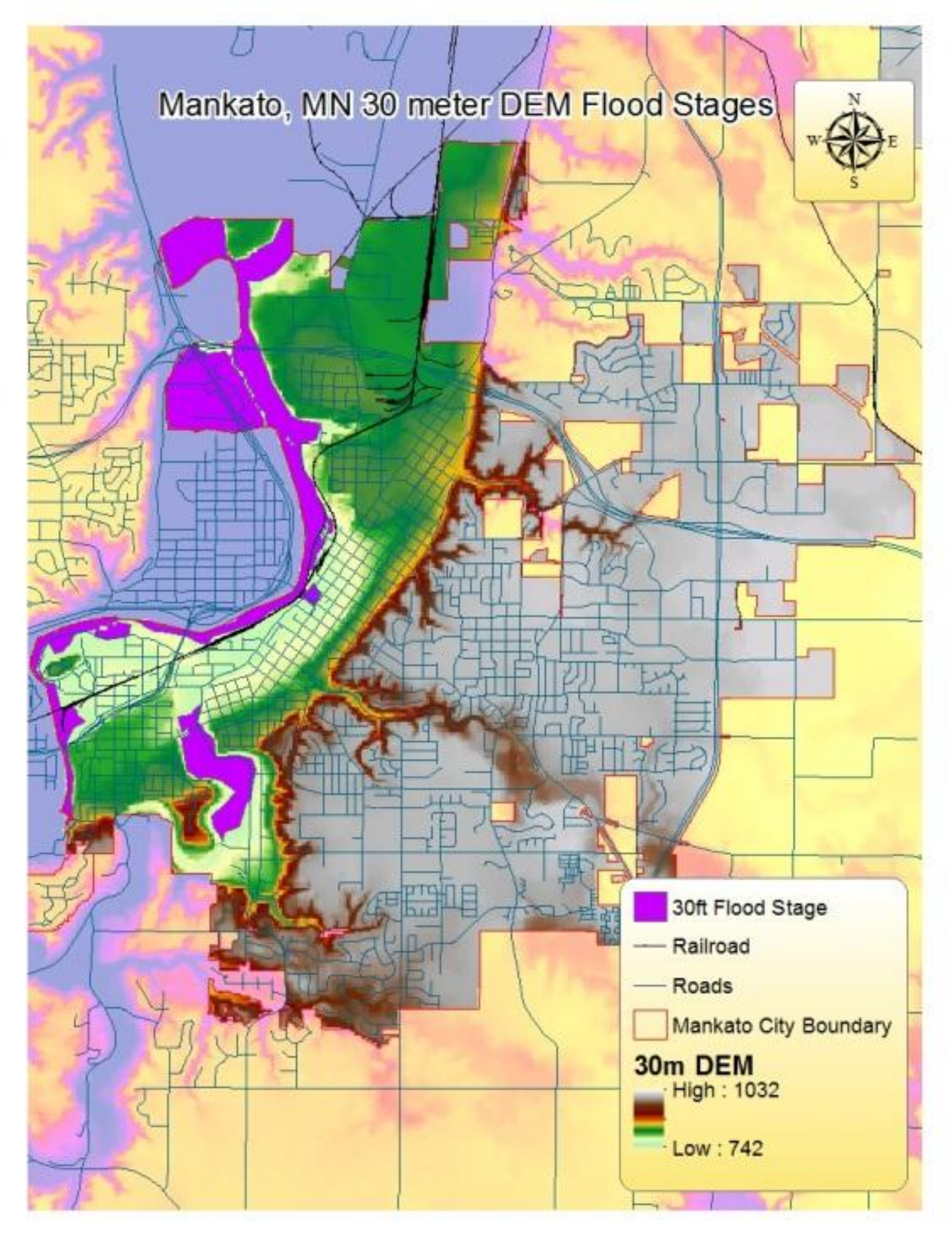


Figure 3.22: 30-meter DEM 30ft flood stage

3.5 Financial Impact Analysis

To fully understand the impact of flooding in the city of Mankato, a financial impact analysis was performed. The various flood stages from each resolution DEM was loaded into ArcMap. Next, the city parcel data was added. Using the 'Select by Location' function in ArcMap, parcels that were completely contained within each respective flooding layer were selected and exported as their own layer (See Figure 3.23). Once these layers were created, the total appraised values of the parcels (including land and structures) could be added to give an estimate of the potential costs of the damages.

Figure 3.23: ArcMap's 'Select by Location' Function Example

Not all parcels will be completely inundated however. By using the lidar-derived building footprints, a more accurate picture of the costs could be calculated. First, a Spatial Join was performed to join the attribute information (which includes the buildings' assessed values) from the parcel shapefile to the building footprints. Using the Select by Location function, the buildings that came into contact with each flood layer could be selected and their attribute information exported and summed.

Chapter 4: Results

4.1 Potential Flood Zone Results Based on CTI & SPI for South Central Minnesota

Before the CTI and SPI layers were merged, high value areas from each of the two were compared to shapefiles showing rivers and streams, lakes, and wetlands. Areas with high CTI values matched very well to areas with lakes and wetlands (See Figure 4.1). Areas with high SPI values matched well with areas containing rivers, streams, and agricultural tiling and drainage ditches (See Figure 4.2). While some areas with high CTI values did not match up with wetlands or lakes shapefiles, it could be possible that these areas are wetlands but are not officially classified as such by the shapefile.

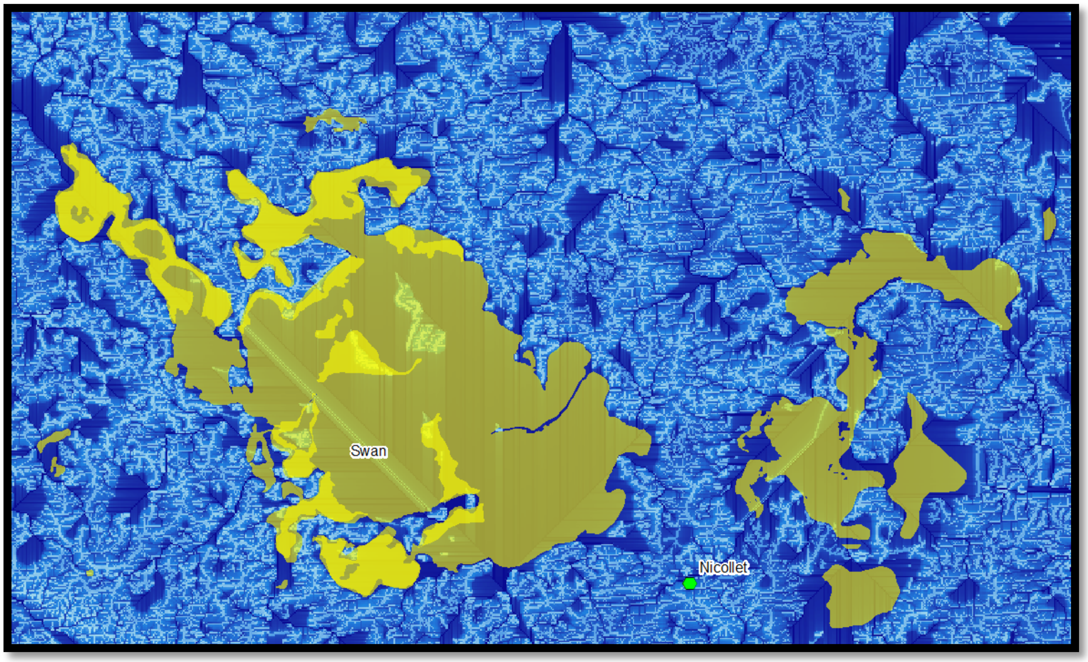


Figure 4.1: CTI Compared to Lakes and Wetlands

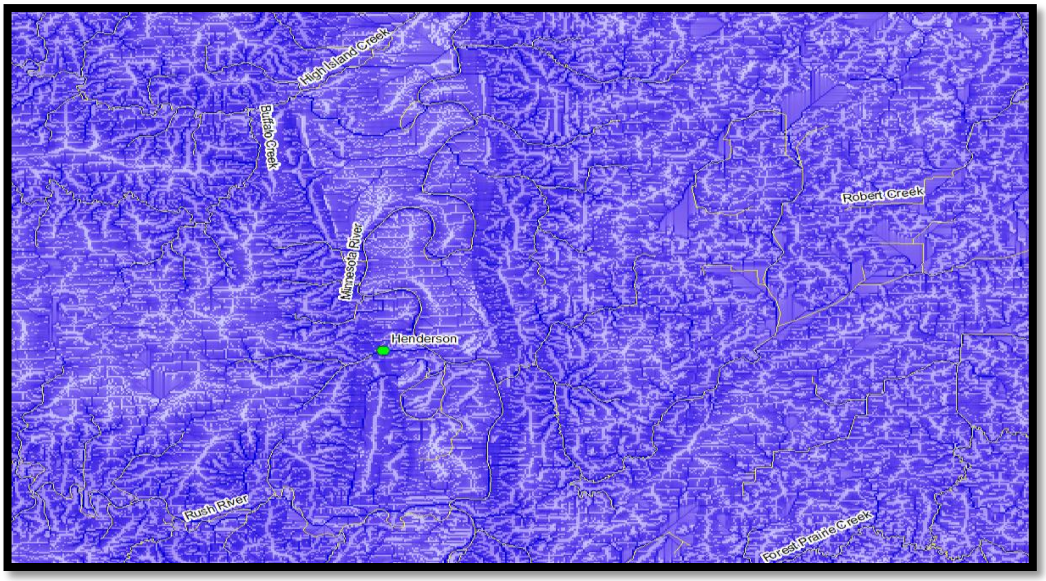


Figure 4.2: SPI Compared to Rivers and Streams

CTI and SPI values were found throughout the multi-county study site making any useful analysis difficult. To lessen this issue, the CTI raster was reclassified to show only the top 90th percentile. The highest concentrations of these values were found in Nicollet County, Le Sueur County, and northern Blue Earth County (See Figure 4.3).

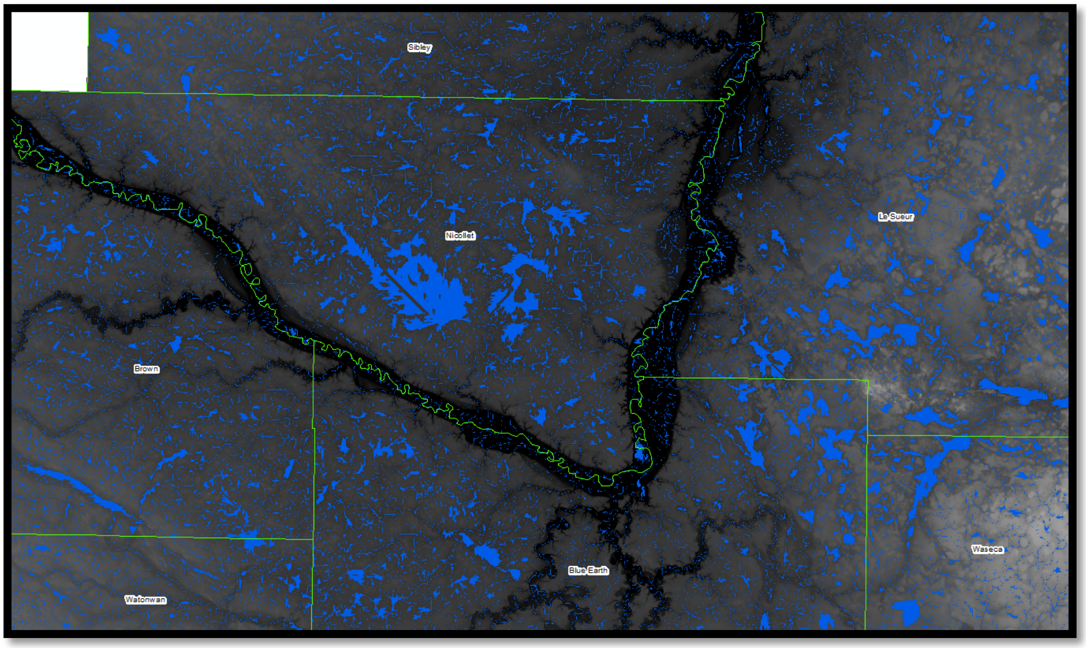


Figure 4.3: Area with high CTI Concentration

Next, the SPI raster was reclassified to show only the top 95th percentile. Again, the highest concentrations of these values were found in Nicollet County, Le Sueur County, and northern Blue Earth County (See Figure 4.4). This is most likely due to the Minnesota River and its' tributaries.

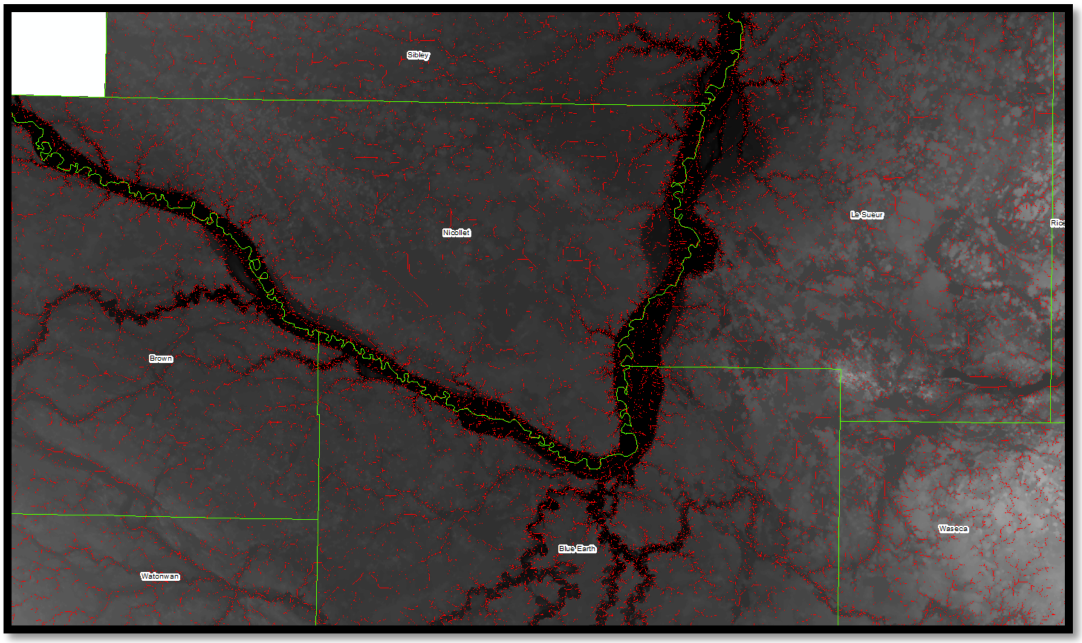


Figure 4.4: Area with high SPI Concentration

By combining these two indexes' values, this study attempted to show areas that could be more highly prone to flooding as a result of having high probability of water pooling and the potential for fast moving erosive water. The geographic mean center (based on the area of the polygons) for these combined values is six miles southeast of Mankato. Again, this verifies the highest values are located in this region. Therefore, rural and urban populations and properties are at a higher risk of flood in this area when compared to the other counties in South Central Minnesota.

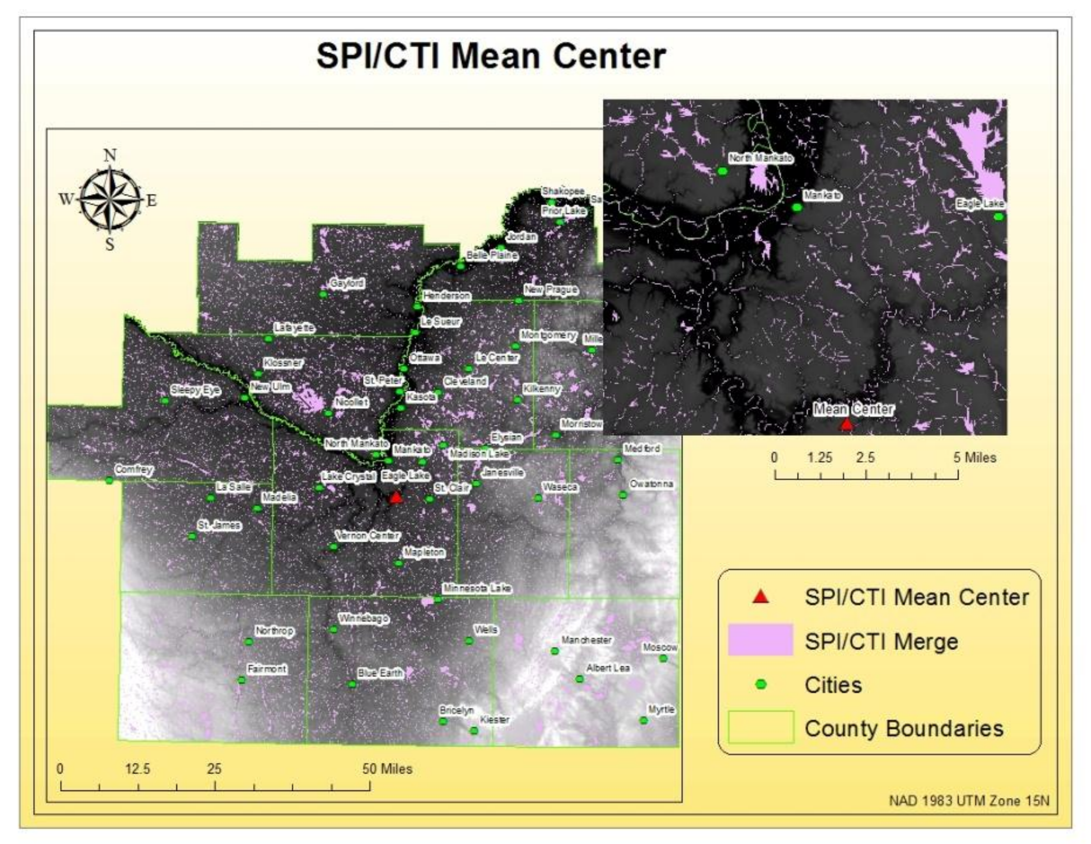


Figure 4.5: SPI & CTI (Merged) Mean Center

4.2 Seven Mile Creek Watershed CTI & SPI

When applying the DEM scaling issue to CTI and SPI for the Seven Mile Creek Watershed, some very interesting results were reached. The 30-meter, 10-meter, and 3-meter resolution DEMs produced nearly identical areas for both indices (See Table 4.1 and Figures 4.6-4.11)

Table 4.1: CTI & SPI area (in acres)

	30m	**10m**	**3m**
CTI	2250	2195	2218
SPI	747	896	906

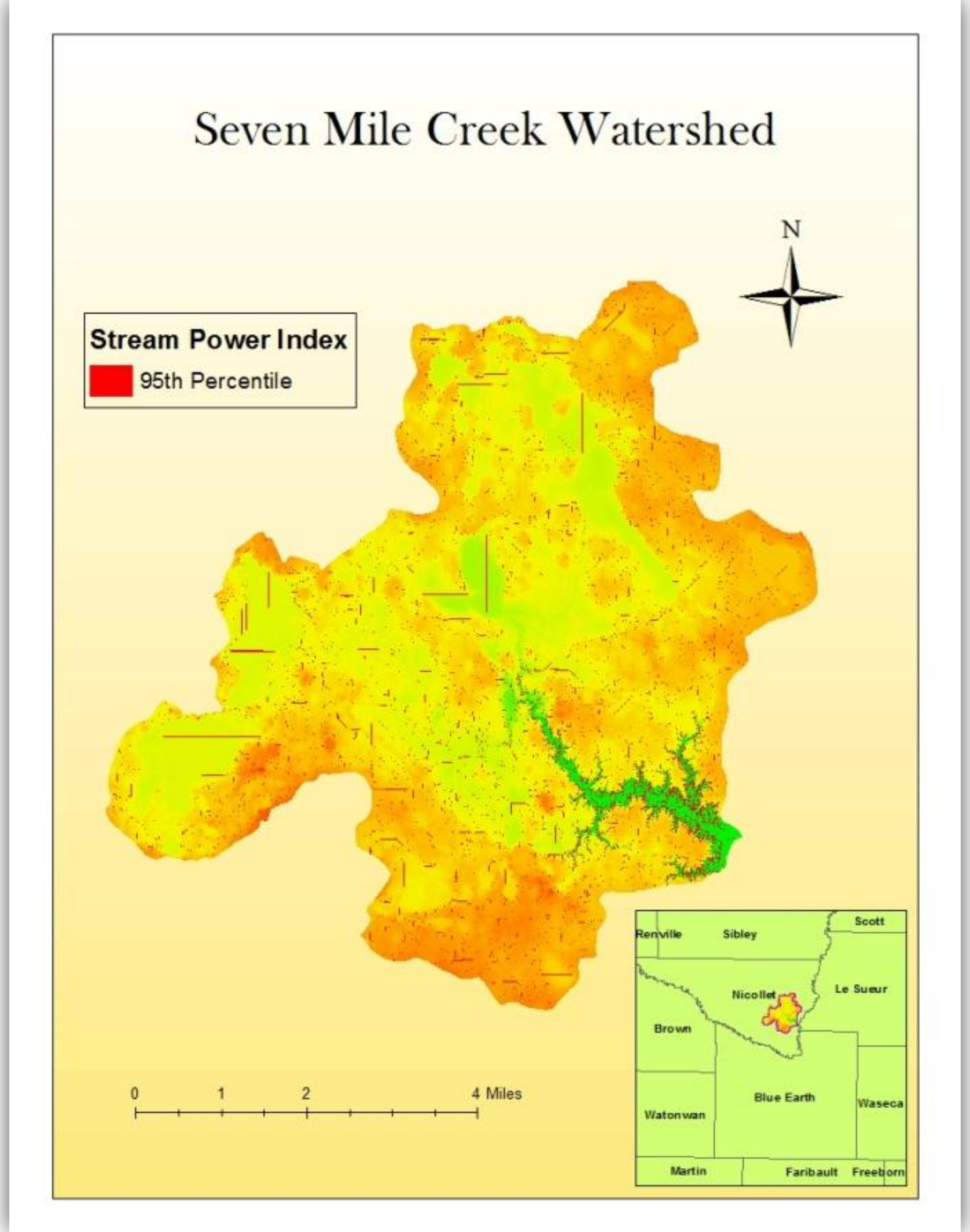


Figure 4.6: 3m DEM SPI Index

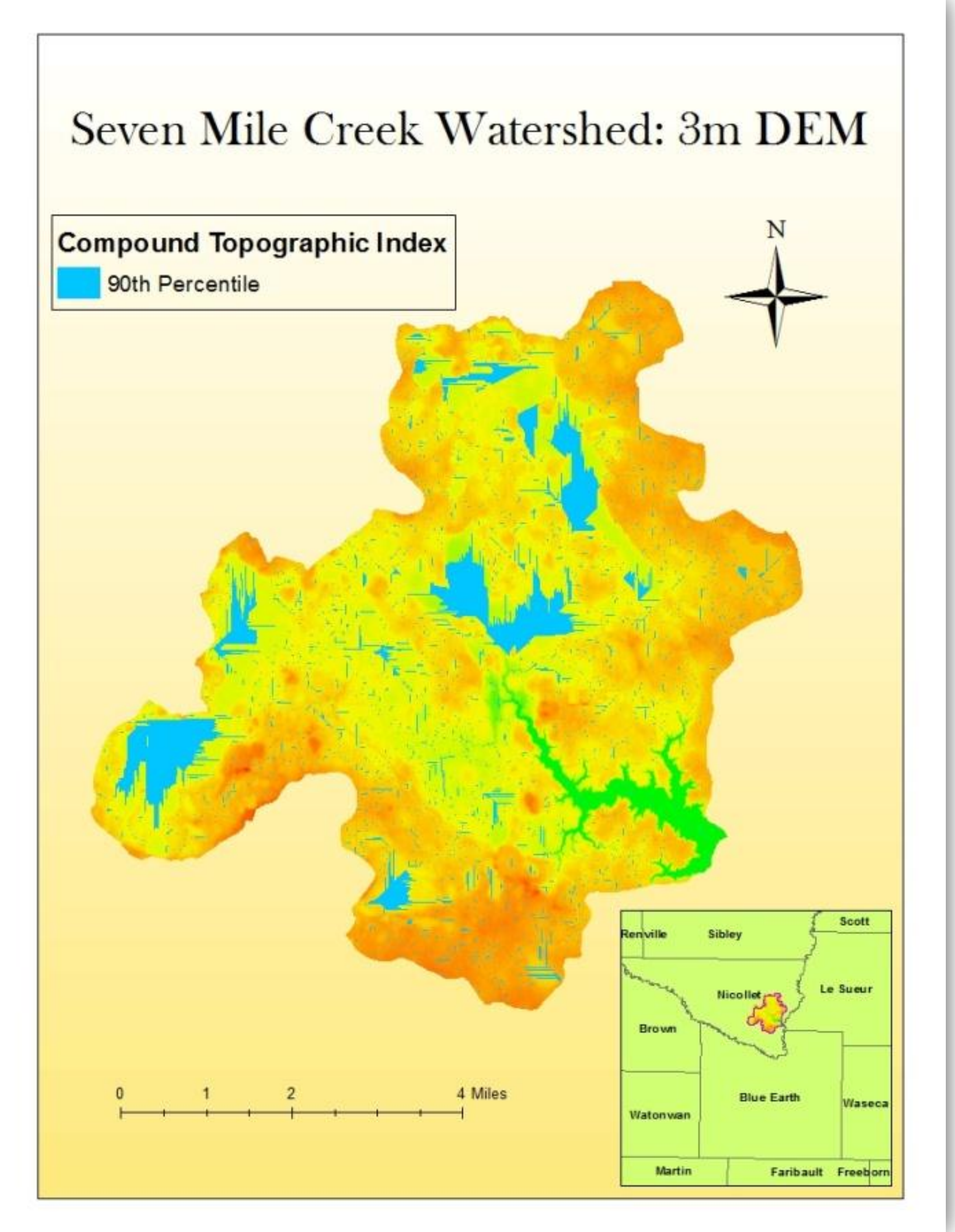


Figure 4.7: 3m DEM CTI Index

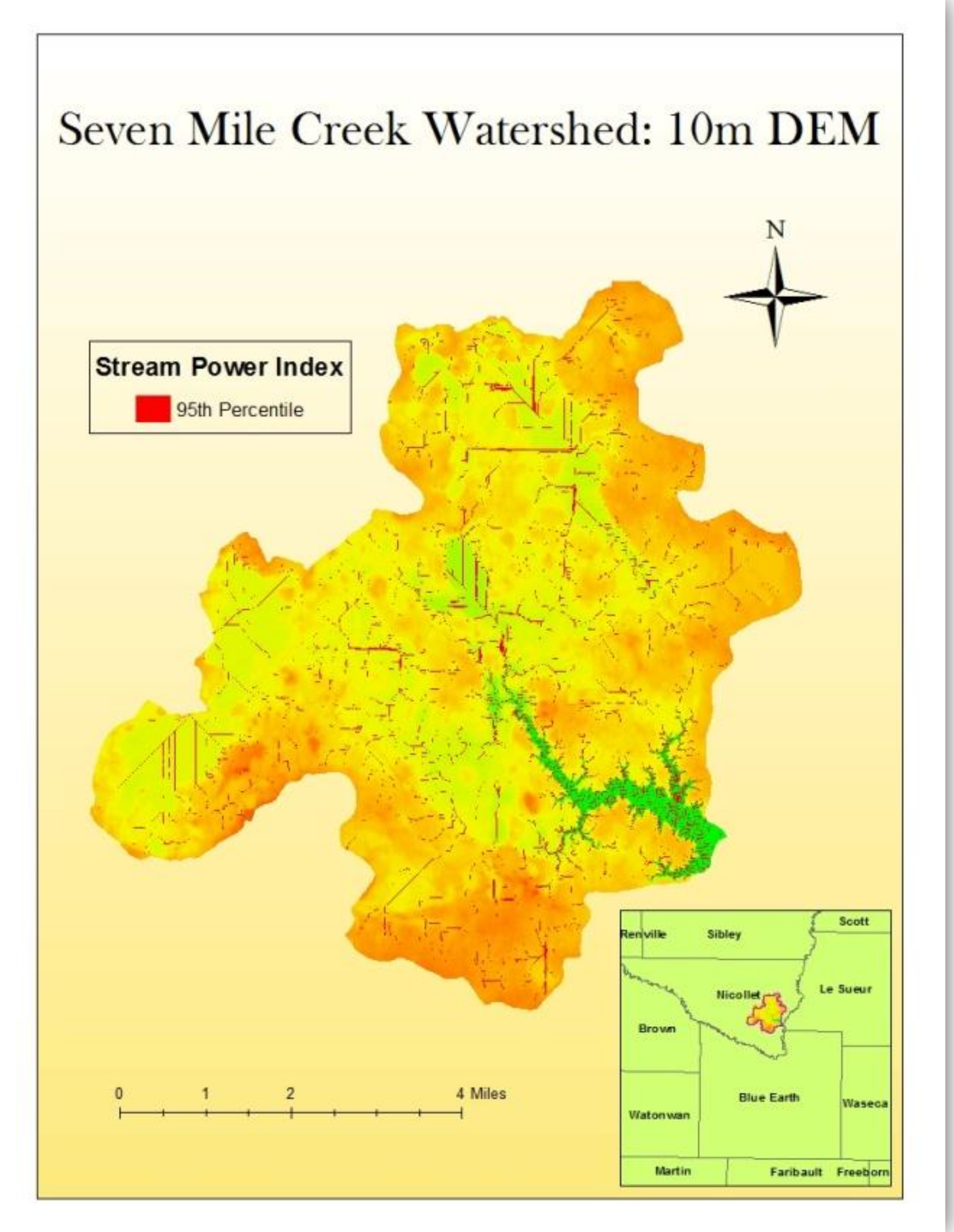


Figure 4.8: 10m DEM SPI Index

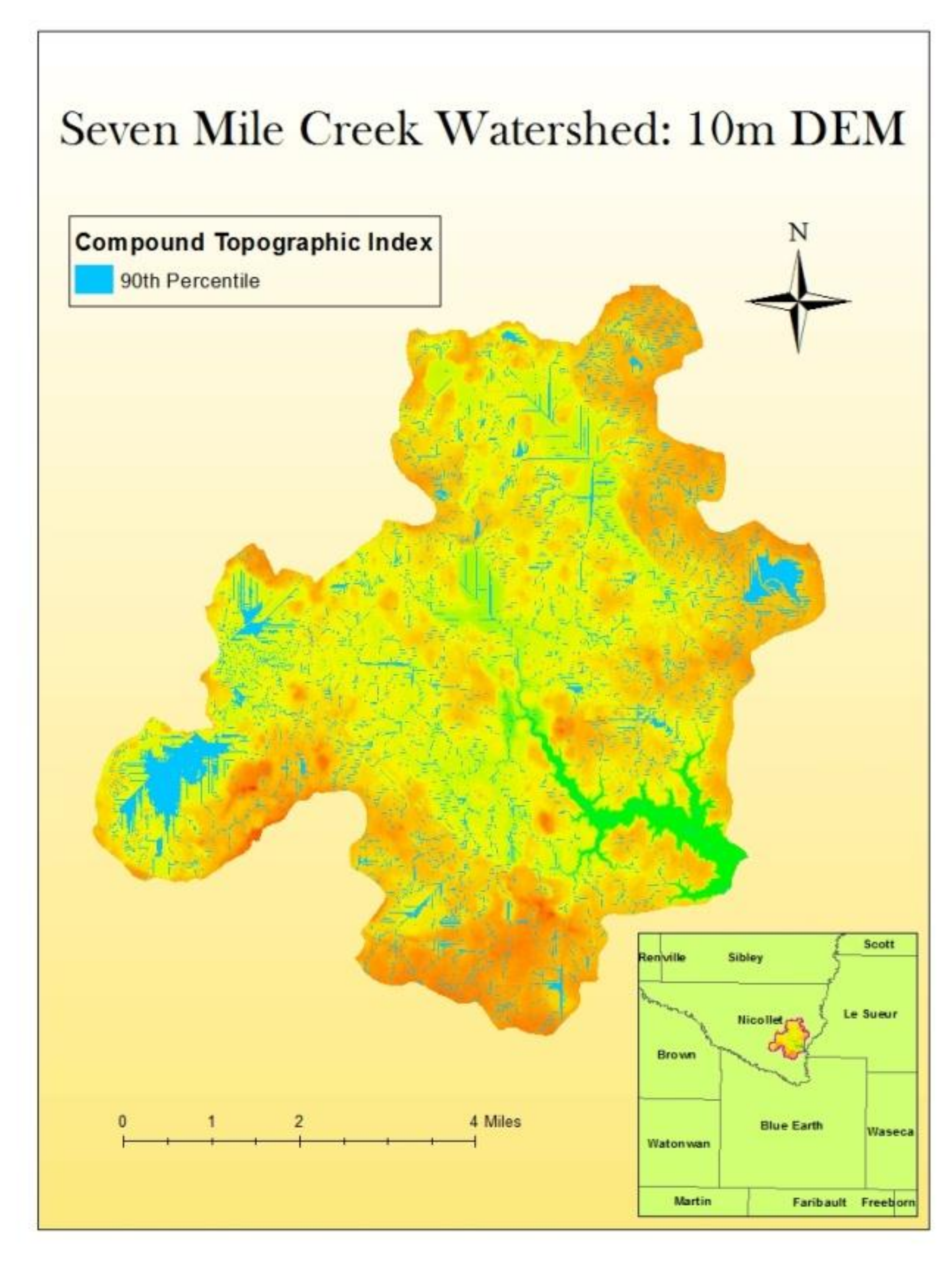


Figure 4.9: 10m DEM CTI Index

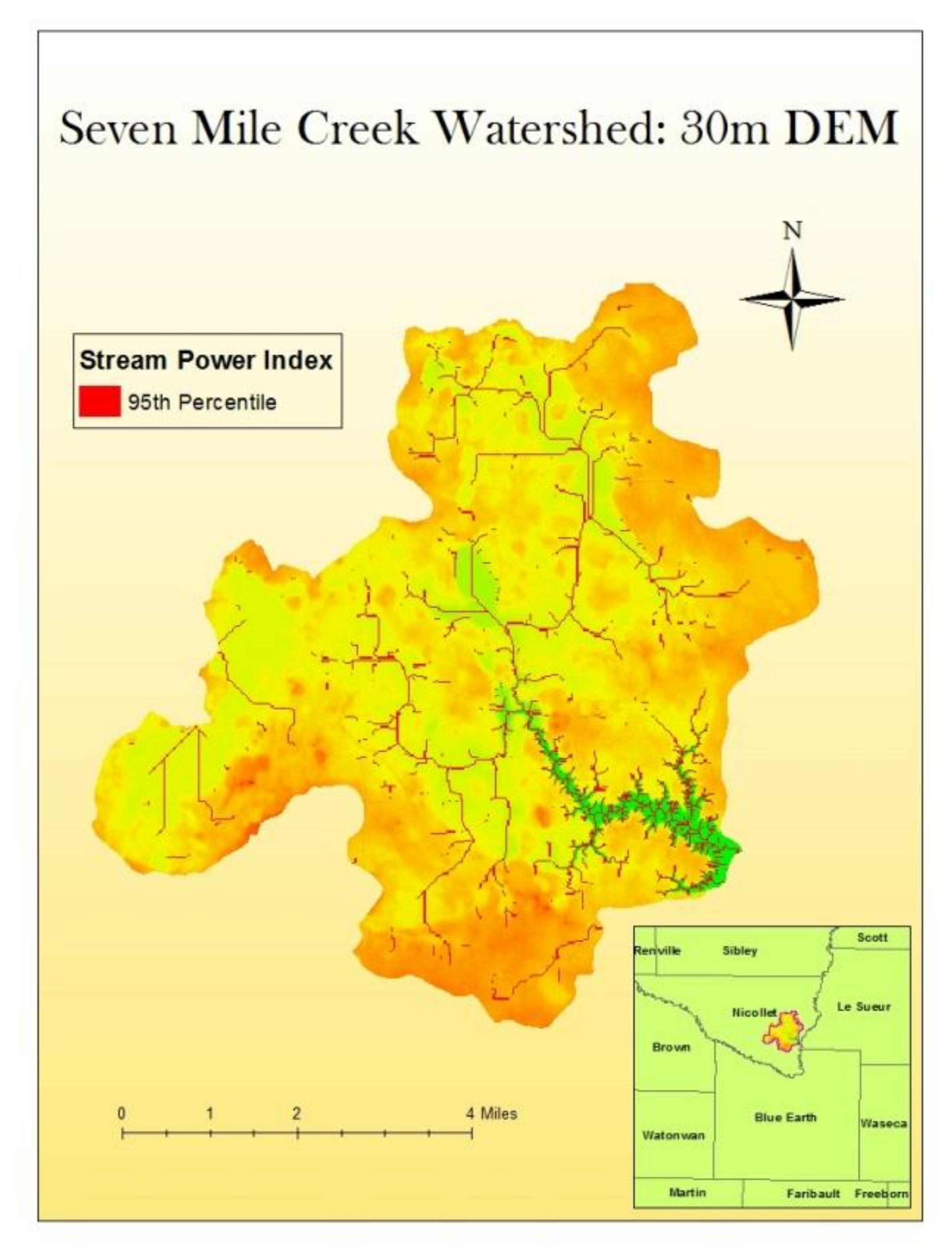


Figure 4.10: 30m DEM SPI Index

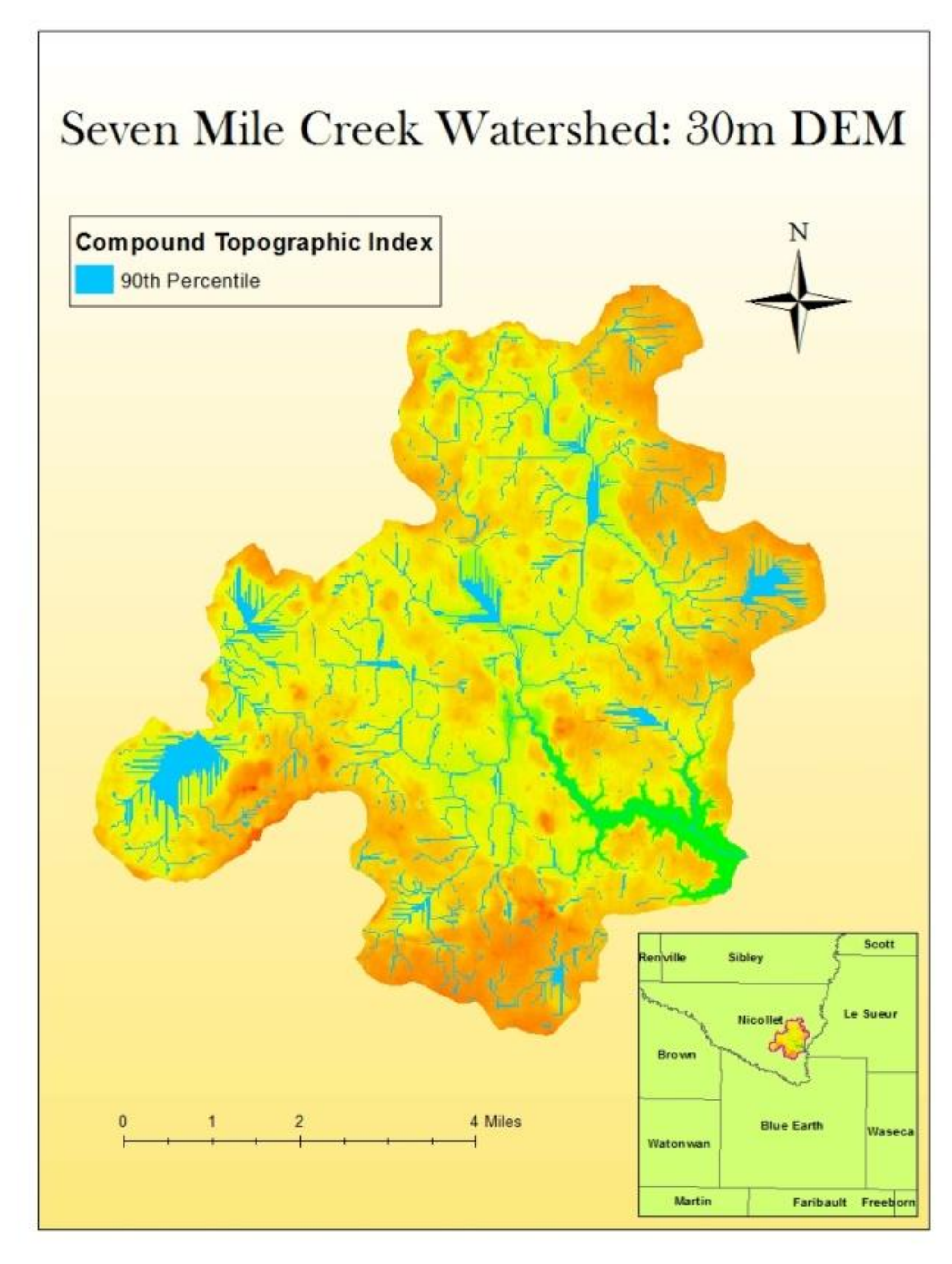
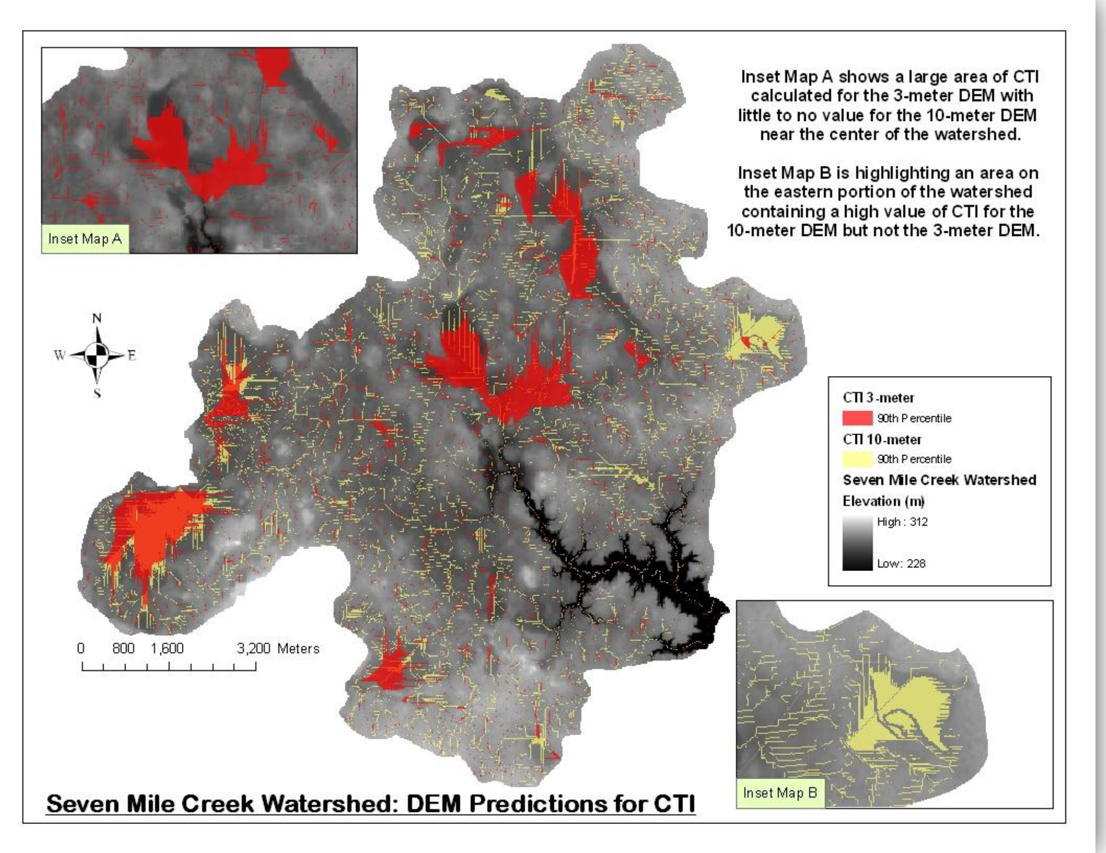


Figure 4.11: 30m DEM CTI Index

The fact that the areas were nearly identical was not as interesting as how the location of the high CTI values changed with the change in DEM resolution (See Figure 4.12)



Inset Map A shows a large area of CTI calculated for the 3-meter DEM with little to no value for the 10-meter DEM near the center of the watershed.

Inset Map B is highlighting an area on the eastern portion of the watershed containing a high value of CTI for the 10-meter DEM but not the 3-meter DEM.

Seven Mile Creek Watershed: DEM Predictions for CTI

Figure 4.12: CTI Predictions for 3-m & 10-m DEMs

While the total number of square acres were nearly identical, different portions of the watershed are showing high values for both CTI and SPI dependent upon the DEM chosen. Therefore, considering the total area of each index solely would give the user misleading results. As with all things geographic, the location of the values must be the prime consideration to gain any sense of value from the indices.

The change in location of these indices could be a result of the number of sample DEMs used. More DEMs used (i.e. 30-meter, 20-meter, 10-meter, 3-meter, 1-meter) will result in more normalized results on a regression line. These normalized results will create a more consistent location curve for the indices throughout the rising of resolution for the DEMs.

The implications for the change in the indices' locations can be great in some situations, however. If applying the indices for flood management and preparation, consulting land-use cover maps and other flood map resources could be useful. In this instance, the large areas of indices difference only covered areas with cropland, open water, and wetlands according to the National Land Cover Database land cover maps from 2001.

4.3 Flood Level Extent at Various DEM Resolutions

Once the various flood levels were created in ArcMap, the extent was determined by both visually examining the areas affected and by totaling the number of square acres contained at each water height. Surprisingly, the amount of area affected by each respective stage does not follow a consistent pattern, up or down, as resolution changes. The 1-meter resolution, 30-foot flood stage seems to follow an inverted bell-curve and predicts the largest extent of the three (See Figure 4.13 and Table 4.2). This could be caused by the cell-selection method used to create the flood levels.

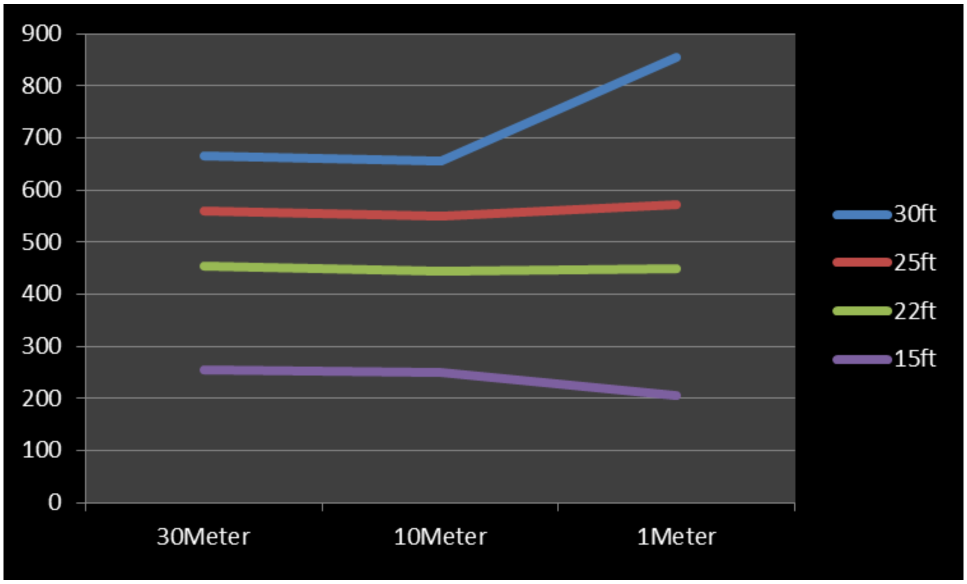


Figure 4.13: Number of acres affected by flood stages in each DEM

Table 4.2: Area of flood stages predicted by each DEM (in acres)

Area in Acres	30meter	10meter	1meter
30ft	665.03	654.44	854.47
25ft	559.53	549.63	572.06
22ft	454.39	443.84	448.47
15ft	255.8	249.14	204.46

Visually it is easy to see there are areas more inundated when using the 30-meter DEM for analysis rather than the 10-meter DEM (See Figures 3.11-3.22). The locations near Rasmussen Woods Park and Sibley Park clearly stand-out. Also, the 1-meter DEM shows a significantly larger number of residential neighborhoods being affected near Sibley Park when compared to the 10 and 30-meter DEMs.

4.4 Financial Impact Analysis

While assessing the total value of properties that come into contact with the flooding stages could be useful, a more accurate assessment involves determining if both the land and any structures on the property come into contact with the water. To do this, parcels containing structures that intersected flood levels were selected and their assessed values were summed. Figure 4.13 shows an example of a neighborhood in Mankato where the water has risen 25ft. Some homes and properties are completely submerged while others are only experiencing water damage to their land.

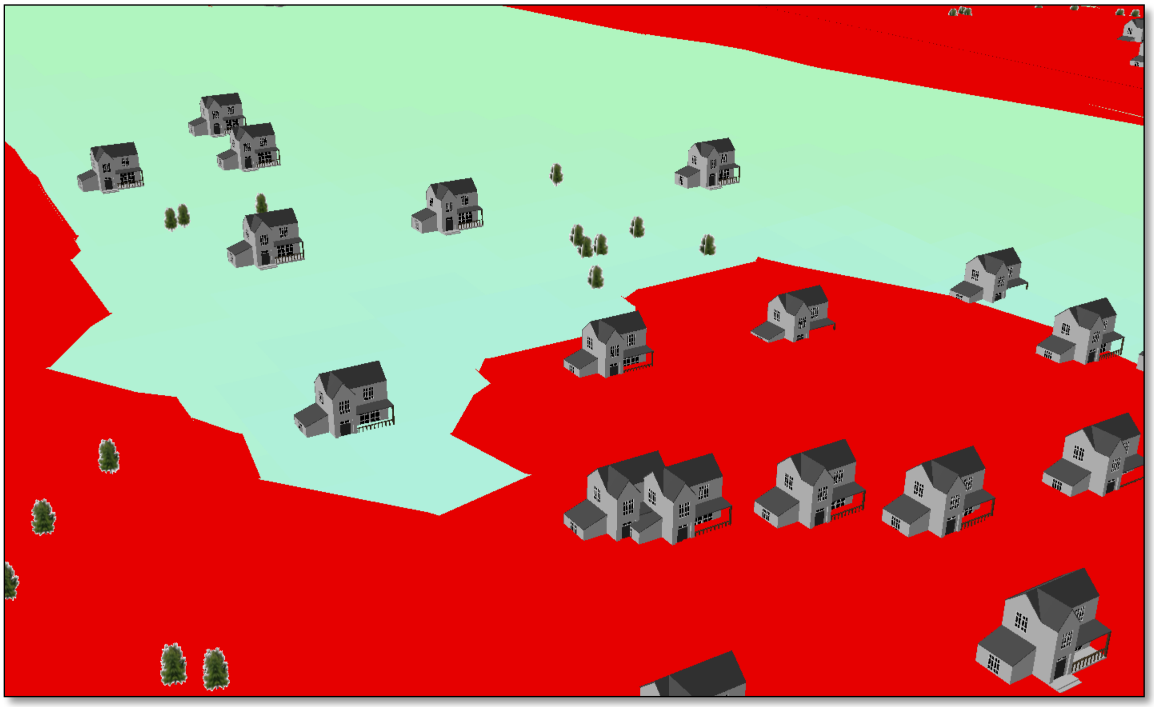


Figure 4.14: Land Parcels & Buildings Intersecting the 15ft Flood Level (shown in red)

Table 4.3: Damaged Buildings Costs Estimates

Buildings Damaged	30m	10m	1m
15ft	$ 3,240,900	$ 3,240,900	$ -
22ft	$ 3,240,900	$ 3,240,900	$ 2,403,600
25ft	$ 3,240,900	$ 3,240,900	$ 3,583,600
30ft	$ 3,754,300	$ 3,471,200	$ 12,915,700

Table 4.4: Damaged Buildings & Land Costs Estimates

Buildings & Land Damaged	30m	10m	1m
15ft	$ 19,517,700	$ 17,464,000	$ 1,303,700
22ft	$ 59,654,800	$ 49,357,300	$ 27,828,500
25ft	$ 109,912,000	$ 109,513,100	$ 52,567,800
30ft	$ 167,268,200	$ 186,404,100	$ 142,551,700

Other parcels consisted of only land that would be affected by each respective stage (See Table 4.5).

Table 4.5: Damaged Lands Costs Estimates

Only Land Damaged	30m	10m	1m
15ft	$ 4,850,900	$ 3,036,700	$ 3,370,100
22ft	$ 6,141,800	$ 4,034,600	$ 6,655,800
25ft	$ 6,421,000	$ 5,187,000	$ 7,892,700
30ft	$ 7,082,300	$ 5,795,900	$ 12,439,100

As a result of there being more commercial development along the river, in total, more commercial property than residential property is predicted by each DEM to be damaged. Also, as a percentage of the total land and building values in the city, the costs of parcels damaged by flooding would be very small. Both land and building damages total less than 5% of the total for the city (See Table 4.6).

Although the extent of the 1-meter DEM was smaller than that of the 30 and 10-meter DEMs, its' financial impact was greater. This could be attributed to its' larger presence in the residential neighborhoods near Sibley Park. The 1-meter DEM predicted the highest cost of building damages and second highest for land damages.

Table 4.6: Lands & Buildings Damages as a Percentage of the Total Value

Total Values for City of Mankato	**Buildings**	**Land**	**Total**
	$ 1,286,954,300	$ 751,056,600	$ 2,038,010,900
30m	1.05%	3.26%	1.86%
10m	1.03%	4.98%	1.53%
1m	1.47%	4.04%	2.42%

Chapter 5: Conclusion & Discussion

Large and small scale flooding events have become more common in the last ten years in South Central Minnesota due to large spring snow melts, increases in agricultural tiling, and changing weather events. Investing in the latest technologies, like lidar, can potentially pay for themselves if applied toward emergency planning and preparedness. This becomes even clearer when considering the large amount of property damage that can be incurred during these events.

CTI and SPI could be useful tools for predicting flood prone areas. Once these areas are generally identified using these indices, more precise measurements and preventative programs can be used. Before this can be true however, the role of DEM resolution in these indices must be examined in further detail. This should include areas of varying topography and relief. Also, the size of the study site should be examined to determine how the ranges in values of the DEM affect CTI and SPI values.

Areas near Mankato, MN contain the highest values of CTI and SPI for South Central Minnesota. This is mainly due to the presence of the Blue Earth River and the Minnesota River. Also, the topography and relief of the landscape contribute to these values. The Seven Mile Creek Watershed in Nicollet County has been an area of interest for some years now because of its land use change and small manageable size. CTI and SPI could be useful in this area as long as a high resolution DEM is used for the inputs (flow accumulation and slope).

The cell selection process used to create the flood levels for Mankato is a useful tool when determining the role of the DEM in flood plain mapping. Also, it is convenient when considering the repeatability of such a process. Using various resolution DEMs in an Army Corp of Engineers' hydrological model would be very helpful to determine how the actual predicted flow of water changes with DEM resolution. Although such a model does not yet exist for the Minnesota River near Mankato, perhaps in the future such an investment would be wise.

According to the methods used, areas along the Minnesota River in Mankato are most prone to flooding damage. The areas affected can greatly change depending on the DEM chosen however. This in-turn affects the monetary damages predicted for these flooding events. For instance, although the 30-meter DEM predicted a larger amount of total land would be inundated, the 1-meter DEM predicted a larger portion of residential land would be damaged. This raised the predicted costs of damages to buildings between the two DEMs considerably.

This paper could obviously not include the 3-dimensional visualization that is possible with a program such as ESRI's ArcScene. With this program, a virtual 'fly-through' was performed. A greater understanding of flooding is possible through improved visualization. In the future, virtual fly-through scenes should be utilized on websites to help citizens better understand how their properties would be affected by various levels of rising water.

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