SELECTION OF BRIDGE LOCATION OVER THE MERRIMACK RIVER IN SOUTHERN NEW HAMPSHIRE: A COMPARISON OF SITE SUITABILITY ASSESSMENTS

by

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
CSV	Comma-Separated Values
DEM	Digital Elevation Map
DOT	Department of Transportation
FEE	Frederick E. Everett
FEMA	Federal Emergency Management Agency
FIPS	Federal Information Processing Standards
FIRM	Flood Insurance Rate Maps
GIS	Geographic Information Systems
GIST	Geographic Information Science and Technology
MCDM	Multiple Criteria Decision Making
MCE	Multi-Criteria Evaluation
NAD	North American Datum
NH	New Hampshire
NHHD	New Hampshire Hydrography Dataset
NLCD	National Land Cover Database
NRPC	Nashua Regional Planning Commission
SSI	Spatial Sciences Institute
US	United States
USACE	US Army Corps of Engineers
USC	University of Southern California

ABSTRACT

The goal of this research was to assess alternative proposed bridge crossing locations over the Merrimack River between the cities of Nashua, NH and Manchester, NH resulting from two site suitability analysis studies that employ different criteria. A new bridge will provide an alternate route for commuters to access the F.E. Everett Turnpike and U.S. Route 3 in southern NH. Historic traffic count trends show that traffic on bridges and collector roads has increased substantially due to residential growth. This thesis compared alternatives proposed by a site suitability study conducted by Nashua Regional Planning Commission (NRPC) in 2003 to new solutions derived in this thesis through weighted overlay analysis, which took into account distance between major population concentrations and roads, position with respect to historic floodways and terrain, and environmental impacts. The comparison shows how the location of the most suitable bridge locations to span the Merrimack River change when the criteria are altered and different suitability analysis processes are used. The thesis includes a description of criteria and data utilized in the research, an explanation of how the standardized input layers were created, an examination of the methodology for the weighted overlay analysis, and the comparison results of the two site suitability analysis studies.

CHAPTER 1: INTRODUCTION

Since the 1950s, there has been a need for a bridge over the Merrimack River between the cities of Nashua, NH and Manchester, NH. Urban growth along the east side of the Merrimack River south of Manchester has produced demand for an alternate route for commuters to access the F.E. Everett Turnpike and U.S. Route 3 in Nashua. Residents who live on the east side of the Merrimack have a great interest in finding a solution to this site suitability problem of locating the optimal location to build another bridge.

Currently there are four bridges over the Merrimack River adjacent to the metro areas of Nashua and Manchester. Drivers wishing to access U.S. Route 3 from the east side of the river have the following options (listed here from south to north):

1. The Tyngsboro Bridge, which provides access to US 3 via Massachusetts Route 113.
2. The Sagamore Bridge, connecting the Everett Turnpike (US 3) to New Hampshire Route 3A in Hudson. With urban growth in areas to the south of Nashua, this bridge has seen a 77% increase in vehicular traffic in the last ten years (City of Nashua 2001).
3. The Taylor Falls/Veteran's Memorial Bridges (otherwise known as the Hudson Bridges), which guides the traffic NH Route 111 through the city streets of Nashua (Hollis St and Canal St). With over 40,000 daily vehicle crossings, these bridges lack the capacity to handle rush hour traffic demand as well as other high volume travel times (City of Nashua 2001).
4. The Raymond Wieczorek Drive/Manchester Airport Access Road bridge, built in 2011, which provides a connection between NH Route 3A in the southern tip of Manchester, a few miles south of Interstate 293, and the Everett Turnpike in the southern corner of Bedford, with an interchange connecting the road with US 3.

Despite having four bridges serving the area in between Nashua and Manchester, there is a 12 mile gap between the Hudson Bridges and the Manchester Airport Access road bridge. A new bridge would provide an additional river crossing between Nashua and Manchester and another viable option for commuters to cross the Merrimack. It would also help alleviate normal and rush hour traffic on the current bridges by providing another viable option across the natural barrier.

The need for a bridge in the region between Manchester and Nashua is driven by social and economic factors. Time spent traveling and ease of getting to locations on opposite sides of the Merrimack River needs to be reduced and improved respectively in order to fulfill the need of the local residents. Reducing travel costs, diverting heavy traffic flow and more efficiently transporting people and goods across the river will make a positive economic impact on the region.

1.1 Study Area

The study area consists of the region between the cities of Manchester and Nashua New Hampshire. It is dominated by the Merrimack River Valley that extends from the Massachusetts border north to central NH. The primary landform is eastern New England Upland, which consists of a hilly landscape with elevation increasing as one moves east or west away from the Merrimack River valley. The soil is fertile with fruits and hay grown in the region along with a mosaic of habitats to include large stands of northern hardwoods, coniferous and mixed forests and wetlands (Netstate 2015). A map of the study area can be seen in Figure 1.

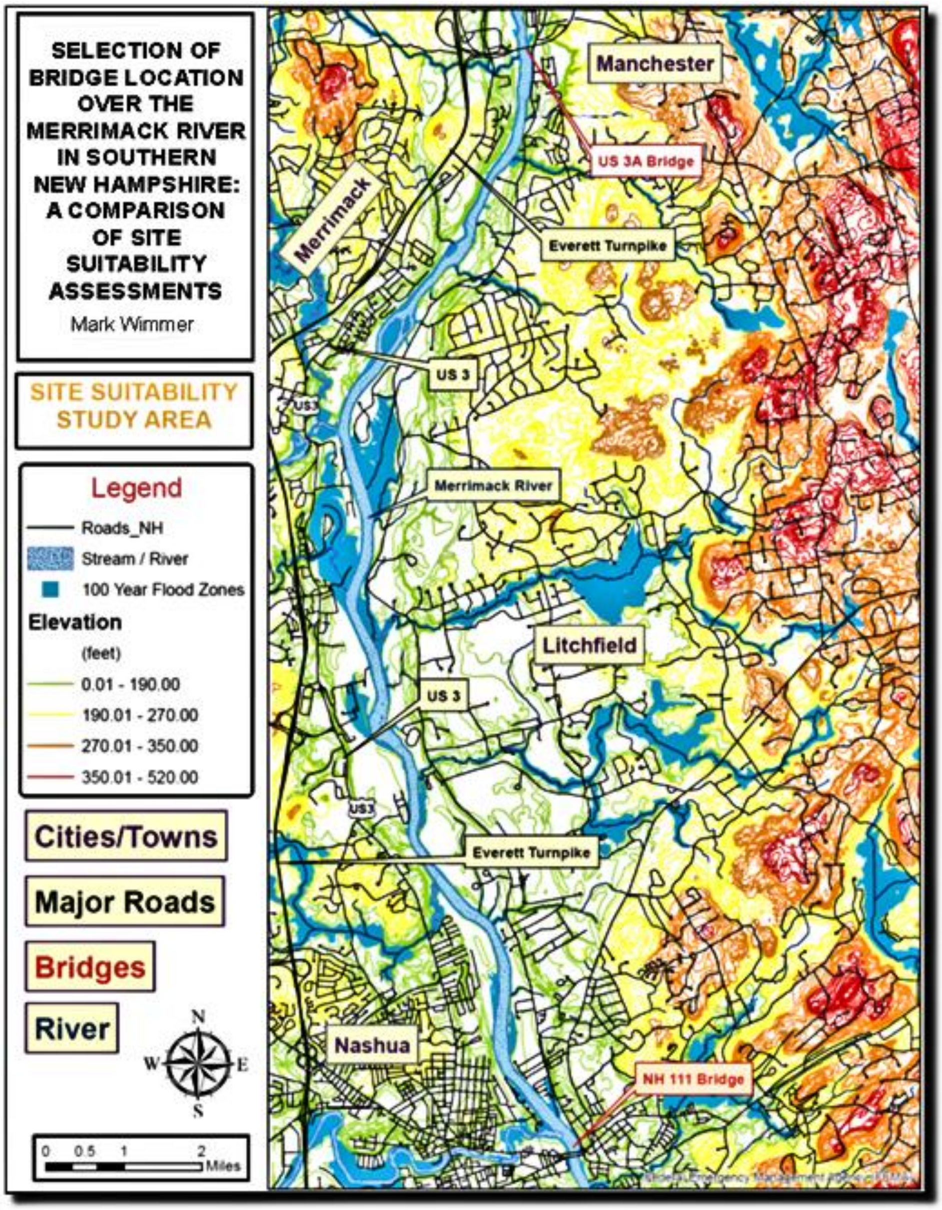

Figure 1: Map of Study Area

The Merrimack valley is also home to New Hampshire's most prominent mill and factory cities and towns. By population, Manchester and Nashua are the first and second largest cities respectively in NH. The communities of Merrimack and Litchfield are located along the Merrimack River between the larger cities. Merrimack on the western side of the river is also a large town with Litchfield located in a more rural area on the eastern side. Figure 2 shows a satellite view of the study area.

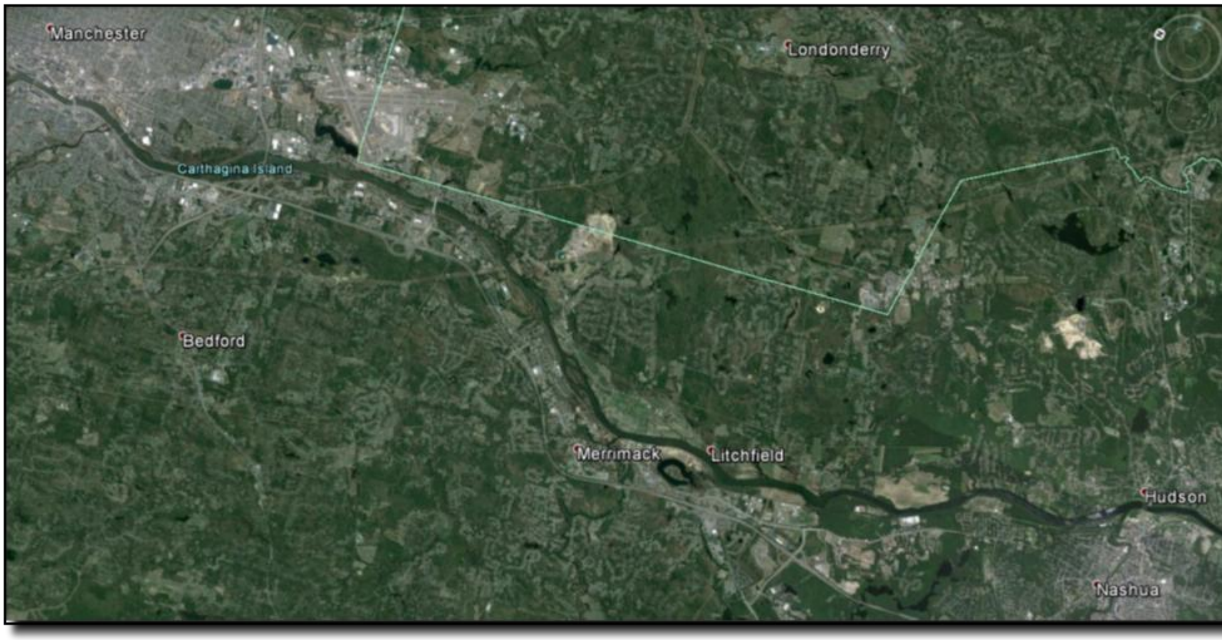

Figure 2: Google Earth Image of Merrimack River between Manchester and Nashua, NH

1.2 A Methodology for Site Suitability

Geographic information systems (GIS) can be utilized to assess suitability of bridge locations by allowing decision makers access to large volumes of spatial data from a multitude of sources (Ardeshir et al. 2014). GIS can help in the determination of suitable and unsuitable locations through data analysis and manipulation. Multiple parameters can be analyzed to determine if they have a higher or lower impact on the results.

Site suitability modeling using raster data is a classic GIS application, utilizing spatial data to identify sites most suitable for a specific use. A site suitability analysis helps to identify suitable sites that meet specific criteria. The results of the site suitability analysis produce a detailed display of the most to least suitable areas for consideration of placement of a certain enterprise, while filtering out unusable or less favorable sites (Kumar and Kumar 2014).

The number of criteria required in a particular analysis depends on purpose, location and circumstances surrounding the area under study (Carr and Zwick 2005). Scale values and a weighting system can be applied to the various levels of suitability to assess the overall suitability for a specific location. The analysis of location suitability is a good method to assist the decision maker to find a better solution that is based on the latest updated geographical information data.

The methodology used in this thesis collectively considers many of the criteria, objectives, and constraints associated with site suitability analysis, while accounting for their relative importance through weighting and scale values. It is implemented to show how the process might be applied using Esri ArcGIS version 10.2.1 to create and overlay the criteria layers and perform the weighted overlay analysis. All GIS work performed in this thesis was administered using Esri ArcGIS version 10.2.1.

This thesis compares alternatives proposed by a site suitability study conducted by Nashua Regional Planning Commission (NRPC) in 2003 to new solutions derived in this thesis through weighted overlay analysis. The methodology of the two analyses is similar, both using specific criteria and weighting to formulate the most favorable location for a new crossing over the Merrimack River. A final comparison of the resulting most suitable bridge locations is done by overlaying all the alternatives from both analyses and assessing how each accomplishes their own criteria.

1.2 Research Objective

The objective of this research was to assess alternatively proposed bridge crossing locations over the Merrimack River between the cities of Nashua, NH and Manchester, NH resulting from two site suitability analysis studies that employ different criteria. A new bridge will provide a unique route across the river so the population of travelers would be well served to better understand the different alternative span locations and the benefits and disadvantages of each site. The results of this research can encourage public participation in the urban decision making process and assist various planners and authorities to formulate a suitable plan for sustained transportation development of the region.

1.3 Outline of the Methodology

The research was accomplished by first establishing criteria. Criteria help identify and reduce the number of solutions that need to be considered by establishing requirements that need to be met. They are derived from needs expressed by customers, experts and users with interest in the outcome of the analysis. Having the correct criteria will help ensure the end result will meet the needs and desires of the users. The criteria used in the NRPC site suitability analysis and the research accomplished in this thesis are found in Sections 2.1 and 3.1 respectively.

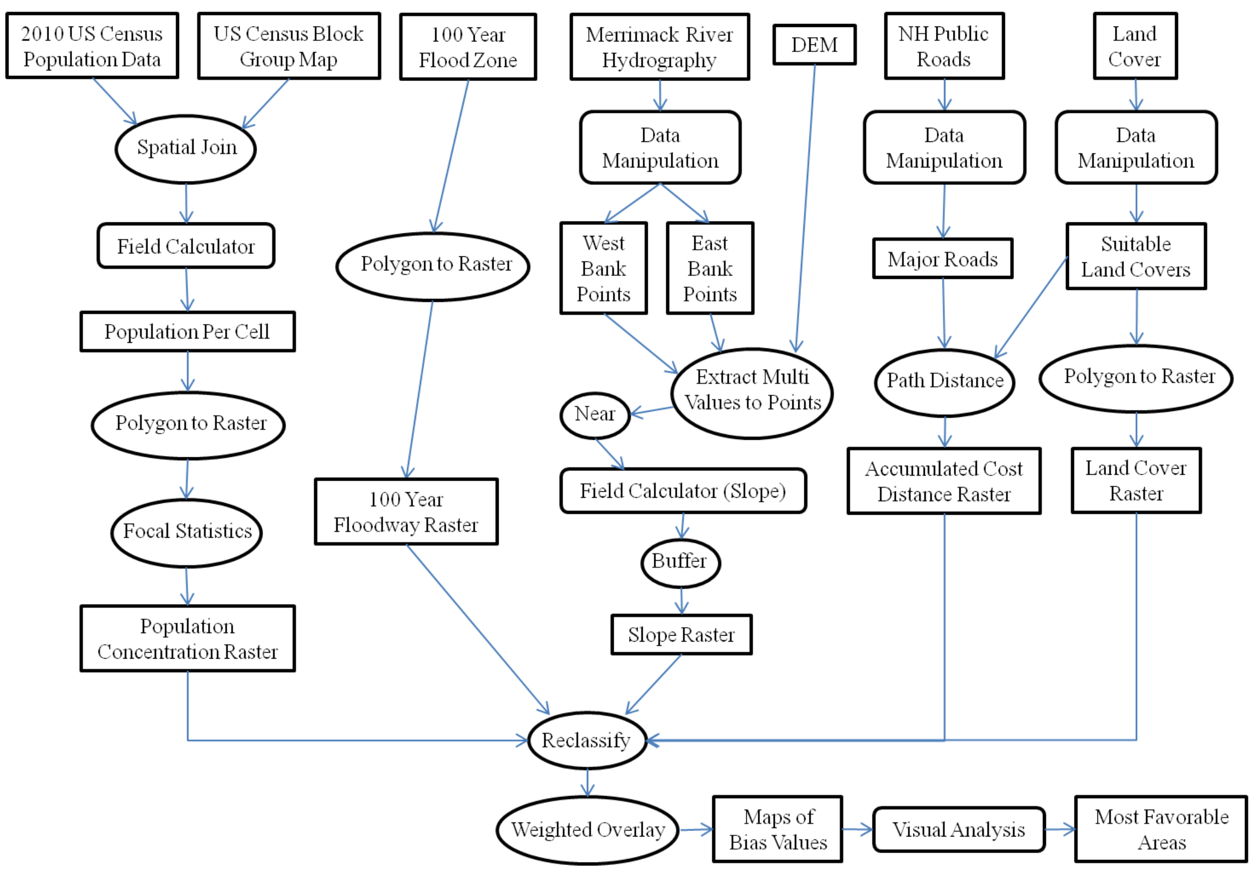

Figure 3: Flowchart of GIS Work

Preparing input layers is the next step in getting the data in a format that can be used in the weighted overlay process. Data must be manipulated into rasters that are standardized by not only projection, but by a consistent scale of suitability. Precise and proper preparation of the input layers will ensure the results are more accurate at the end of the analysis. A flowchart of the entire process is shown in Figure 3. Layers are represented by square rectangles, GIS operations by rounded rectangles, ArcGIS tools by ellipses and order of operations by blue arrows.

Once the input layers are ready for the weighted overlay process, a weight is applied to each of the input layers to represent different biases toward each criterion that are deemed more or less important by the user. The layers are then multiplied by the assigned weighted value and for each cell, the resulting values are added together. Higher values in the output raster generally identify those locations as being the best while lower values are less favorable.

The comparison phase is not so much intended to choose one location over another, but to identify the best suitability for the set of criteria. Rarely is GIS analysis used as a decision making system that dictates a solution, rather it enables the user with the capability to evaluate two different results. The final comparison is done between alternatives identified as favorable in the NRPC site suitability analysis and the locations found most suitable in the weighted overlay analysis done in this thesis.

1.4 Thesis Organization

Chapter One has introduced the background behind the need for a new bridge across the Merrimack River and outlined the methodology and objectives of the past and present studies. Chapter Two offers a background to the site suitability analysis performed by the NRPC and the alternative bridge locations that resulted. Chapter Three identifies the criteria and data preparation of the weighted overlay analysis as well as outlines the standardization and data used in the process. Chapter Four discusses the results of the weighted overlay analyses. It also provides an explanation of the visual process used in determining the most favorable bridge locations and a sensitivity analysis to show the stability of the model. Chapter Five expounds on the comparison of the NRPC Alternatives against the weighted overlay results. Finally Chapter Six discusses the advantages and limitations of the methodology, considers its usability and suggests potential improvements and future work.

CHAPTER 2: PRIOR STUDIES - OVERVIEW AND RESULTS

This chapter provides background regarding bridge location site suitability analysis in general and the analysis performed by the Nashua Regional Planning Commission (NRPC) specifically. The three alternative bridge locations formulated by the NRPC are presented. Also, this chapter provides an overall assessment of the locations of the three alternative bridge locations.

2.1 Alternative Bridge Location Site Selection Methods

Selecting the ideal location for a bridge location is as important as building the bridge itself correctly. Previous studies have used a representation of static, dynamic, deterministic or stochastic mathematical programming models to determine the optimal site location. Static and deterministic location models use fixed criteria, relying on the fact that the demand for a facility in one location will not change (Plastria 2001). On the other hand, dynamic and stochastic location models assume that future values such as environmental factors and population shifts are variable (Owen & Daskin 1998). These formulations attempt to capture the uncertainty of time-dependent input parameters such as forecast demand or geological factors. Other methods such as Multi-Criteria Evaluation (MCE) use a multi-objective programming model to allow the decision maker to take into account present and future goals (Schilling 1980). By using analytic hierarchy process (AHP) or multiple criteria decision making (MCDM) approaches, site suitability analysis produces a detailed display of the most-suitable areas for consideration of placement of a certain facility, while filtering out unusable or less desirable sites (Kumar & Shaikh 2012).

In respect to the bridge site over the Merrimac River, the NRPC performed a site suitability analysis in 2003 formulating three possible locations for a new bridge. The future bridge would be part of a project called the Circumferential Highway, a transportation project first proposed in the late 1950s intended to provide additional crossings of the Merrimack River and mitigate congestion in NH cities of Hudson and Nashua (NRPC 2003). All three alternative sites were derived using the same criteria, though sites differ in overall suitability. The following is a list of criteria used by the NRPC:

1. Must reduce traffic congestion based on NRPC's regional traffic model
2. Road connector to bridge needs to have a posted speed limit of at least 45 miles per hour and the capacity to two lanes
3. Cannot place linkage roadway in the Pennichuck Brook watershed

2.2 Alternative Bridge Locations

The following describes the three primary alternative bridge locations determined by the NRPC. All three use the same NRPC site suitability model to anticipate land development patterns, needs for traffic to move between the origin and destination places in the region and how traffic will be represented in 2025 (NRPC 2003).

2.2.1 NRPC Alternative #1

Alternative #1 is a bridge connecting Concord St and NH 3A near the Hudson and Litchfield border. The NRPC gave the traffic congestion and road capacity criterions higher weighting in this alternative analysis. Figure 4 shows the location determined by the NRPC. A larger version of this map can be found in Appendix A.

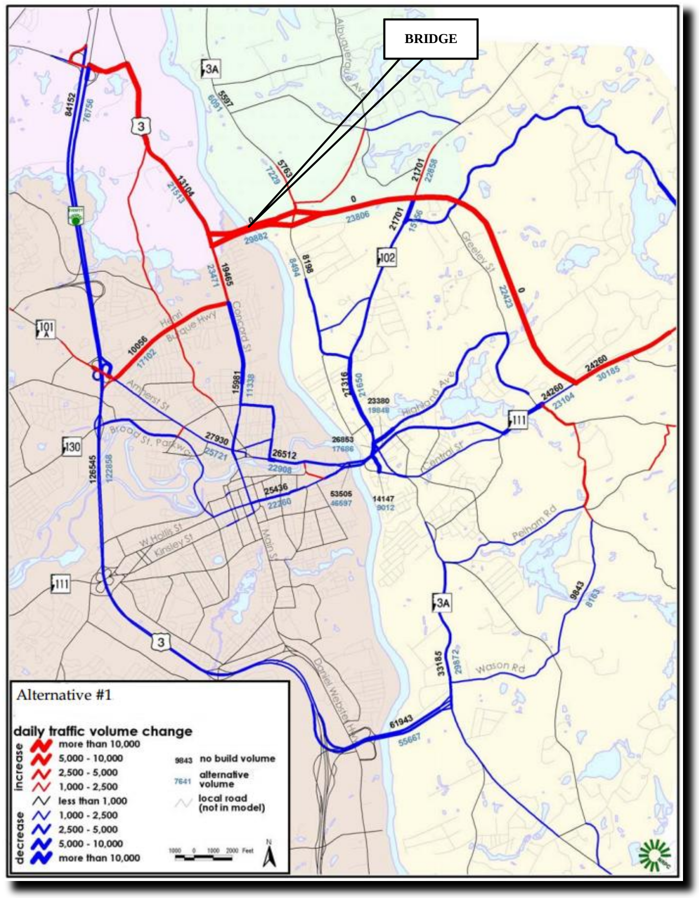

Figure 4: NRPC Alternative #1 Bridge Building Site (Source: NRPC 2003)

2.2.2 NRPC Alternative #2

Alternative #2 prescribes a bridge extending from the east end of Industrial Drive in Merrimack, in a southeasterly direction across the Merrimack River through Litchfield to an intersection with NH 111. This connects the new bridge to the Frederick E. Everett (FEE) Turnpike, a major north-south highway in western NH. The NRPC gave traffic congestion and impacts on the watershed criterions higher weighting in this alternative analysis. Figure 5 shows the second location determined by the NRPC. A larger version of this map can be found in Appendix A.

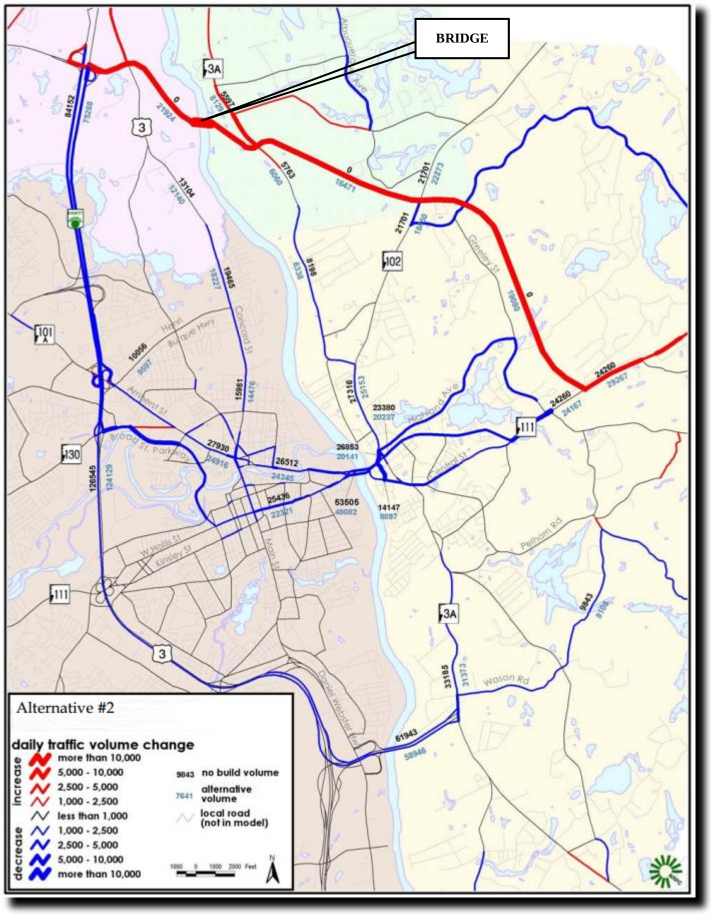

Figure 5: NRPC Alternative #2 Bridge Building Site (Source: NRPC 2003)

2.2.3 NRPC Alternative #3

Alternative #3 proposes a bridge starting at the Henri Burque Highway, extending east across the Merrimack River and ending at NH 111 on the east side of Hudson. The NRPC gave traffic congestion and road capacity criterions higher weighting in this alternative analysis. The location is similar to Alternative #1, though the road linkage is different in order to access another suitable crossing site over the Merrimack River by avoiding the Pennichuck Brook watershed. Figure 6 shows the location of this alternative as determined by the NRPC, and again, a larger version of this map can be found in Appendix A.

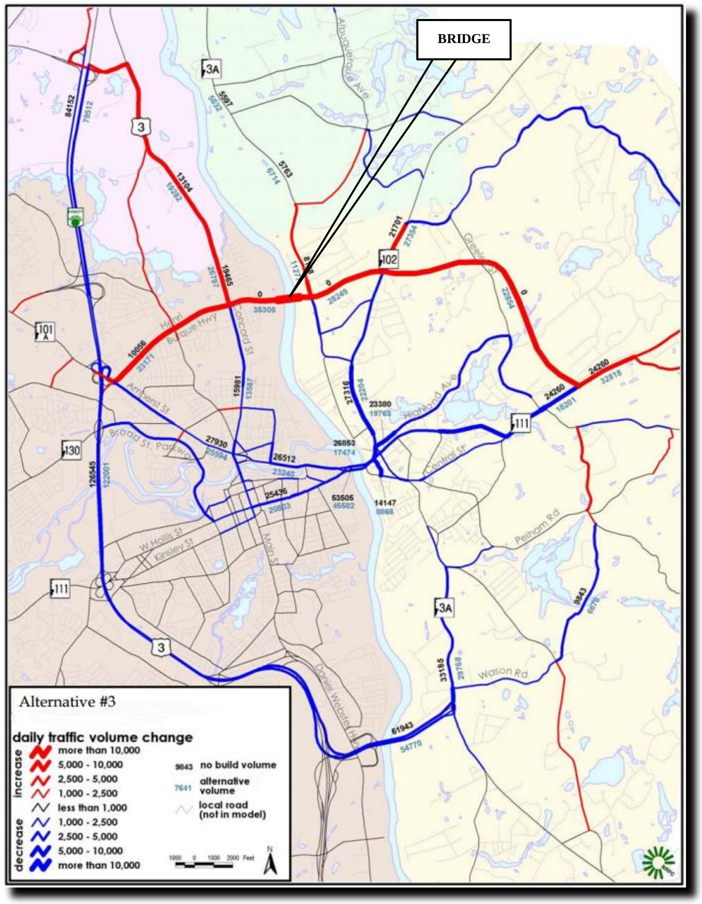

Figure 6: NRPC Alternative #3 Bridge Building Site (Source: NRPC 2003)

2.3 NRPC Site Suitability Analysis

The site suitability analysis accomplished by the NRPC was thorough and resulted in the three alternatives outlined above. Though as stated through their own admission in the NRPC Circumferential Highway White Paper, the alternatives proposed from the site suitability analysis did not always provide the best location. The analysis of the alternatives was weighted heavily on reducing traffic flow and less on the capacity of the road connectors and placement of the linkage roadways outside of the watershed. Often times the new bridge location would decrease traffic rates on major roads but cause detrimental effects on secondary roads feeding the new bridge (NRPC 2003). Also, by building linkage roads directly through the Pennichuck Brook watershed on two of the three alternatives, traffic flow was again lowered by using shorter routes but placed the bridge in an area of low suitability as defined by the third criterion.

Of the three Alternatives submitted, Alternative #1 did produce a future bridge site with fewer impacts on natural and residential environments than the other two Alternatives by using the existing road network and not building any addition linkage roads. Alternative #2 will have substantial right-of-way impacts on agricultural lands and residential development in Litchfield and Merrimack and will also impact important natural resources along the Merrimack River to include a mining pit, wetlands and wintering grounds for the bald eagle shown in Figure 7. Alternative #3 would pass through existing developed areas in both Nashua and Hudson, resulting in intense right-of-way impacts in existing neighborhoods. The location could also potentially impact Alvirne High School in Hudson and surrounding residential areas by locating new supporting roads through school property and rural communities.

Figure 7: NRPC Alternative #2 Right-of-Way Impacts

Alternative #2 does reach its traffic flow objectives but the NRPC forecast that it would never pass the Environmental Impact Statement process due to severe environmental impacts to wetlands and habitat in the project area (NRPC 2003). Alternative #1 also achieved its traffic goals by providing the largest reduction in traffic on the Taylor Falls/Veteran's Memorial Bridges, though its success was built on increasing traffic volumes on the Daniel Webster Highway in south Merrimack, Concord Street in Nashua and the Henri Burque Highway to the highest levels of any other Alternative. Additional problems with NRPC's suggested sites can be shown with the extra bridging needed to span an adjacent rail yard in north Nashua in Alternative #3, which would result in a longer bridge and subsequently increased costs.

The NRPC site suitability analysis does produce three valid alternative river crossings, though the heavy weighting to reduce traffic congestion results in alternatives that are vulnerable in other suitability factors. Different weighting biases should be employed showing weights that favor other criteria instead of primarily the traffic flow reduction. By accomplishing a weighted overlay analysis that incorporates a more varied and balanced weighting of criteria, it will provide the population of southern New Hampshire different options to take into consideration. The next chapter outlines the methodology used here for a site suitability analysis that addresses these varied factors.

CHAPTER 3: IDENTIFICATION OF CRITERIA AND DATA PREPARATION

This chapter outlines the methodology taken to produce the raster layers needed to perform the weighted overlay analysis to re-assess suitable sites for Merrimack River bridges. The process begins with identifying the evaluation criteria and then continues by outlining the processes required to assemble data appropriate for each criteria.

3.1 Identify Criteria

In order to perform the intended analysis, site requirements or criteria are required to assess the overall site suitability. Each criterion can be expressed in varying degrees of suitability for the decision under consideration. Criteria can be considered either a factor or constraint. A factor is a criterion that makes a location favorable for the placement of the facility in question. If a specific criterion is considered a constraint, the constraining attribute values make the location an unfavorable site. The selection criteria used in this study to identify favorable locations for the bridge are:

1. The river crossing should be near population concentrations between the four municipalities of Manchester, Nashua, Litchfield and Merrimack.
2. The new bridge location should be in the vicinity of major roads, not exceeding five miles for ease of linkage.
3. Bridge abutments cannot be located in the 100yr floodway
4. Roadway surface cannot exceed 1% grade between banks
5. Location needs to minimize environmental impacts by avoiding wetlands, forested and residential zones

Each of the criteria is described in detail in the next sections while later sections describe the data sources and preparation of each criterion raster.

3.1.1 Population Concentrations between the Four Municipalities

The river crossing should be located where there are high numbers of nearby residents. It needs to be near the highest cluster of users, or population concentrations of the four municipalities of Manchester, Nashua, Litchfield and Merrimack it would serve. By using population data from the 2010 US Census, population concentrations were found by joining block groups population count data to the study area block groups boundaries. To assess this criterion, a surface was created during the weighted overlay process in which each cell in the study area was given a suitability value based on how many people are within a specified distance of each cell.

3.1.2 Distance from the Nearest Major Road

The new bridge location should be in the vicinity of major roads, not exceeding five miles for ease of linkage. When acting as a connector, the bridge needs to provide access to major roads capable of handling traffic volume that will result from the everyday demand of the river crossing. A major road is defined as a route that provides largely uninterrupted travel and is designed for speeds greater or equal to 45 miles per hour. The Hudson River Bridges are at an optimal location to provide a large population easy access to a river crossing but they only link to secondary city streets. These secondary streets are unable to handle the flow of users trying to access the bridges and cause congestion. The new span needs to connect to major roads in order to facilitate flow of traffic to and from itself. To meet this criterion a surface was created in which each cell in the study area was given a suitability value based on the proximity to major roads.

3.1.3 Bridge Abutments Cannot Be Located in the 100 Year Floodway

The NH Department of Transportation requires all new bridge construction to have the roadway surface over the bridge abutments above the floodway of a 100 year event. Bridge abutments are the substructures at the ends of the bridge deck where the bridge contacts and rests on the banks of the river. In case of flooding, the bridge roadway should not be under water to allow continued use of the bridge through the high water event timeframe. Locations in the 100 Year Flood Zone Map indicate areas prone to flooding if a 100 Year flood occurred. Therefore these would be not suitable locations for the bridge to be located. During the weighted overlay analysis, locations inside the floodway designated area were given restricted values to ensure the final location cannot be located in the 100 Year Floodway.

3.1.4 Roadway Surface Cannot Exceed 1% Grade between Banks

The NH Department of Transportation dictates that the bridge roadway surface cannot exceed a 1% grade. This means that the span between the abutments on the opposing river banks needs to maintain a less than 1% grade so the construction requirements can be met. The slope between locations on opposing banks of the Merrimack River was used to determine if this criterion can be fulfilled at a specific site. During the weighted overlay analysis, the identified locations on opposite banks that have a slope greater than 1% were given restricted values to ensure the final site cannot be located where the grade of the bridge roadway would exceed construction requisites.

3.1.5 Location Needs To Minimize Environmental Impacts

Introduction of new construction always changes the environment around the site, but city planners and engineers try to avoid disturbing fragile or hard to replace natural environments which are most likely to occur in wetlands and forested zones. Similar environmental impacts can be seen to occur when uprooting people. Eminent domain can be exercised but engineers try to avoid positioning a new bridge in the middle of a densely populated residential area. Involuntary resettlement has been shown to cause destructive repercussions on humans to include loss of employment, degraded access to equal housing, marginalization and social disarticulation (Contractor, Madhiwalla, and Gopal 2006). This criterion will be accomplished by avoiding building the bridge in areas that will cause detrimental impacts on both human and animal environments. During the weighted overlay process, suitability values were applied to each different land cover based on impacts that bridge construction could cause on the environment and residents.

3.2 Assemble Relevant Data

Preparations for site investigations include collecting topographical maps, infrared photography, remote sensing images and aerial photographs (Groenier & Gubernick 2008). The process of precisely positioning a river bridge consists of a comprehensive study of preliminary engineering, hydrology and hydraulics, roadway alignment, along with environmental and geological surveys (Groenier & Gubernick 2007). The objective of this thesis though is not to identify an exact final location for a new river crossing, but to show where the suitable locations are for a potential final plat.

Once the criteria used to measure the degree a particular objective(s) is being met are determined, data are sought that may be used to represent these criteria. All data was gathered and stored in a geodatabase that could be manipulated in ArcMap 10.2.1 for suitability value assessment. The following sections detail the data layers used in the GIS analysis.

3.2.1 Merrimack River Hydrography

The New Hampshire Hydrography Dataset (NHHD) contains stream segments that make up the surface water drainage system for the Merrimack River. It also includes flow direction, names, stream orders and centerline representations for areal water bodies. The hydrography dataset was used to reference the location of the Merrimack River and its tributaries. Metadata for the NHHD is shown below in Table 1.

Table 1: Merrimack River Hydrography Dataset Metadata

Source	NH GRANIT: New Hampshire's Statewide Geographic Information System (GIS) Clearinghouse, retrieved from http://www.granit.unh.edu/
Originator	Complex Systems Research Center, University of New Hampshire
Format	Personal Geodatabase Feature Class (.gdb)
Date of compilation	Jan 2006

3.2.2 Digital Elevation Model (DEM)

The Digital Elevation Model (DEM) is a terrain elevation data set in a digital raster form consisting of regularly spaced grid of elevation points. The standard DEM consists of a regular array of elevations cast on a designated coordinate projection system. Elevation data was used to calculate slope between the opposing locations along the banks of the Merrimack River to determine if the roadway surface grade criteria could be met. Metadata for the DEM is shown below in Table 2.

Table 2: Digital Elevation Model (DEM) Metadata

Source	Downloaded through the National Map Viewer (http://nationalmap.gov)
Originator	US Geological Survey
Format	Digital Elevation Map (DEM) Raster
Resolution	1 Arc Second (approximately 30 meters)
Date of compilation	04 Feb 2014

3.2.3 100 Year Flood Zone

A 100 year Flood Zone is derived from Flood Insurance Rate Maps (FIRM) produced by the Federal Emergency Management Agency (FEMA). The 100-year flood is referred to as the 1% annual exceedance probability flood, since it is a flood that has a 1% chance of being equaled or exceeded in any single year. The NH Department of Transportation requires all new bridge construction to have the roadway surface over the bridge abutments above the floodway of a 100 year event. The flood zone data was utilized to determine if the 100 year flood zone criteria could be met. Metadata for the 100 Year Flood Zone is shown below in Table 3.

Table 3: 100 Year Flood Zone Dataset Metadata

Source	Federal Emergency Management Agency (FEMA)
Originator	Federal Emergency Management Agency (FEMA)
Format	Shapefile Line Feature Class (.shp)
Date of compilation	05 Dec 2011

3.2.4 NH Public Roads

The NH Public Roads dataset is a statewide dataset containing the location of state, local and selected private roads in NH and their associated attributes, including road names. Rural and urban arteries, interstates and collectors as well as local and public roads are included in the data. This dataset was utilized to analyze the location of major roads in respect to proximity of favorable river crossing locations. Table 4 shows metadata for the dataset.

Table 4: NH Public Roads Dataset Metadata

Source	NH GRANIT: New Hampshire's Statewide Geographic Information System (GIS) Clearinghouse, retrieved from http://www.granit.unh.edu/
Originator	NH DOT Bureau of Planning and Community Assistance
Format	Shapefile Line Feature Class (.shp)
Accuracy	Horizontal accuracy of approximately 12 meters
Date of compilation	30 Sep 2013

3.2.5 Land Cover

National Land Cover Database (NLCD) classification schemes are based primarily on a decision-tree classification of circa 2011 Landsat satellite data along with ancillary data sources, such as topography, census and agricultural statistics, soil characteristics, wetlands, and other land cover maps. NLCD 2011 keeps the same 16-class land cover classification scheme that has been applied consistently across the United States in previous years. The data used in this thesis was from the National Land Cover Database (NLCD) map of Superzone 13, which covers all of New England and Mid-Atlantic US. Table 5 shows metadata for the dataset.

Table 5: Land Cover Dataset Metadata

Source	Downloaded through the National Map Viewer (http://nationalmap.gov)
Originator	US Geological Survey
Format	Shapefile Polygon Feature Class (.shp)
Resolution	Spatial resolution of 30 meters across the conterminous U.S.
Date of compilation	04 Apr 2014

3.2.6 Population Dataset

Population data presented in Census block groups was used in the calculation of population density in the thesis research. Census block groups are geographical units used by the US Bureau of the Census to collect and tabulate decennial census data. They are bounded by streets, roads, railroads, streams and other bodies of water, other visible physical and cultural features (US Census Bureau 2010). Population data is released by the Census in a comma-separated values (CSV) table format and needs to be joined to a block group map in order to use the population data in spatial analysis. Table 6 shows metadata for the dataset.

Table 6: Population Dataset Metadata

Source	2010 US Census
Originator	US Census Bureau
Format	Joined Shapefile Polygon Feature Class (.shp) and CSV table
Spatial Unit	Census Block Groups
Date of Collection	01 Apr 2010
Date of Compilation	19 Aug 2014

3.3 Standardization

When aggregating spatial data in an overlay analysis, the coordinate systems of all layers need to be uniform. The Projected Coordinate System used for all the layers in this analysis was the NAD 1983 StatePlane New Hampshire FIPS 2800 (Meters). All datasets were projected to this coordinate system to ensure proper integration during the various integrated analytical operations.

All the final rasters used for input to the overlay analysis needed to have a uniform spatial resolution, or cell size. Determining the appropriate cell size is a balance of resolution and higher spatial accuracy with faster processing and display as well as smaller file size. Since the bridge is the primary focus of the spatial analysis, the cell size would need to be large enough to appropriately cover the lanes of a span while remaining small enough in size to have the spatial accuracy needed to determine features impacting the construction of a two to four lane bridge. 30 meters was decided to be the scale of analysis as that is approximately the distance across a two lane road. The 30 meter scale provides resolution small enough to capture roadway influences, while at the same time being large enough to not cause data or file size problems.

To ensure the cell alignment of all final rasters, a Snap Raster was used during the processing of the raster. A workable area was clipped out of the available data to include the area of prime interest. This clipped section makes certain the area of study was included in the processed area while also eliminating the need to crunch data that would never be used in the spatial analysis due to its distance from the study area. A raster was made from the clipped region, with cell size the prescribed 30 meters, and designated the Snap Raster. Through the environment settings in ArcGIS, the output extent can be ensured to be the same as the Snap Raster. By using the Snap Raster in creating all the final rasters, it ensures the output cell size of all process rasters is the same as the snap raster cell size, as the cells in the output rasters are all aligned with the cells of the Snap Raster.

To perform the final weighted raster overlay process, each criterion can be expressed in varying degrees of suitability for the decision under consideration. This can be done by reclassifying the data values into a common range of values. The range of 1 to 9 was used with "1" being Restricted and 9 being the Highest Suitability. For example, distance from the nearest road would be treated not as a Boolean statement all-or-none buffer zone of suitable locations, but rather, as a continuous expression of suitability according to a special range of values. A Boolean constraint can also be used if a criterion has a yes/no tolerance (Eastman 1999), where the Restricted suitability value is assigned with the no value. Table 7 shows all the Suitability Values and corresponding definitions.

Table 7: Suitability Values

Suitability Value	Definition
1	Restricted
2	Lowest Suitability
3	Lower Suitability
4	Low Suitability
5	Moderately Low Suitability
6	Moderately High Suitability
7	High Suitability
8	Higher Suitability
9	Highest Suitability

3.4 The 100 Year Floodway Raster

The 100 year floodway criterion states that the bridge abutments cannot be located in the 100 year floodway. This drives a Boolean dataset with only two possible values, outside the floodway (suitable) or inside the floodway (not suitable). Creating a raster dataset for this criterion was relatively straight forward. The polygon for the 100 year floodway was converted into a raster (ArcGIS Polygon to Raster Tool [Conversion]). The raster was reclassified (ArcGIS Reclassify Tool [Spatial Analysis]) with values inside the polygon assigned a value of 1 and values outside a 9. Figure 8 shows the final reclassified raster dataset for the 100 year floodway.

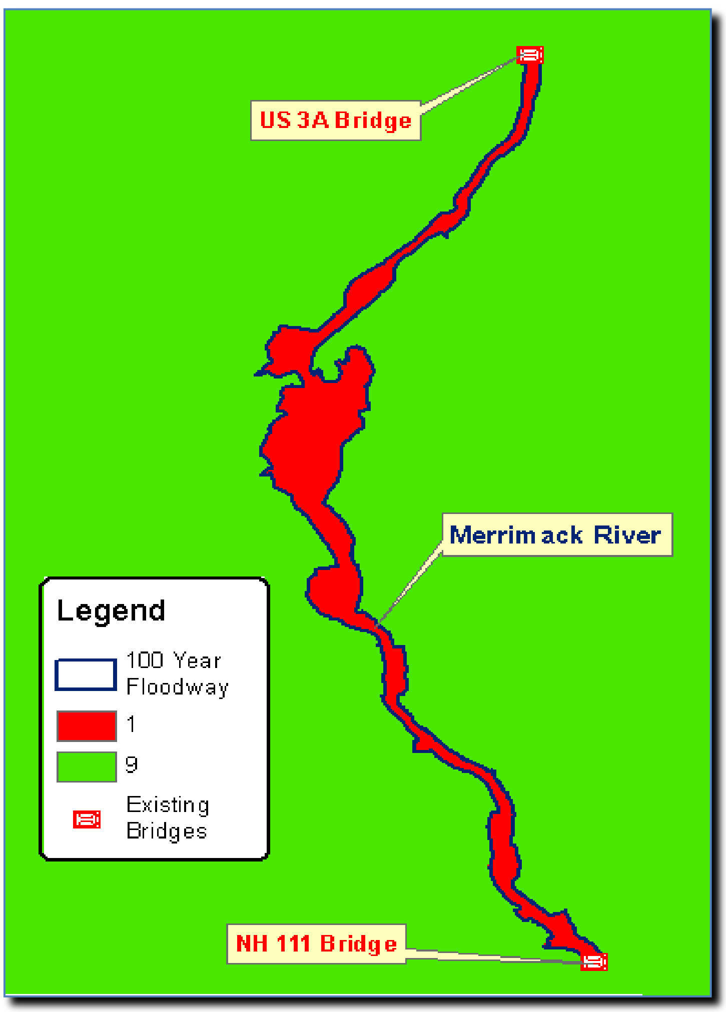

Figure 8: Final 100 Year Floodway Raster Dataset

3.5 Slope Between Opposite Riverbanks

In order to determine if the slope of the roadway surface between the opposing banks of the river meets the criterion of not exceeding a 1% grade, the elevations of the locations along the river banks was needed. The distance between locations opposite each other on opposing river banks was also required to calculate the slope between them. Since the bridge abutments could not be built in the 100 year floodway, the location of the usable river banks would need to be determined by the area of the 100 year floodway. Figure 9 shows the Merrimack River and the expanded riverbanks caused by the 100 year floodway.

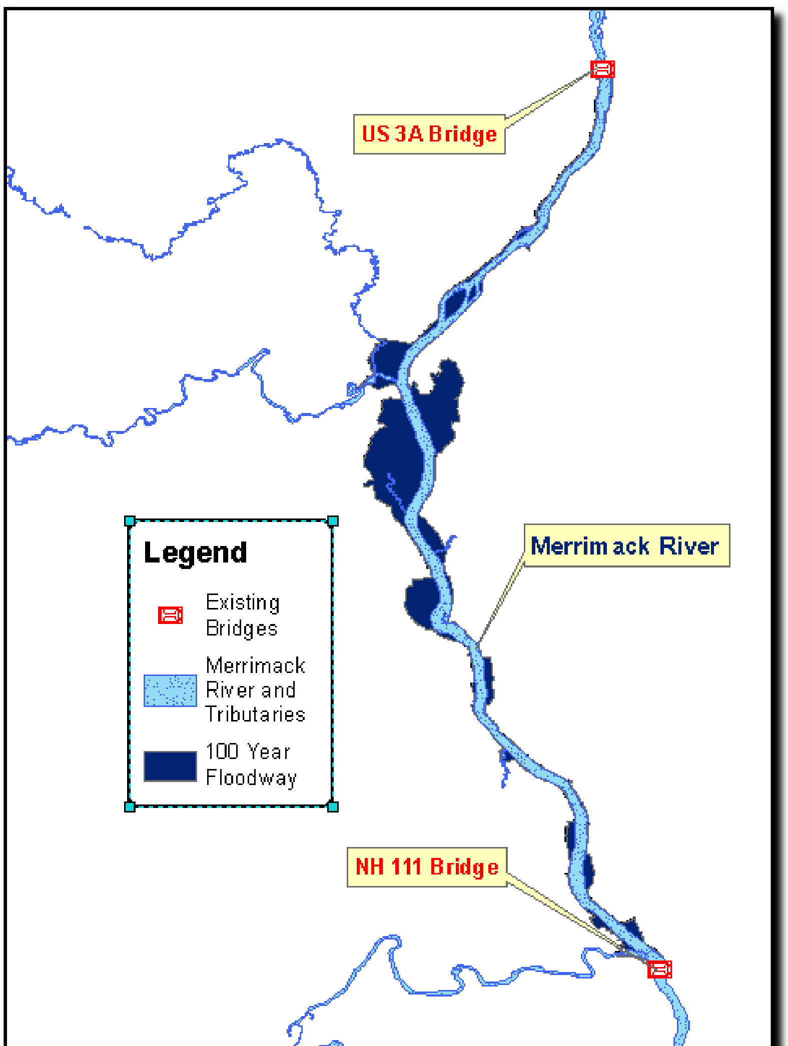

Figure 9: Merrimack River and 100 Year Floodway

To fully capture the extent of the 100 year floodway, positions every 30 meters were plotted along the outside edge of the 100 year floodway along the river. Then by using the elevation raster, the value of the cell corresponding with each of these locations along the banks was recorded to the attribute table of the point feature class (ArcGIS Extract Mutli Values Points Tool [Spatial Analyst]).

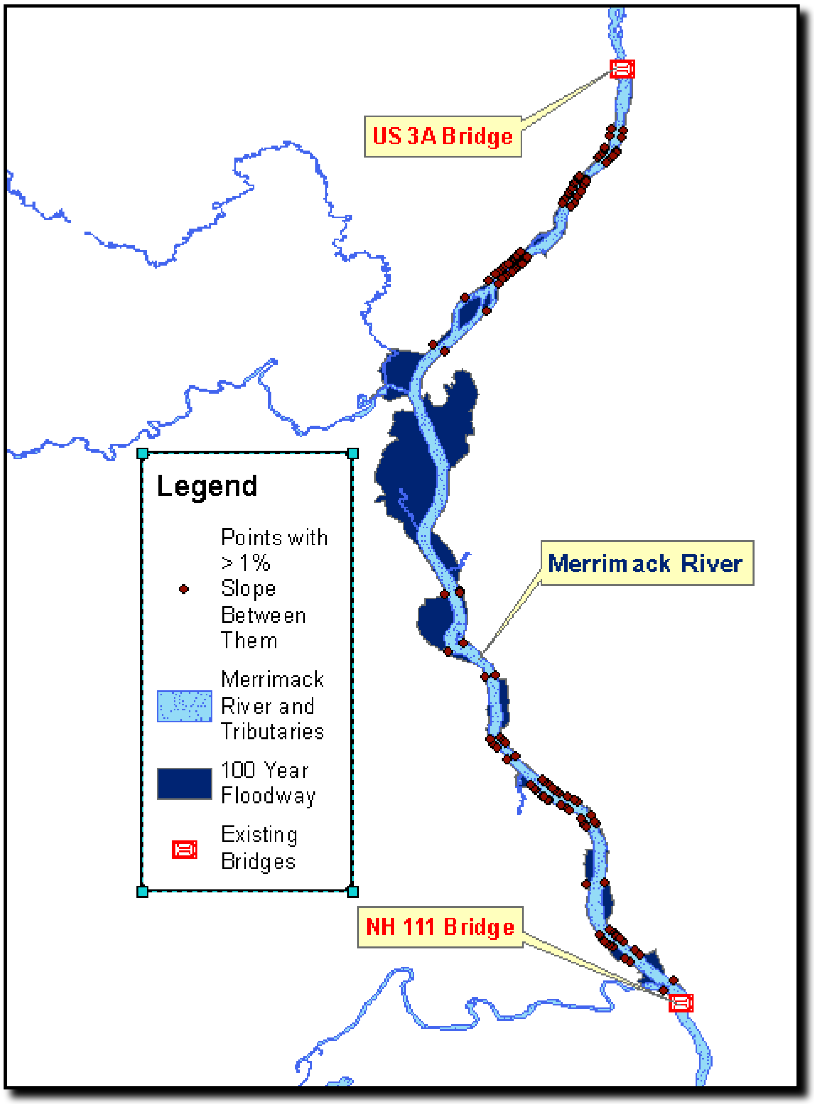

Figure 10: Points with > 1% Slope between Them

Next, the nearest point on the west side of the river was found for each point on the east side (ArcGIS Near Tool [Analysis]). This process adds both the ID of the nearest west side point and the distance from it to the east side point attribute table. Then, by joining this west side points by ID to the east side points, the elevation of both sides of the river and the distance between them can be used to get the slope from any east side point to the nearest west side point. Slope was calculated between the joined points by using the difference in their elevations divided by their distance apart. Points with greater than 1% slope between them were identified and can be seen in Figure 10. The points were buffered (ArcGIS Buffer Tool [Analysis]) out to 30m to ensure they included any roadway surface that would be built over them. The resulting polygons from the buffering were converted into a raster dataset (ArcGIS Polygon to Raster Tool [Conversion]).

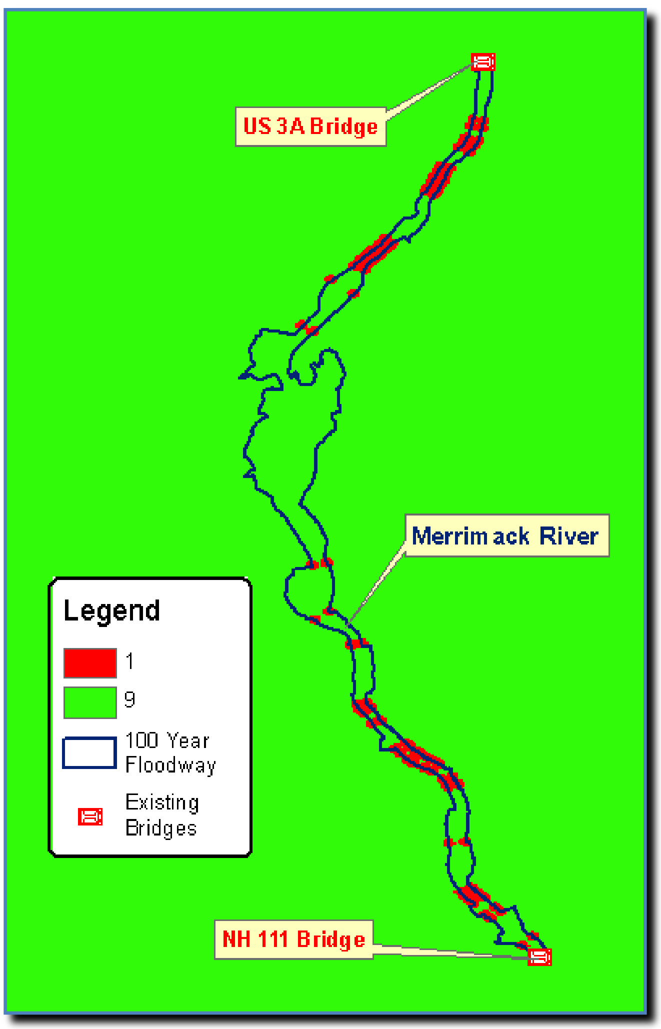

Figure 11: Final Slope Raster Dataset

The final step was to reclassify (ArcGIS Reclassify Tool [Spatial Analysis]) the values in the raster. Since the data type for this criterion is Boolean with only two possible values, < 1% grade (suitable) or > 1% (not suitable), values inside the polygons were assigned a value of 1 and values outside a 9. Figure 11 shows the final reclassified raster dataset for the slope criterion.

3.6 Land Cover

The physical and biological cover over a parcel of land can be a big determinant of how it is used for current or future activities. If the parcel has already been disturbed by human action, it is considered more readily available for continued human use than non-disturbed areas. Residential zones are the home environment to humans, in the same manner that forests are the domiciles to deer, raccoons, birds, moose, etc. So when the criteria states that the bridge location should minimize environmental impacts, this specification means impacts to both natural and human areas.

In building a raster layer, the first step was to identify what types of land covers could be used that would not cause a big environmental impact. From the available NLCD, the land covers were assessed on whether construction would cause detrimental environmental effects to natural or human habitats. Table 8 shows the available land covers that were included in the dataset and the rationale for their inclusion / exclusion into the availability to be considered as a bridge construction site.

Table 8: Available Land Covers and Availability to Build

Land Cover Type	Rationale	Availability to Build Bridge on
Residential / Commercial	Do not want to uproot residents or businesses	Cannot build on
Open Wetlands	Cannot destroy wetland environment	Cannot build on
Forested Wetlands		
Beech / Oak	Do not want to disturb	Cannot

Land Cover Type	Rationale	Availability to Build Bridge on
Paper Birch / Aspen	standing timber / forests	build on
Other Hardwoods		
White / Red Pine		
Spruce / Fir		
Hemlock		
Mixed		
Orchards	Do not want to remove standing trees	Cannot build on
Water	Need to build bridge over river	Can build on
Hay / Pasture	Land disturbed by humans to raise non-indigenous plants and or livestock	Can build on
Crops	Land disturbed by humans to raise non-indigenous plants	Can build on
Other	Miscellaneous land disturbed by humans	Can build on
Transportation	Existing roads	Can build on
Disturbed	Land disturbed by humans during past event that left the parcel changed from natural habitat	Can build on

The criterion's objective is to utilize land covers that would cause only minimal impact on the environment. The use of wetlands, forested and residential zones were made unavailable to meet the intention of the criterion. The Pennichuck Brook watershed, on the western side of the Merrimack River between the towns of Merrimack and Nashua, consists of wetlands and forested land and therefore it was not set as suitable and consequently avoided. Tearing down houses and deforestation are not minimal environmental impacts.

Despite the fact the bridge needs to span water, its abutments cannot actually be built in water. The water land cover cannot be totally excluded because the bridge will cover some section of water for the end result, but any possible locations cannot be located in the middle of a water land cover. Setting a scale value to Restricted assigns a value to a cell in the output weighted overlay result that is the minimum value of the evaluation scale set, minus 1. This will ensure that no water type land covers will be identified as suitable locations but will not eliminate the areas as potential span areas. Making the water unsuitable would exclude viable areas from suitability consideration.

For the areas that were deemed buildable, it is next necessary to rank them in terms of suitability. Transportation and Disturbed areas have the highest suitability as both have already been impacted by man and are the cheapest and most feasible for construction. Areas designated as Other were set with High Suitability as these areas have been disturbed by man at some point in history, but may still have the potential to be returned their natural environment. Hay/Pasture and Crop areas were deemed buildable areas but only given a Moderately High Suitability as it is more favorable to raise crops and hay on these parcels than to be the location of supporting roadwork or the span itself. Table 9 shows the land covers that could be used and their suitability level of little or no environmental impact.

Table 9: Selected Land Cover Types and Assigned Scale Values

Land Cover Type	Scale Value	Suitability Level
Water	**1**	Restricted
Hay / Pasture	**6**	Moderately High Suitability
Crops	**6**	Moderately High Suitability
Other	**7**	High Suitability
Transportation	**9**	Highest Suitability
Disturbed	**9**	Highest Suitability

Once the buildable land covers were identified, a layer was built that only included the land covers listed in Table 8. This layer was converted into a raster (ArcGIS Polygon to Raster Tool [Conversion]) and reclassified (ArcGIS Reclassify [Spatial Analysis]) with the scale values shown once again by Table 8. White areas on the map are locations where the land cover was deemed unsuitable. They were removed from further consideration in this analysis by setting the associated pixel values to NULL. Figure 12 shows the final reclassified raster dataset for the land cover criterion.

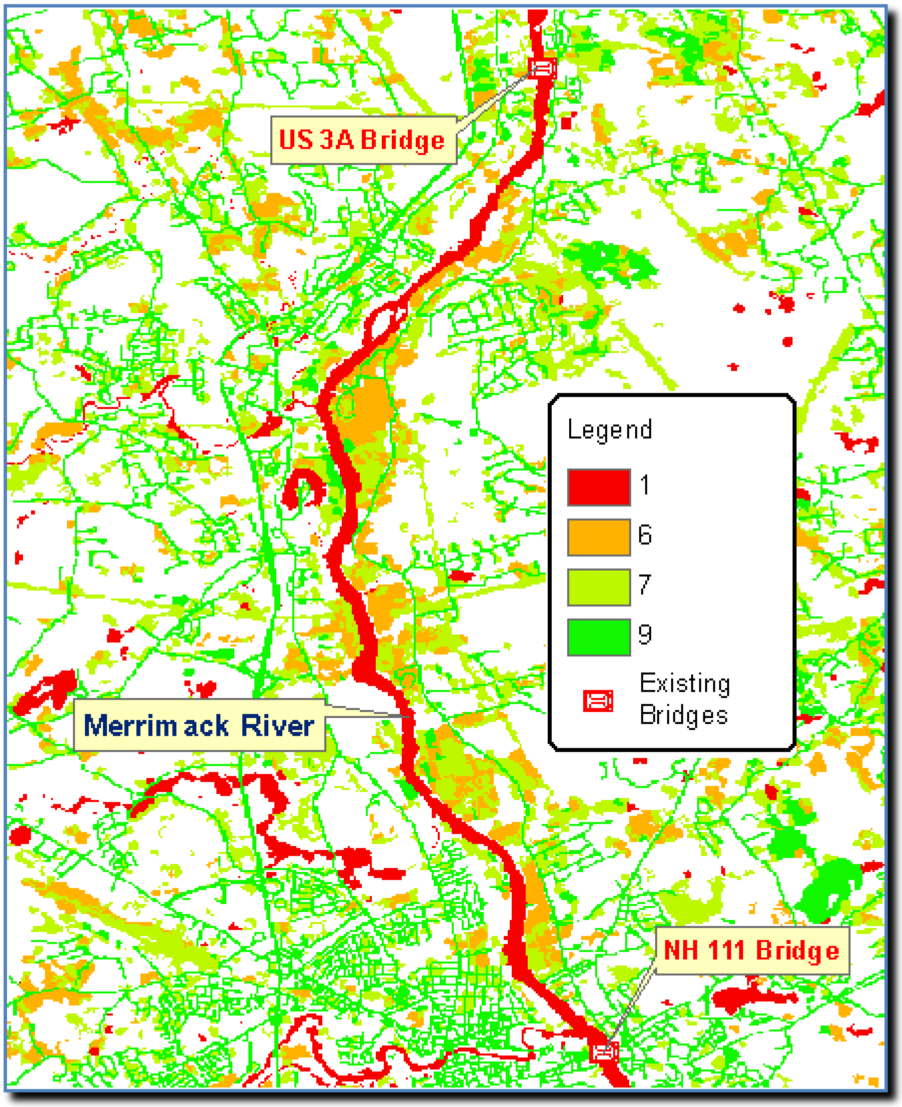

Figure 12: Final Land Cover Raster Dataset

3.7 Distance from the nearest Major Road

In order to properly handle the flow of traffic, the new bridge location needs to be in the vicinity of major roads, not exceeding five miles for ease of linkage. To best incorporate this criterion into the spatial analysis, a dataset with suitability values that correspond to the proximity to a major road was needed. Major roads were those considered to be principal arteries or collectors of the roadway network in the study area. Table 10 shows the classes of roads from the NH Public Roads dataset that were included as major roads.

Table 10: Major Road Classes

Road Class	Definition
17	Urban Collector
16	Urban Minor Arterial
14	Urban Principal Arterial - Other
11	Urban Principal Arterial - Interstate
7	Rural Major Collector
6	Rural Minor Arterial
2	Rural Principal Arterial – Other
1	Rural Principal Arterial - Interstate

There are three major roads, the Everett Turnpike, US Route 3 and NH Route 3A, that run north and south parallel to the Merrimack River. The Everett Turnpike and US Route 3 are located on the western side of the river, acting as the major connectors for local and transient traffic between the large metropolitan areas of Nashua and Manchester. NH Route 3A is a major thoroughfare on the eastern side of the river, providing the same access to the major urban areas though more for the local population in the region. Since these three major roads parallel the Merrimack River and have equal opportunity for connection to a crossing point anywhere along their path, they were removed from the major road dataset. The connector roads that need to be considered are those running east and west, as those are the arteries that will bring traffic flow to a river traverse. Proximity to where the east and west running roads intersect the river is the primary influence on the placement of a new bridge. A line shapefile was created consisting of all major roads and can be seen in Figure 13.

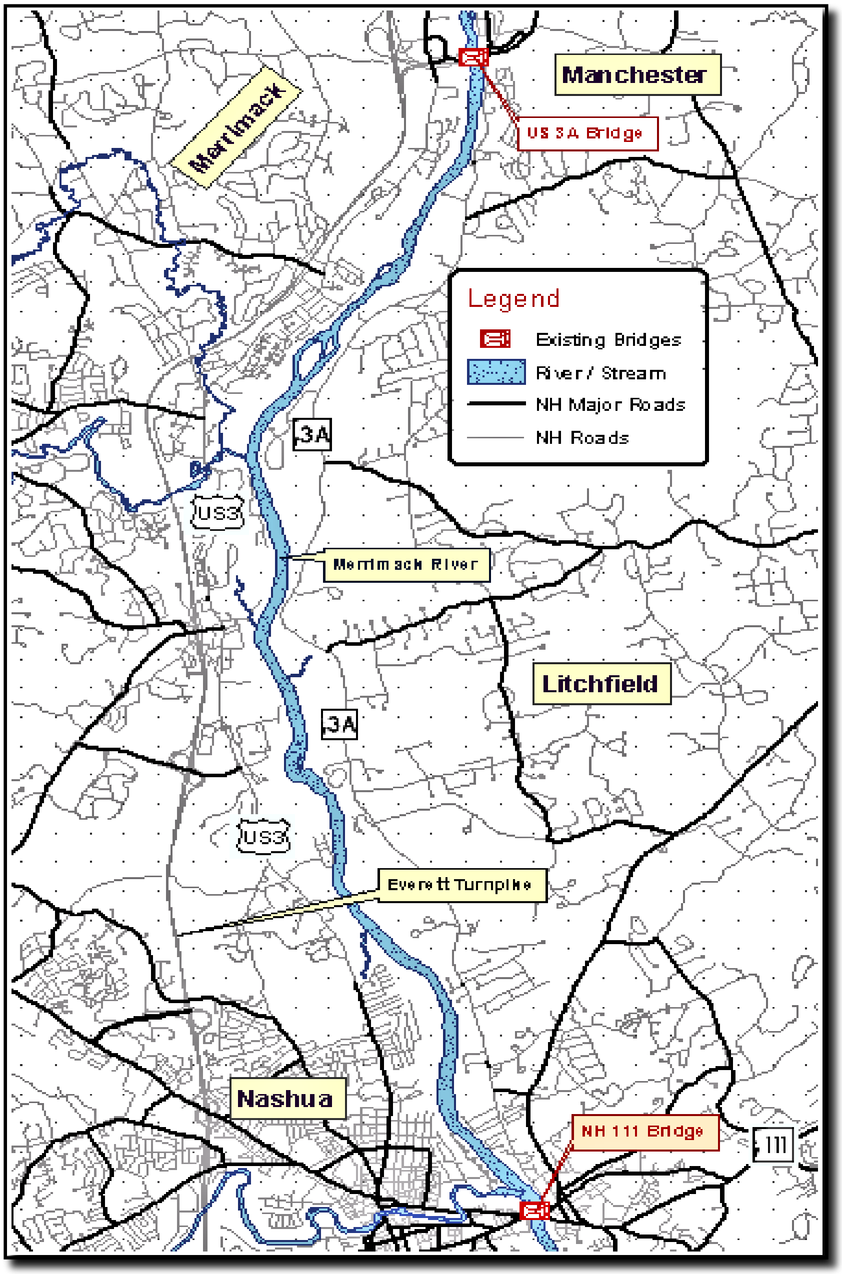

Figure 13: Final Road Dataset

Once the major roads were identified, the distance of each location to the nearest road needed to be assessed. Of course, in the real world, roads are not built in straight lines. Rather, they are constructed around natural barriers such as waterways and terrain. For this analysis, unsuitable land cover also acted as barriers to straight-line travel since access roads would not be built across these areas. In order to take into account this non-Euclidean distance, the raster dataset for this criterion was built using a distance with barriers. A path distance tool (ArcGIS Path Distance [Spatial Analysis]) was used to create a raster in which the assigned cell values are the accumulative distance of traveling through adjacent cells to the nearest road, avoiding areas with restricted land cover types (set as NULL). Figure 14 shows the values of the accumulated cost distance through adjacent, not NULL cells to the nearest major road.

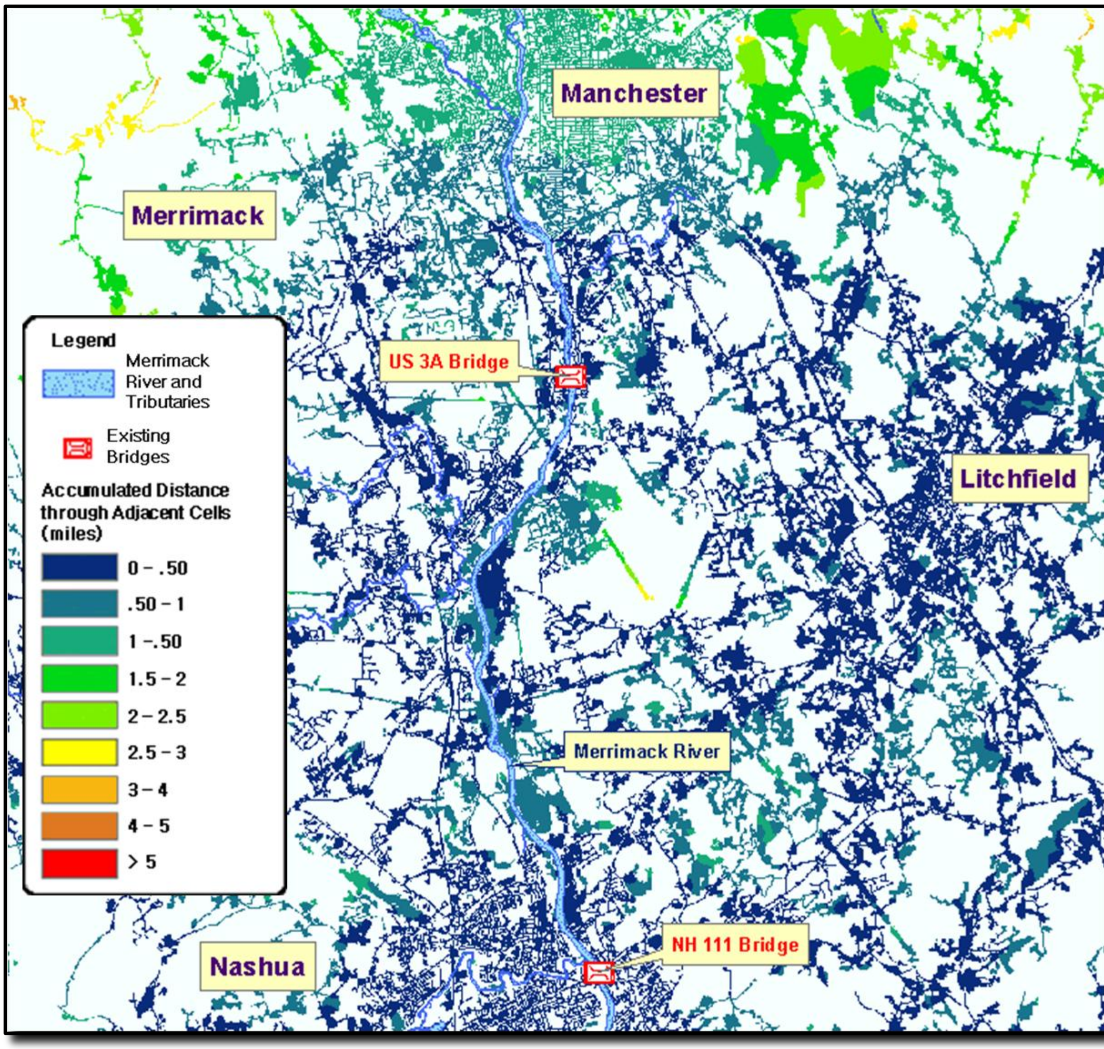

Figure 14: Accumulated Cost Distance through Adjacent Cells

The major roads shapefile and land cover raster were used to produce this raster. The raster was reclassified (ArcGIS Reclassify [Spatial Analysis]) with scale values from 1 to 9, with 1 being the least suitable and 9 being the most. Suitability was determined by the proximity to a major road, with the highest suitability being the closest (most accessible) and the lowest suitability assigned to the largest distances with values decreasing by a simple linear decay function. No cells had distances greater than 5 miles so there was no need to eliminate any as unsuitable. Figure 15 shows the final reclassified raster dataset for the distance to major road criteria. The effect of the barriers caused by land cover patches through which travel is not permitted (white areas) is evident in the isolated red and yellow areas.

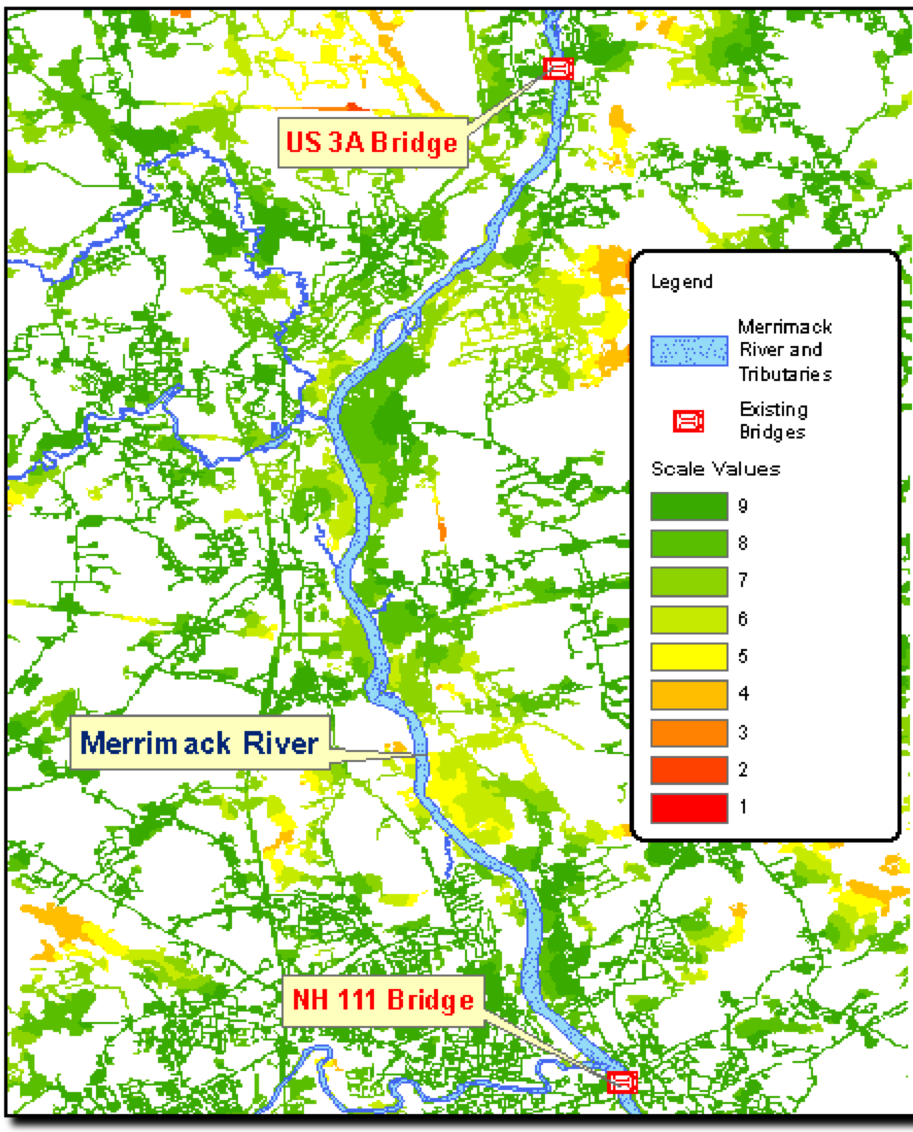

Figure 15: Final Road Raster Dataset

3.8 Population Concentration

In order to serve the highest number of people, the bridge should be located where there are high numbers of nearby residents. Areas where people are clustered together are called population concentrations. Data from the 2010 US Census was utilized to find the population concentrations by first joining (ArcGIS Spatial Join [Analysis]) block groups population count data to the study area block groups boundaries, shown in Figure 16.

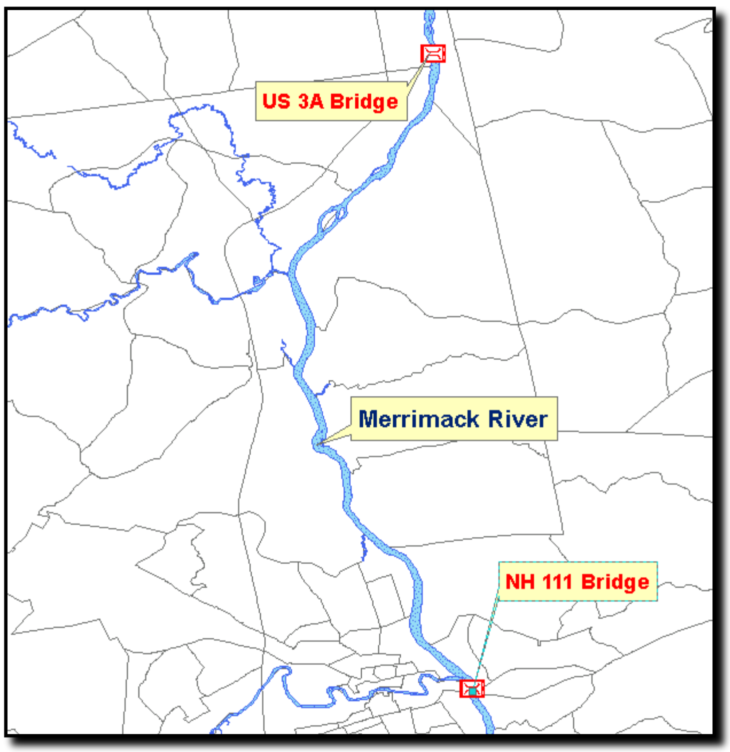

Figure 16: US Census Block Groups across Study Area

To determine the population concentration for each cell, it was necessary first to generate a raster in which population counts could be assigned to each cell. The population counts for each block group were first converted to density per square meter using the field calculator. Since the size of the eventual raster cell would be 30 meters by 30 meters, the field calculator was again utilized to multiply that value by 900, resulting in a density value of people per 900 square meters assigned as an attribute to each of the block group polygons. Finally, the polygon shapefile was converted to a raster (ArcGIS Polygon to Raster Tool [Conversion]), allowing the block group density attribute value to be equal to the count of individuals in each cell. Figure 17 shows the results of the raster conversion and the resulting population per cell created from the US Census block group population counts.

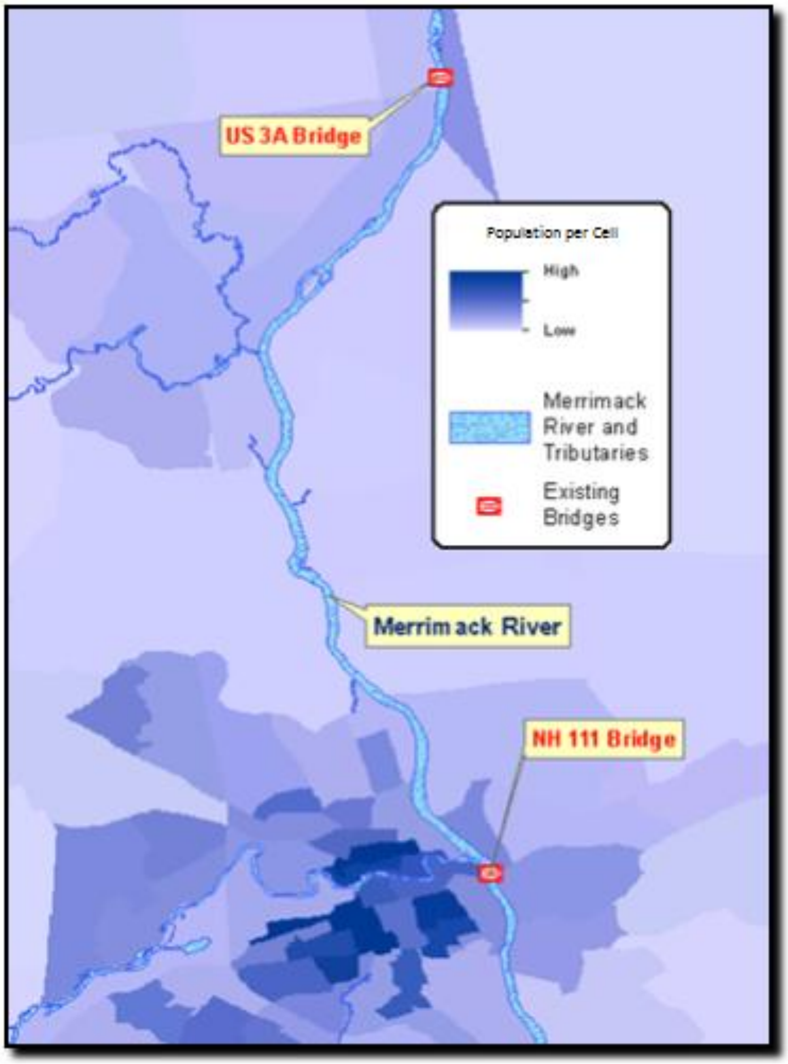

Figure 17: Raster Display of Population per Cell

The last step was to employ the focal statistics tool (ArcGIS Focal Statistics [Spatial Analysis]) to produce an output raster where the value for each output cell is a function of the sum of all values in a specified neighborhood around the input cells. The desired vicinity was approximately one kilometer so a 30 x 30 cell neighborhood was used to create the final raster.

The resulting raster values then indicate how many people are within approximately one kilometer of each cell. The raster was reclassified (ArcGIS Reclassify [Spatial Analysis]) with scale values from 1 to 9, with 1 being the least suitable and 9 being the most. Suitability was determined through a linear function by the amount of population, with the highest suitability being the greatest numbers and subsequently the lowest suitability with the smallest. Figure 18 shows the final reclassified raster dataset for the population criteria.

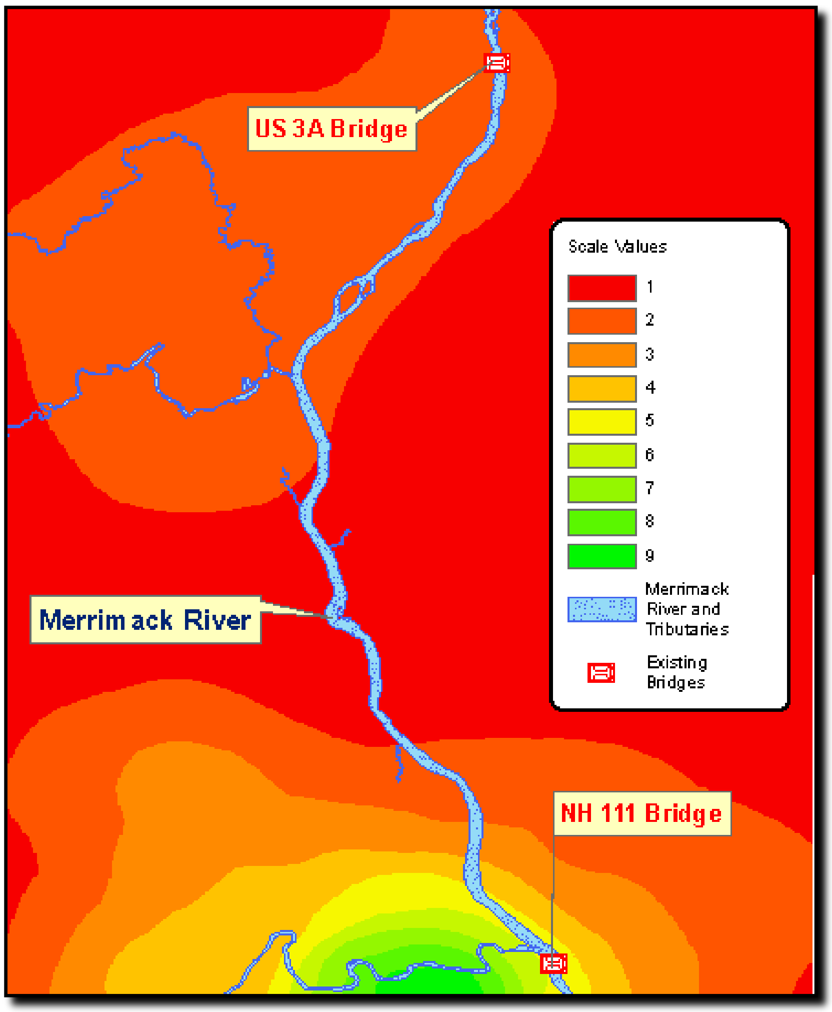

Figure 18: Final Population Concentration Raster Dataset

With the set of criteria rasters standardized, proceeding onto the weighted overlay analysis was now possible. The next chapter discusses the weighted overlay analysis process and the output derived from the different biases implemented.

CHAPTER 4: WEIGHTED OVERLAY ANALYSIS AND RESULTS

This chapter discusses the weighted overlay analysis and its results. While conducting the overlay analysis, influence percentages were sequentially modified to reflect different biases resulting in different outcomes regarding favorable bridge locations. The chapter also includes an explanation of the visual process used in determining the most favorable bridge locations and a sensitivity analysis to show the stability of the analysis model.

Weighted overlay analysis commonly is used to solve multi-criteria problems such as optimal site selection or suitability modeling. It is a technique for applying a common scale of values to diverse and dissimilar inputs to create an integrated analysis that begins with a set of standardized raster layers that are reclassified with the common evaluation scale. During the overlay calculation, the cell values in each raster are multiplied by a weighting percentage representing the importance of that criterion to the final suitability result. Finally, each of these weighted values is summed for each cell. The result is a raster whose cell values represent the suitability. Higher values generally indicate that a location is more suitable.

In this weighted overlay analysis, four different biases were assessed by changing the weighting percentages. The analysis allows the various factors to have different importance by adjusting the weighting percentage. These biases implemented are:

1. Equal Weights - No bias with all weighting percentages equal
2. Environmental Bias – Bias towards lessoning environmental impact
3. Engineering Bias – Bias with higher weighting on construction criteria
4. Transportation Bias – Bias on roads and population the traffic network would serve

Each of these is expanded on in separate sections below. A section to explicate the process for selecting suitable bridge locations based on the results of the weighted overlay analysis also follows.

4.1 Weighted Overlay with Equal Weights

For the first weighted overlay (ArcGIS Weighted Overlay Tool [Spatial Analyst]), the same weighting percentage was applied to all the selection criteria as shown in Table 11. By using a uniform weight, the resulting map has no bias towards any of the selection criteria since it uses each equally toward modeling the suitability. Figure 19 shows the resultant overlay.

Table 11: Selection Criteria and Associated Weighting Percentage for the Equal Weights Weighted Overlay

Selection Criteria	Weighting Percentage Used
Central to Populations of Four Municipalities	20%
Distance to Nearest Major Road not Exceed 5 miles	20%
Bridge abutments cannot be located in 100yr floodway	20%
Roadway surface cannot exceed 1% grade between banks	20%
Location needs to minimize environmental impacts	20%

Using a process of visual analysis that is described in detail in the following section, two suitable areas were found, 1.5 miles north of the Hudson Bridges (Inset #3) and just upstream from Reed’s Island in Merrimack, NH (Inset #2). The first area is inside the network of major roads and populace of Nashua, making the land suitable for building a structure across the river as the area has already been urbanized. The second area also has urbanization and a robust road network down to the river banks on both sides, though it is farther from a major population. Both locations are also outside the 100 year floodway and any slope restrictions, resulting in good, suitable locations. With equal weights for each criterion, there is no distinction between them.

For comparison purposes, Inset #1 in Figure 19 shows an unfavorable area south of big bend in the river. There is a large area of restricted on both sides of the river. This area is where the 100 year floodway is very wide, a condition that consequently lowers the suitability.

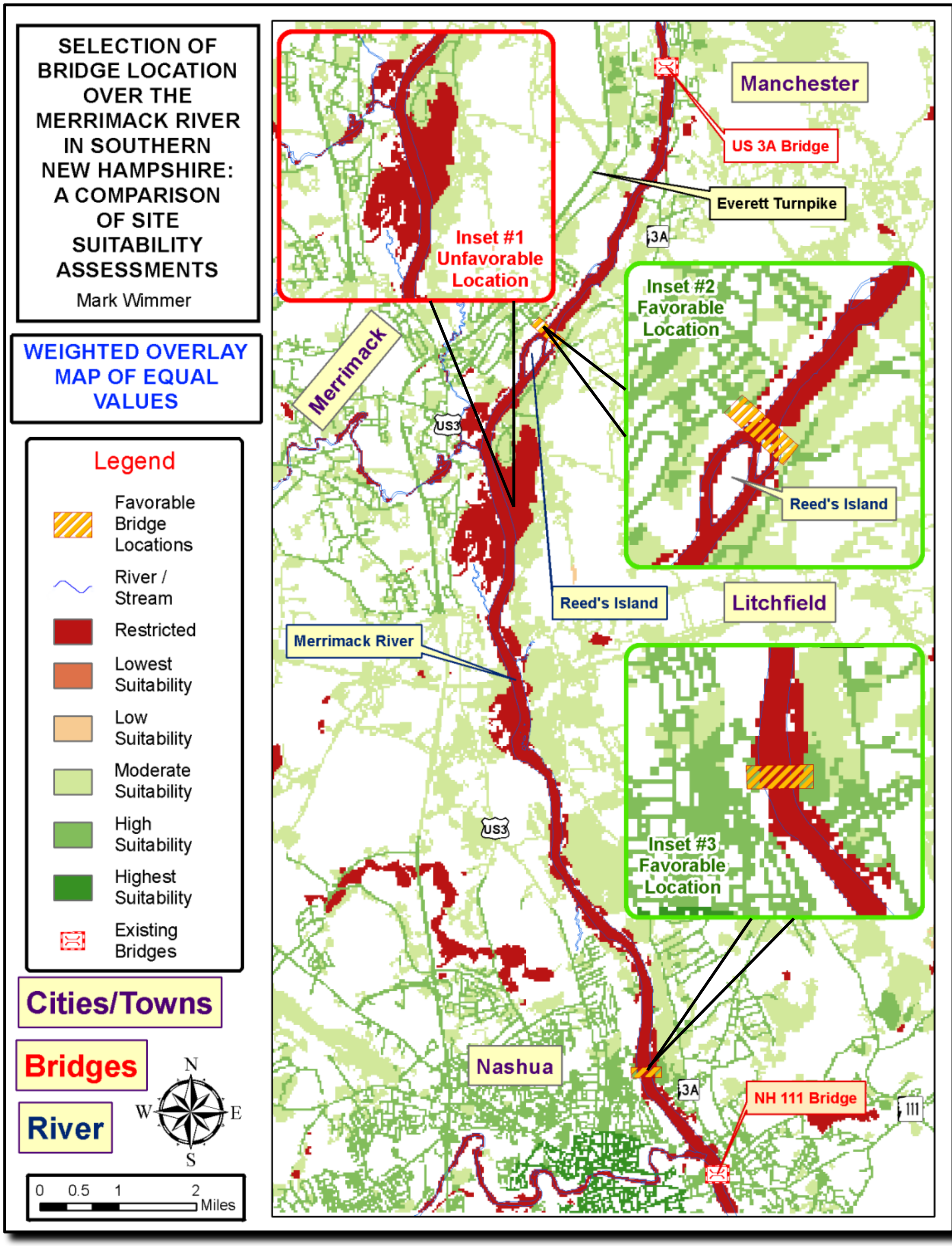

Figure 19: Weighted Overlay of Equal Selection Values

4.2 Process for Selecting Suitable Bridge Locations

After completing the weighted overlay analysis (ArcGIS Weighted Overlay Tool [Spatial Analyst]), a visual analysis of the map was accomplished to identify the most favorable bridge locations. Visual analysis consisted of scanning the mapped areas alongside the Merrimack River's path from the US 3A Bridge in Manchester south to the NH 111 bridges in Nashua. Areas that had the highest suitability both on directly opposite sides of the river as well as in a close proximity to the river were identified as most favorable.

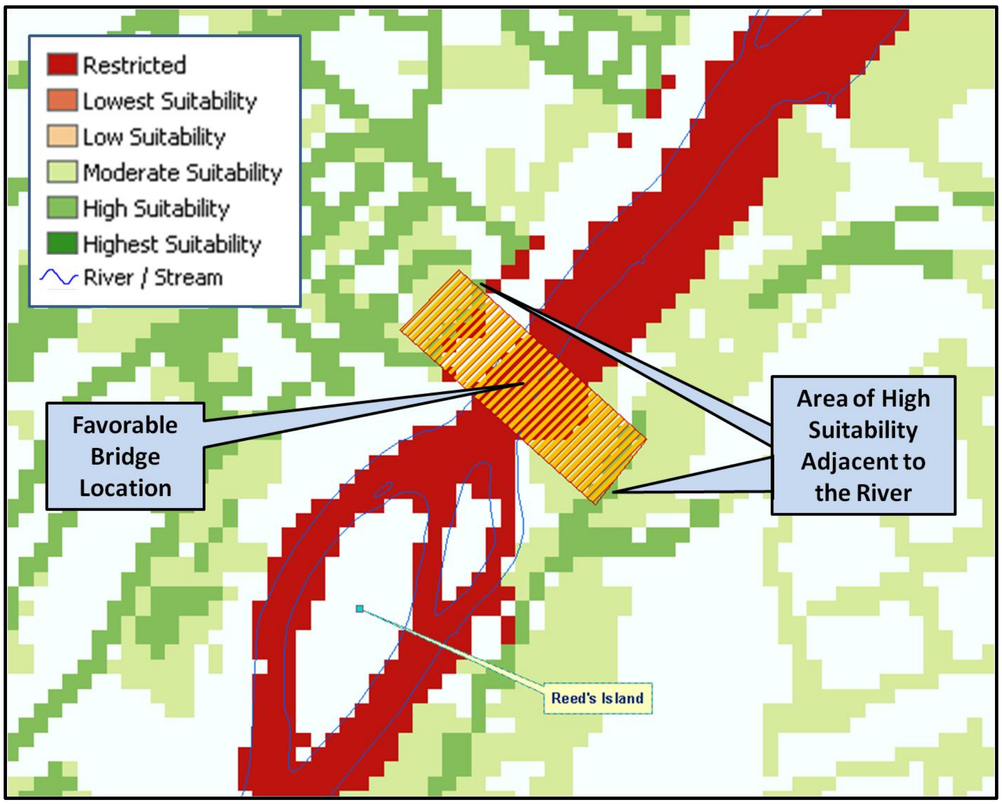

Figure 20: Northern Favorable Bridge Location

The weighted overlay results with equal weights can be used as an example of the area selection process through visual analysis. By doing a visual assessment of the final map, it can be seen that areas of the highest suitability ended being located around the Reed's Island location. Figure 20 shows how this northern favorable bridge location has areas of high suitability adjacent to the water with matching areas of the same suitability directly across the river. The thinnest area of the river was selected as keeping the span across the river short will save on construction costs and requires less of an environment footprint. Figure 21 shows the southern favorable bridge location also with areas of high suitability adjacent to the river and matching areas of the same high suitability directly across on the opposite bank.

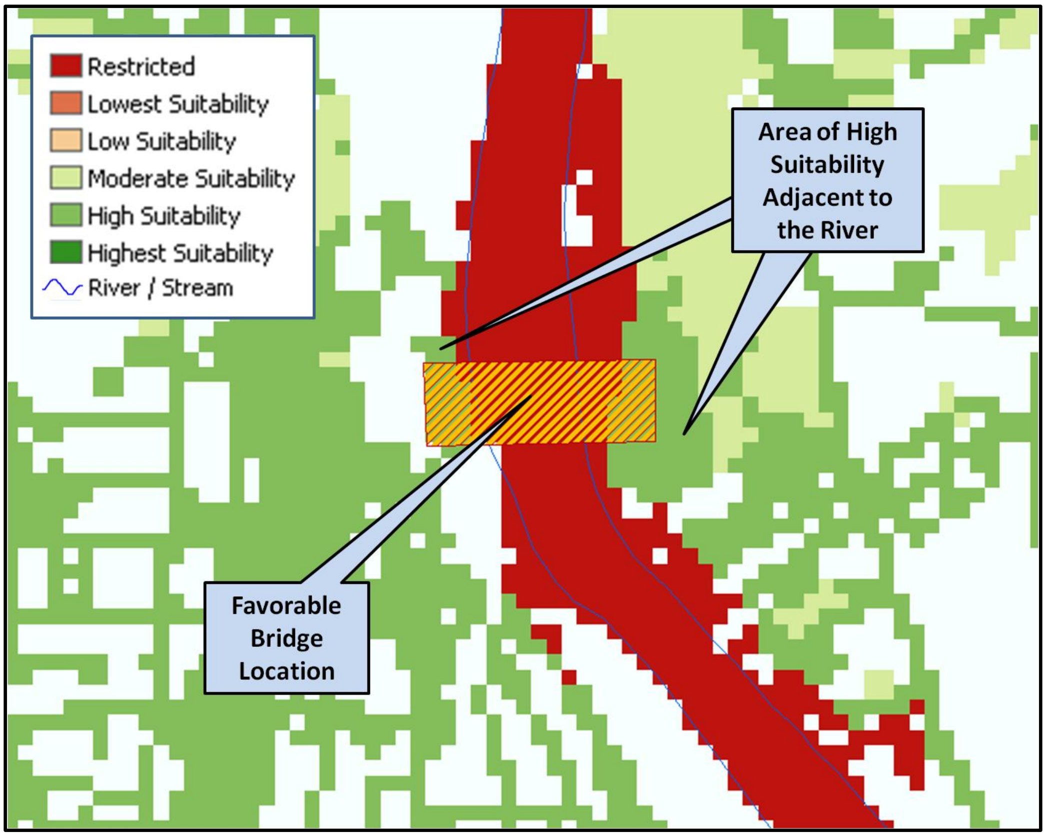

Figure 21: Southern Favorable Bridge Location

Visual analysis was also used to identify areas along the river that were unfavorable for the bridge location. By identifying unfavorable areas, sections of the river could be determined to be unfavorable for a new bridge location and eliminated from the selection process that determines the most favorable location. Attention could be focused away from these areas and back to the more favorable ones. Figure 22 shows parts of the river that have a very wide 100 year flood way, which become restricted areas through the weighted analysis process. When the restricted areas become too wide, the areas become less favorable due to the long length of bridge that would be needed to span them.

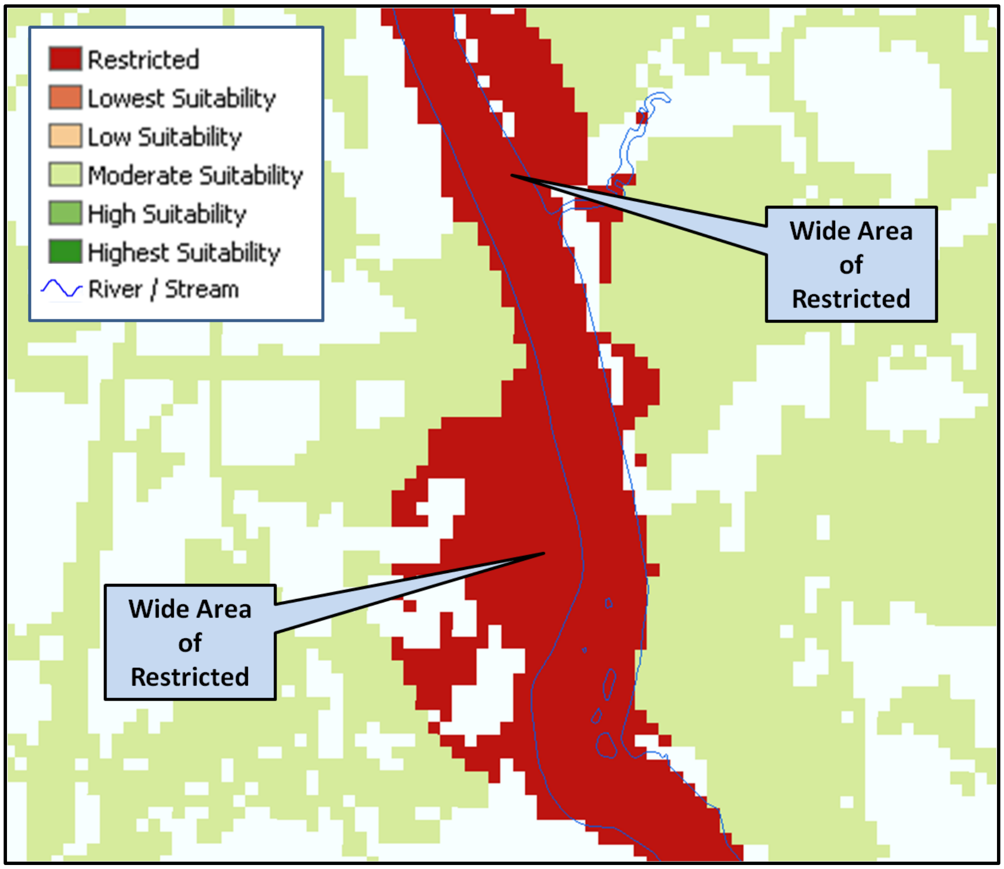

Figure 22: Restricted Areas along the River

Figure 23 shows other less favorable areas identified through the weighted overlay process. A thin area of high suitability runs parallel to the river in the upper left portion of the figure, though it is located far from the river. The area directly across the river that would match this area consists of only moderate suitability. So despite it being adjacent to the river, its lower suitability and the fact it has a poor matching area on the opposite side of the river make this area less favorable than the ones shown in Figures 20 and 21. Similarly, a matching problem exists in the bottom part of Figure 23 where only one area of high suitability is close to the river. Though not as unfavorable as areas shown in Figure 22, the areas in Figure 23 have matching and suitability deficiencies that make them less favorable than the areas in Figures 20 and 21.

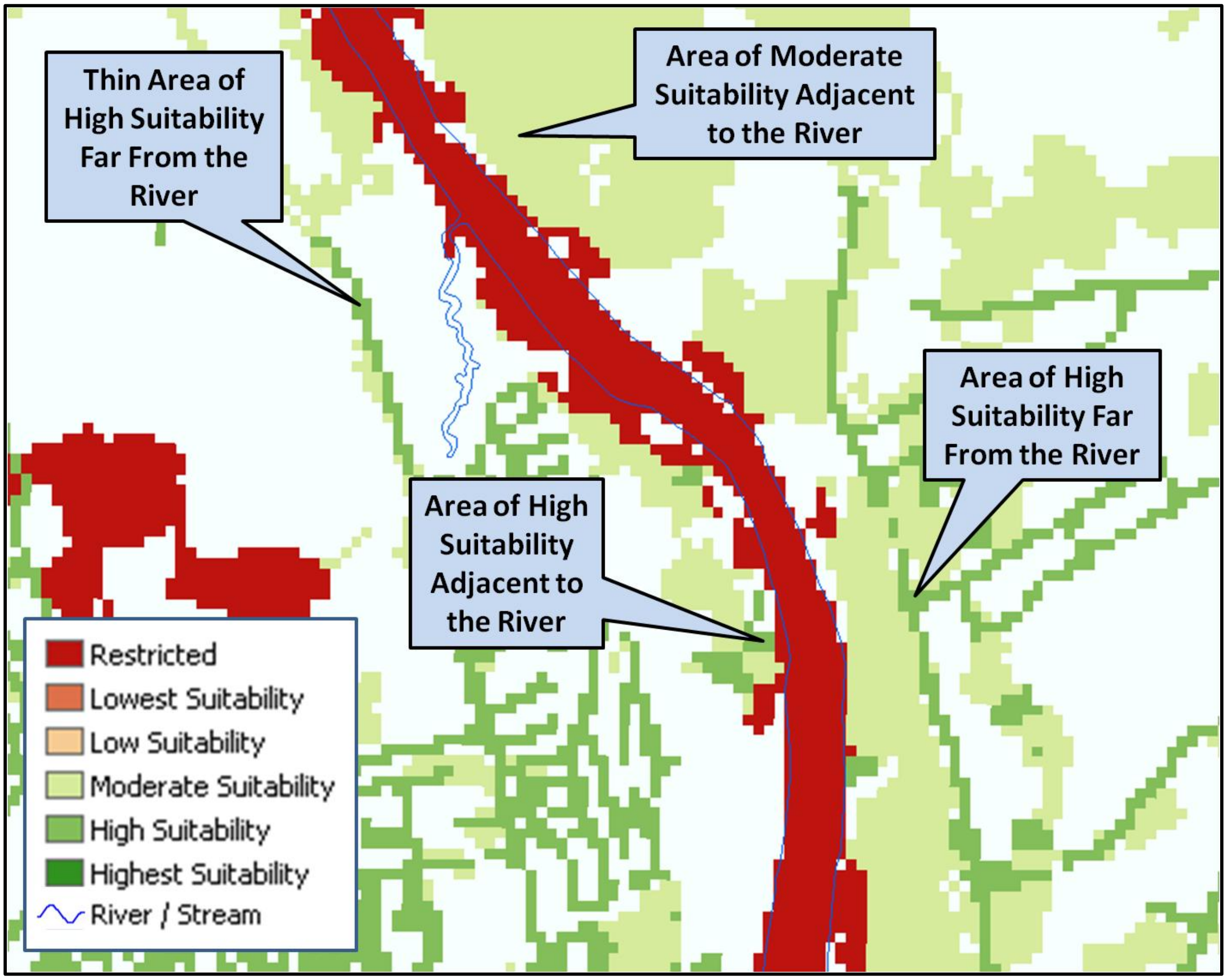

Figure 23: Less Favorable Areas along the River

When areas of highest suitability are located distant from the Merrimack River, they are not considered as favorable build locations. Since the primary objective of the study is to identify a location for a bridge over the Merrimack River, only highly suitable areas adjacent to the Merrimack River were considered. Figure 24 shows an area of Highest Suitability on both sides of the Nashua River. This would be a favorable location for a bridge crossing the Nashua River. But since the areas are not adjacent to the Merrimack River, they were not considered to indicate a favorable location for a building site. This exclusion rule was be applied to all highly suitable areas far from the banks of the Merrimack River.

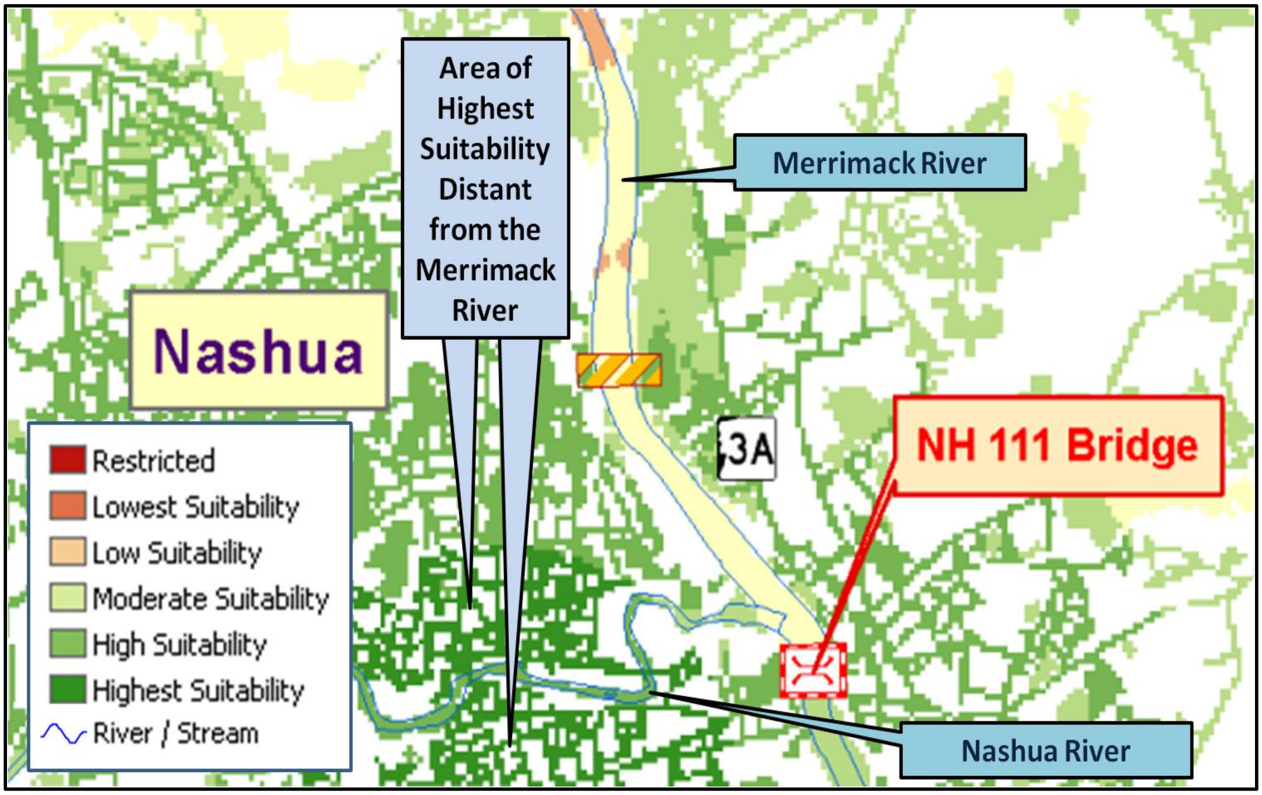

Figure 24: Highest Suitability Distant from the Merrimack River

White areas on maps should not be misconstrued as missing data or unknown suitability. During the building of the land cover layer, all unsuitable land covers were set as NULL in order to prevent them from being considered in the process. During visual analysis, any area of white can be affirmed to be an unsuitable land cover and subsequently should be avoided when determining favorable locations. Figure 25 shows large areas of white that represent large expanses of unsuitable land covers and should be not considered as favorable building sites.

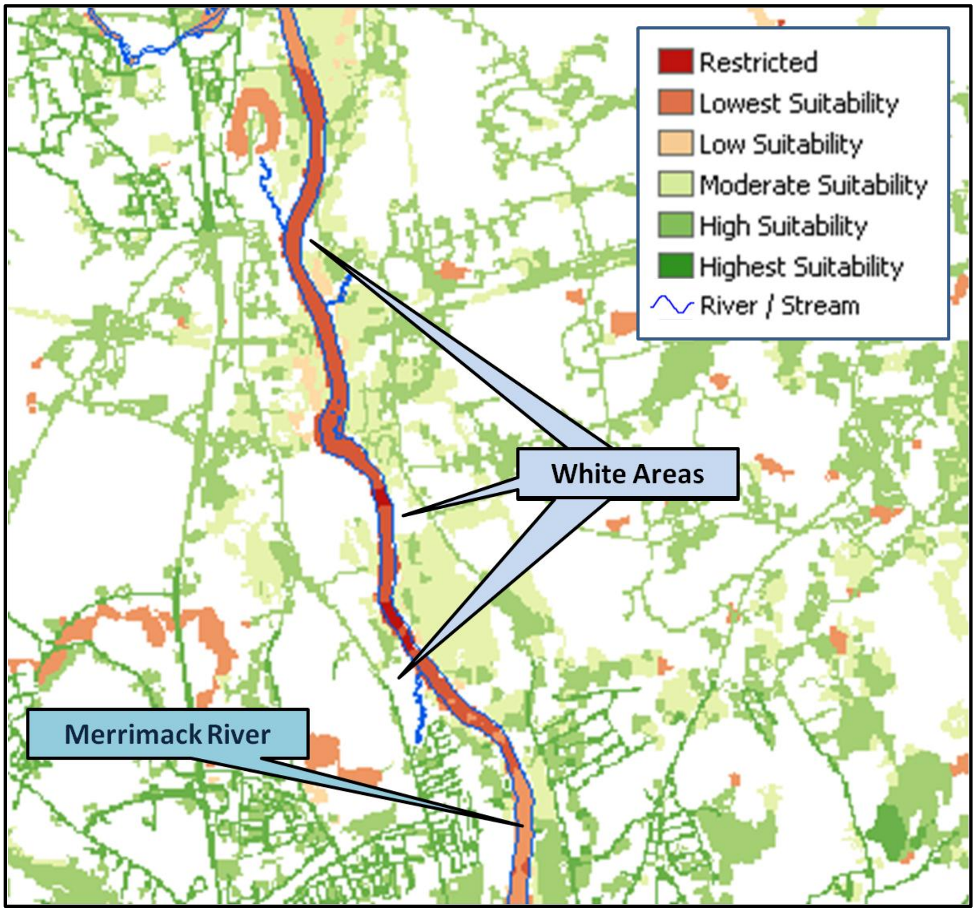

Figure 25: White Areas Indicating Unsuitable Build Areas

This visual analysis process of identifying adjacency, matching and suitability plus deficiencies was applied to identify all the favorable bridge locations for each of the weight overlay bias runs discussed in the sections below. The compilation of all the favorable bridge locations from the visual analysis performed can be found in Chapter 5.

4.3 Weighted Overlay with Environmental Bias

Environmental concerns play an important role in determining a suitable bridge site. The second weighted overlay (ArcGIS Weighted Overlay Tool [Spatial Analyst]) was run to put more weight on the need to minimize environmental impacts. This was done by increasing the percent weighting of the Land Cover raster. Population and roads were kept somewhat relevant as areas with roads and population tend to already have an urban footprint, so using the areas lowers the amount of undisturbed land that needs to be developed on. The selection criteria of slope and the 100 year floodway were set lower since they are more derived from engineering governances. Weighting percentages used for the environmental bias are shown in Table 12.

Table 12: Selection Criteria and Associated Weighting Percentage for the Environmental Bias Weighted Overlay

Selection Criteria	Weighting Percentage Used
Central to Populations of Four Municipalities	20%
Distance to Nearest Major Road not Exceed 5 miles	20%
Bridge abutments cannot be located in 100yr floodway	10%
Roadway surface cannot exceed 1% grade between banks	10%
Location needs to minimize environmental impacts	40%

Figure 26 shows the Environmental Bias overlay. Two suitable areas were found through visual analysis, again 1.5 miles north of the Hudson Bridges (Inset #3) and just upstream from Reed's Island near Merrimack, NH (Inset #2). The first area was selected under the weighted overlay with equal weights as well as through this weighted overlay bias as it is located in the urban zone of northeast Nashua. The area has already been urbanized so there would be little to no environmental impact if construction would take place at this location to cross the river. The second area has urbanization down to the river banks on both sides, with light industry on the west side and a housing development on the east side. Environmentally this site would not increase the human footprint, though by saving natural areas, the bridge would need to be placed through homes and businesses. The weighting definitely keeps potential construction away from environmentally sensitive areas, but will sacrifice urban areas to reach its ecological goals.

Inset #1 shows an unfavorable area south of horseshoe pond. There are large areas of low suitability on both sides of the river. On the east side moderate suitability is found next to the river but there is no matching suitability on the western bank. The lower suitability on the western side forms an area that would have to be traversed with a longer bridge span. Unsuitable land covers occupy this area, lowering the suitability.

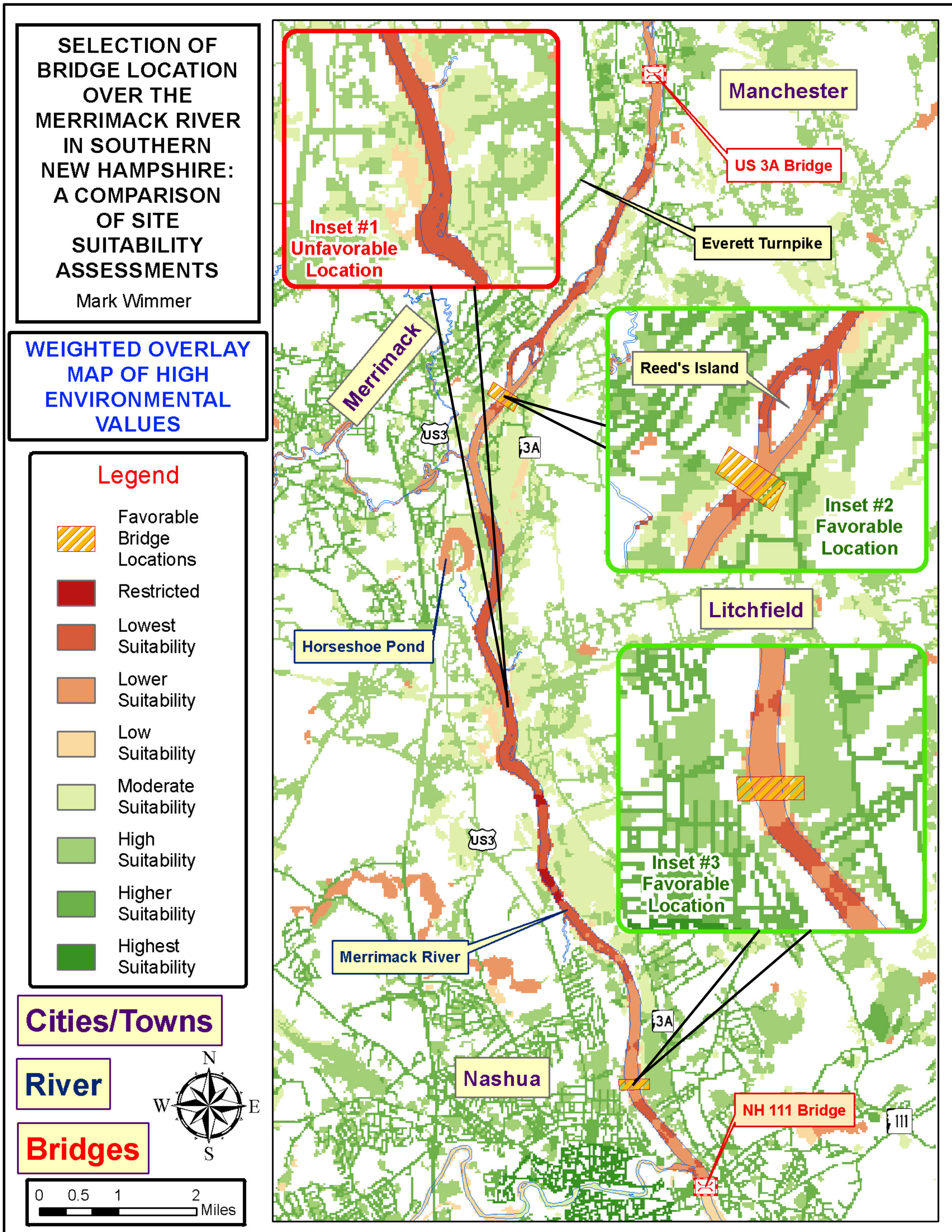

Figure 26: Weighted Overlay of Environmental Bias Values

4.4 Weighted Overlay with Engineering Bias

For the third Weighted Overlay (ArcGIS Weighted Overlay Tool [Spatial Analyst]), the weighting percentage values were set to provide an Engineering Bias. This weighted overlay focuses on finding suitable bridge locations based solely on criteria that are pertinent to the construction and engineering of the structure. Slope of the bridge roadway between the abutments, building out of the 100 year floodway and proximity to major roads are all key engineering criteria. The engineering biased weights used are shown in Table 13.

Table 13: Selection Criteria and Associated Weighting Percentage for the Engineering Bias Weighted Overlay

Selection Criteria	Weighting Percentage Used
Central to Populations of Four Municipalities	05%
Distance to Nearest Major Road not Exceed 5 miles	30%
Bridge abutments cannot be located in 100yr floodway	30%
Roadway surface cannot exceed 1% grade between banks	30%
Location needs to minimize environmental impacts	05%

Figure 27 shows the Engineering Bias weighted overlay. Two suitable areas were found, the first 2 miles north of the Hudson Bridges (Inset #3) and just upstream from the location identified by the Equal and Environmentally Biased overlays (Inset #2). The second takes advantage of electrical power lines crossing the river south of Merrimack, NH. The first area is shifted a little north from the other dually located area due to more favorable slope along the river further upstream. The second area also better avoids the slope and 100 year floodway restrictions. The high bias towards roads cements the second location which is close to two principal arterial on ramps, or collectors. The second site would be a very ideal location for the bridge due to its prime location near connecting roads, centrally located geographically between the existing bridges and acceptable slope and distance outside the 100 year floodway. The stretch of land right along the river, which is undisturbed forested land, kept this spot from being located until the environmental weight was lowered. The weighting values used before kept potential construction away from the environmentally sensitive area.

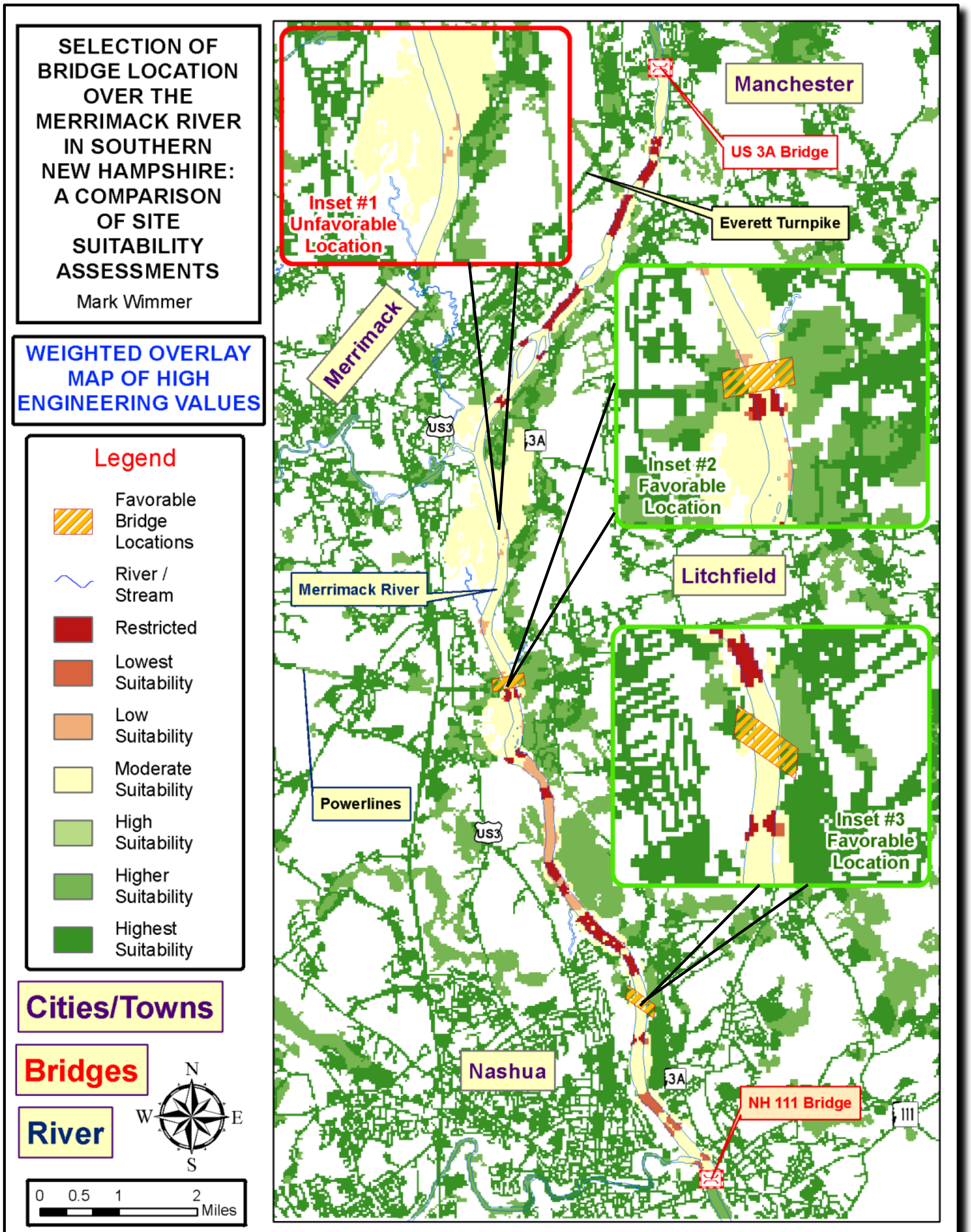

Figure 27: Weighted Overlay of Engineering Bias Values

Inset #1 shows an unfavorable area just south of the major bend in the river. There are large areas of moderate suitability on both sides of the river. On the east side higher suitability is found next to the river in the southern part of this area but there is no matching high suitability on the western bank. This area is where the 100 year floodway is very wide and subsequently lowers the suitability.

4.5 Weighted Overlay with Transportation Bias

For the final Weighted Overlay (ArcGIS Weighted Overlay Tool [Spatial Analyst]), the weighting percentage values were set to provide a Transportation Bias. The weighted overlay focuses on finding suitable bridge locations based on criteria that are pertinent to the distance of major roads with a minor focus on location of population. The primary role of roads is to move population efficiently and in a timely manner, so the population weighting was left high to reflect this important relationship. The transportation biased weights used are shown in Table 14.

Table 14: Selection Criteria and Associated Weighting Percentage for the Transportation Bias Weighted Overlay

Selection Criteria	Weighting Percentage Used
Central to Populations of Four Municipalities	25%
Distance to Nearest Major Road not Exceed 5 miles	45%
Bridge abutments cannot be located in 100yr floodway	10%
Roadway surface cannot exceed 1% grade between banks	10%
Location needs to minimize environmental impacts	10%

Figure 28 shows the Transportation Bias overlay and the suitable areas for a bridge crossing. Two suitable areas were found, the first 1.5 miles north of the Hudson Bridges (Inset #3), at a very similar location to those identified by the Equal and Environmentally Biased overlays. The second is very close to the Engineering Bias northern location near the electrical power lines crossing south of Merrimack, NH (Inset #2). The first area is aligned well with the urban road structure and population base in northeast Nashua. The second area is close to two principal arterial on ramps, or collectors, on the west side of the river. The fact that this second site shows as high suitability with the higher population weighting shows that it is geographically centered location between the larger metropolitan centers of Nashua and Manchester proves to be a plus for serving the population needs of the region.

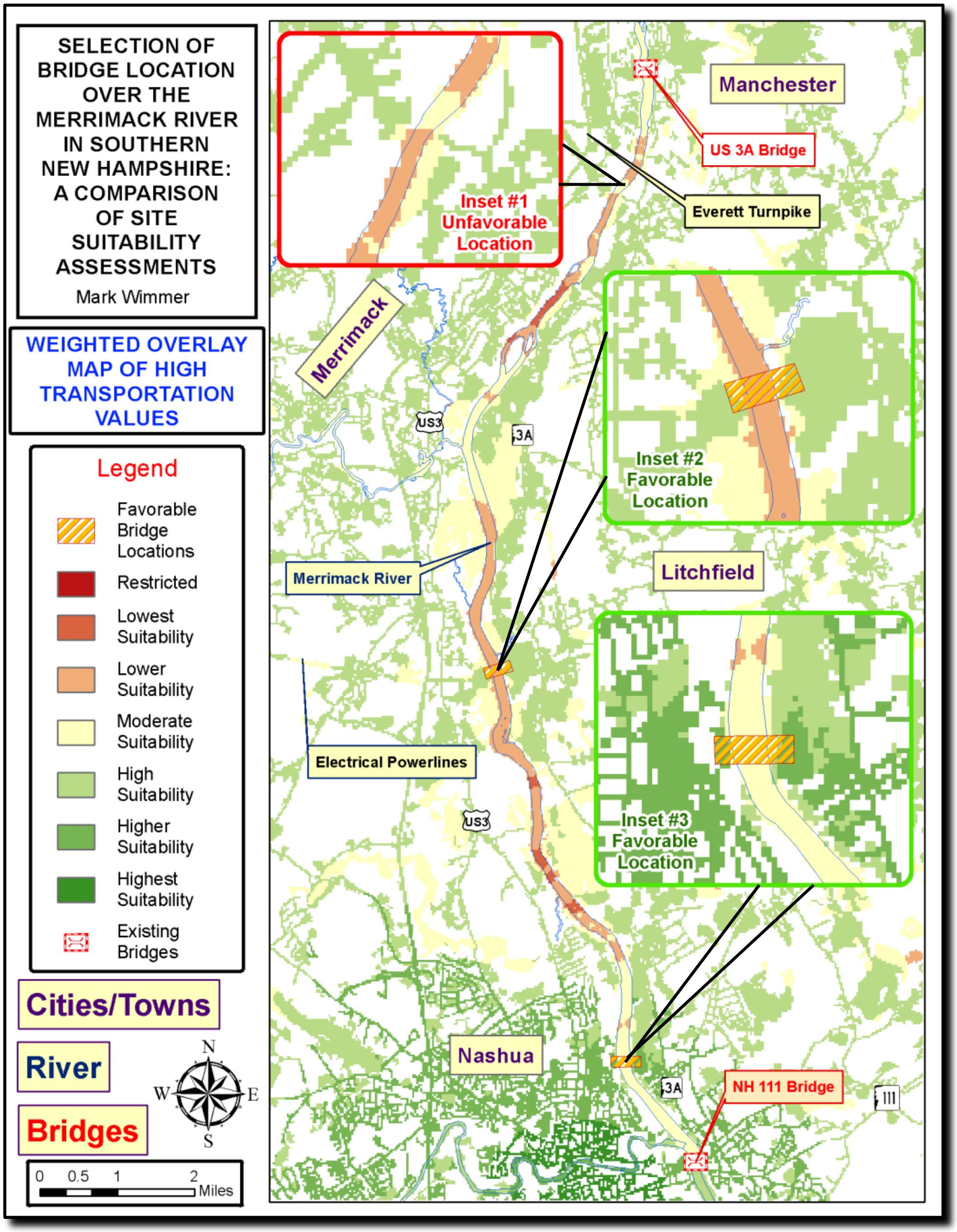

Figure 28: Weighted Overlay of Transportation Bias Values

Inset #1 shows an unfavorable area just south of the US 3A Bridge. There is an area of moderate suitability on the east side of the river and nothing on the west side. This is due to no roads nor population in the vicinity on the west side. Without favorable roads or people in the area, the location is unfavorable.

Chapter 5 summarizes the locations selected in this set of overlay analyses and compares them to the NRPC study. Before looking to that final comparison, the next section examines the stability of these results through a sensitivity analysis.

4.6 Sensitivity Analysis

In order to test the stability of the weighted overlay analysis output, sensitivity analysis can be performed to determine just how sensitive the results are to small changes in the scale values of the criterion. Such small variations can be used to reflect the amount of uncertainty in the subjective assignment of these values. This modified input is then used in the original weighted overlay analysis so that the results can be compared to the original output to determine the amount of the difference such changes make. Large differences would show a high sensitivity and small differences would indicate a low sensitivity to this uncertainty. Lower sensitivity is desired, making the overall results of the weighted overlay output more stable.

The scale values for the land cover criterion were chosen for the sensitivity analysis since the assignment of values was somewhat subjective. The slope and 100 year floodway scale values are Boolean in nature and therefore have no changeable values. The population and roads criterion scale values are determined by a straight-forward linear decay function. It is logical and sensible to place the bridge near population centers and existing road networks, and a simple distance decay from these is relatively objective as a scaling method. However, what type of land cover is most suitable for a bridge can be argued different ways. A more environmental approach might choose that undisturbed land is not used, while a cost efficient approach might favor undeveloped land.

The original scale values used during the initial land cover weighted overlay analysis can be found in Table 15. Water was set to “1” because despite the fact the bridge needs to span water, its abutments cannot actually be built on water. Transportation and Disturbed areas were set at “9” as both have already been impacted by man and are prime locations for construction. Other areas were set to a “7” as these areas have been disturbed by man at some point in history, but may be on their way to returning to their natural state. Hay/Pasture and Crop areas were deemed buildable areas but only given a “6” to make them less favorable. However, it is equally reasonable to set these lower to reflect the environmental value of these lands. Thus in this sensitivity analysis they were both set to “2”, making them less suitable for site construction. Table 15 also shows the values used for the sensitivity analysis.

Table 15: Original and Tweaked Scale Values of the Land Cover Criterion

Land Cover Type	Original Scale Value	Tweaked Scale Value
Water	1	1
Hay / Pasture	6	2
Crops	6	2
Other	7	7
Transportation	9	9
Disturbed	9	9

Once the correct scale values for the sensitivity analysis were identified, the raster was reclassified. The weighted overlay analysis for the environmental bias was rerun as it has the land cover criterion as its highest weighting percentage, which is shown in Table 12 in Section 4.3. A raster calculator was used to determine the difference between the original and new weighted analysis output. Figure 29 shows the results of the difference calculation.

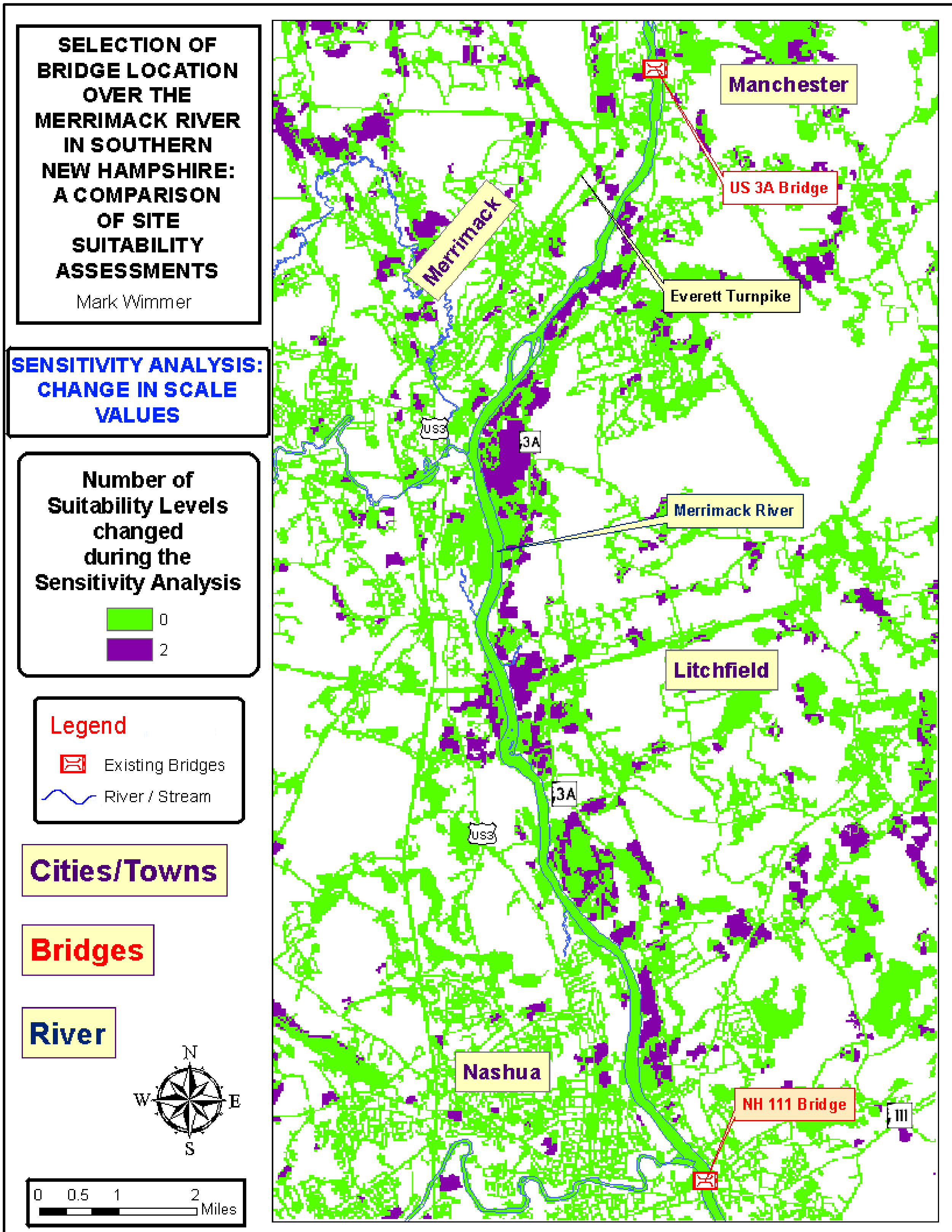

Figure 29: Sensitivity Analysis Results

The results show there was not a major change in suitability levels and thus it is concluded that the model is stable, despite the uncertainty in some of the rating values. Some differences can be seen when the changes are made so the results also prove that model inputs do have an effect on the output. This effect is logical as decreasing the scale value for areas with Hay / Pasture and Crops resulted in a decrease in suitability for those same areas in the output at the end of the weighted overlay process.

CHAPTER 5: COMPARISON OF RESULTS

It is now possible to compare the results of the weighted overlays against the three alternatives the NRPC concluded after their spatial analysis. Figure 30 shows the highest suitability areas from this weighted overlay analysis and it also displays the NRPC Alternatives. Figure 30 allows the results of the weighted overlays to be compared directly against the results of the NRPC spatial analysis results. Only the NRPC Alternative #3 shares a common result with any of the weighted overlay results. The following sections break down further how the three NRPC Alternatives compare directly against the weighted overlay results.

5.1 Comparison of NRPC Alternative #1 against the Weighted Overlay Results

NRPC's Alternative #1 is the middle option of the three displayed on Figure 30. It is placed moderately well to be within good distance of major roads. It is also out of the 100 year floodway. However it is located in a restricted area of slope, meaning the grade between the opposing river banks have a slope greater than 1% between them, which is not allowed by construction standards. In order to build at this location, the abutments for a bridge would need to be pushed back away from the river far enough to relax the future bridge surface grade below 1%. Unfortunately this would further the detrimental environmental impact as both sides of the river at this location has forested areas that would need to be cut down to make way for the construction of the bridge. When considered in the context of the criteria examined, Alternative #1 does not present a favorable location.

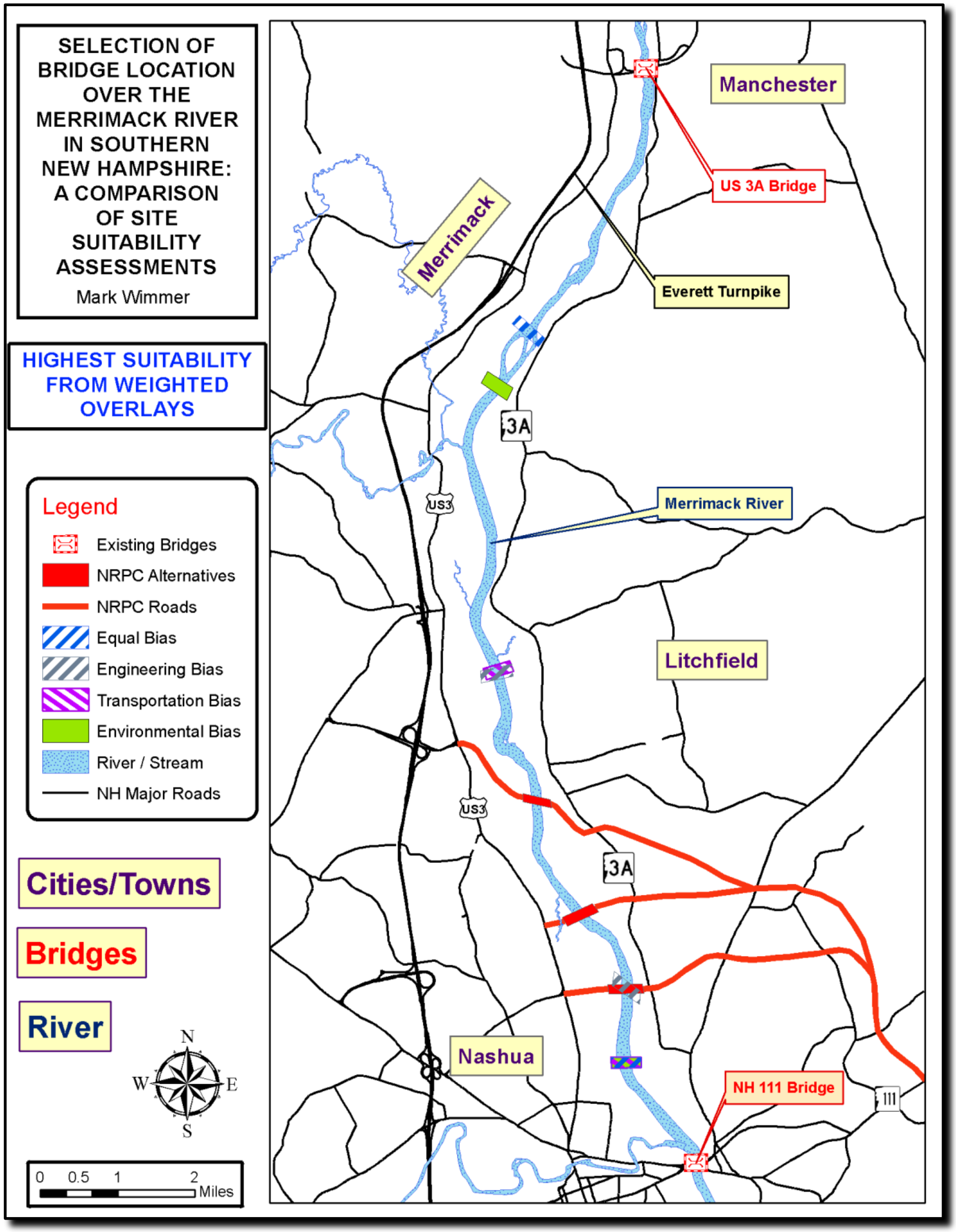

Figure 30: Highest Suitability Areas from Weighted Overlays Compared against NRPC Alternatives

5.2 Comparison of NRPC Alternative #2 against the Weighted Overlay Results

NRPC's Alternative #2 is the farthest north option of the three displayed on Figure 30. Like Alternative #1 it out of the 100 year floodway but has forested areas on both sides of the river. On the eastern side, farmland would have to be used to build the needed support roads to make the bridge viable at this location. Unlike Alternative #1, slope is not a restricting criteria but it is still in a low suitable area, meaning the grade between the opposing river banks is less than 1% but still close enough to potentially cause problems. Alternative #2 is a better choice than Alternative #1, though it still does not favorably meet all the criteria.

5.3 Comparison of NRPC Alternative #3 against the Weighted Overlay Results

NRPC's Alternative #3 is the southernmost option of the three displayed on Figure 30. Like Alternative #1, it is placed moderately well to be within good distance of major roads and it is also out of the 100 year floodway. Though unlike Alternatives #1 and #2, there are no slope issues at this place in the river. In fact, Alternative #3 shares a highly suitable area with the results of the Engineering biased weighted overlay, meaning slope is highly suitable at this location. Alternative #3 is the only one of the three NRPC Alternatives to share an area with one of the weighted overlay results. The western side of the river is forested but the eastern side is lightly urbanized, making the eastern bank a favorable location for the bridge. This plus Alternative #3 meeting the other criteria makes it the best of the three NRPC alternatives.

5.4 Comparison Conclusion

The conclusions of both site suitability analyses indicate that there are multiple locations in the study area that are favorable for bridge construction. The comparison shows how the location of the most suitable bridge locations to span the Merrimack River changes when the criteria are altered and different suitability analysis processes are used. The varied alternatives are all valid conclusions for the respective criteria used. Therefore in order to find the most suitable bridge location, any future plans would need to define the criteria to best meet the objectives of the users.

CHAPTER 6: DISCUSSION AND CONCLUSIONS

This chapter examines the shortcomings of the data and limitations of the methodology and provides several recommendations for expanding future suitability analysis. Final conclusions and future work regarding the placement of a bridge over the Merrimack River in southern NH are also discussed.

6.1 Data Shortcomings and Limitations of Methodology

While there are many advantages of the methodology used in this thesis, there are many limitations that may reduce the accuracy of the conclusions. The disadvantage of the weighted analysis is that it provides only areas of suitability and no definitive answer. The classes of suitability are subjective and can change with the definition of the criterion. How each thing is rated depends on what is determined important by the user. While an analysis of the results can conclude that there is a perfectly acceptable final solution, another reasonable conclusion could be derived through a different perspective with divergent criteria.

Furthermore, the shelf life of the conclusions formulated in this thesis is short. The findings are tied to land cover assessments, which can change with urban development, natural disasters or other major shifts in human activity in a specific area. Transportation networks can change with the building of new roads or expanding current traffic corridors. Rapid changes in population are also possible in the study area with the ever expanding housing developments and urbanization in this growing region. Current and accurate data is key to running the site suitability analysis to produce up-to-date results.

With the ever changing data, comes the inability for this methodology to quickly incorporate the new assessments. For example if land covers were to drastically change in the region, the new features would have to be projected, the suitability classes reevaluated and the weighted overlays analysis performed again. A change in any of the base data would result in the need to repeat many steps. An introduction of new parameters would also drive a repetition of the overall process.

When assigning suitability classes, many assumptions are made in terms of the driving forces behind bridge placement. Deciding differently on whether environmental concerns justify extra construction costs or if proximity to current road networks is a higher priority than being closer to population centers can lead to considerably different results Expert opinions and research into what are the most suitable factors will increase the probability that a proposed location will best fulfill all the required mandates.

One last shortcoming of the weighted overlay analysis is the loss of fidelity when using low weight percentages in the overlay process. Some criteria have Boolean datasets which strictly allow or disallow a bridge to be placed in a certain area. If the weighting percentage of a Boolean criterion is set too low, the other criteria may have enough weight to produce areas of suitability that may mask a disallowed area into appearing like a favorable location. A simple check of favorable site locations against any Boolean criteria will ensure this shortcoming does not occur. Figure 31 shows such a check of the different bias results against the 100 year floodway and 1% slope do not build areas. No favorable location from any of the biases lies inside the 100 year floodway nor in any specified areas where slope is greater than 1%.

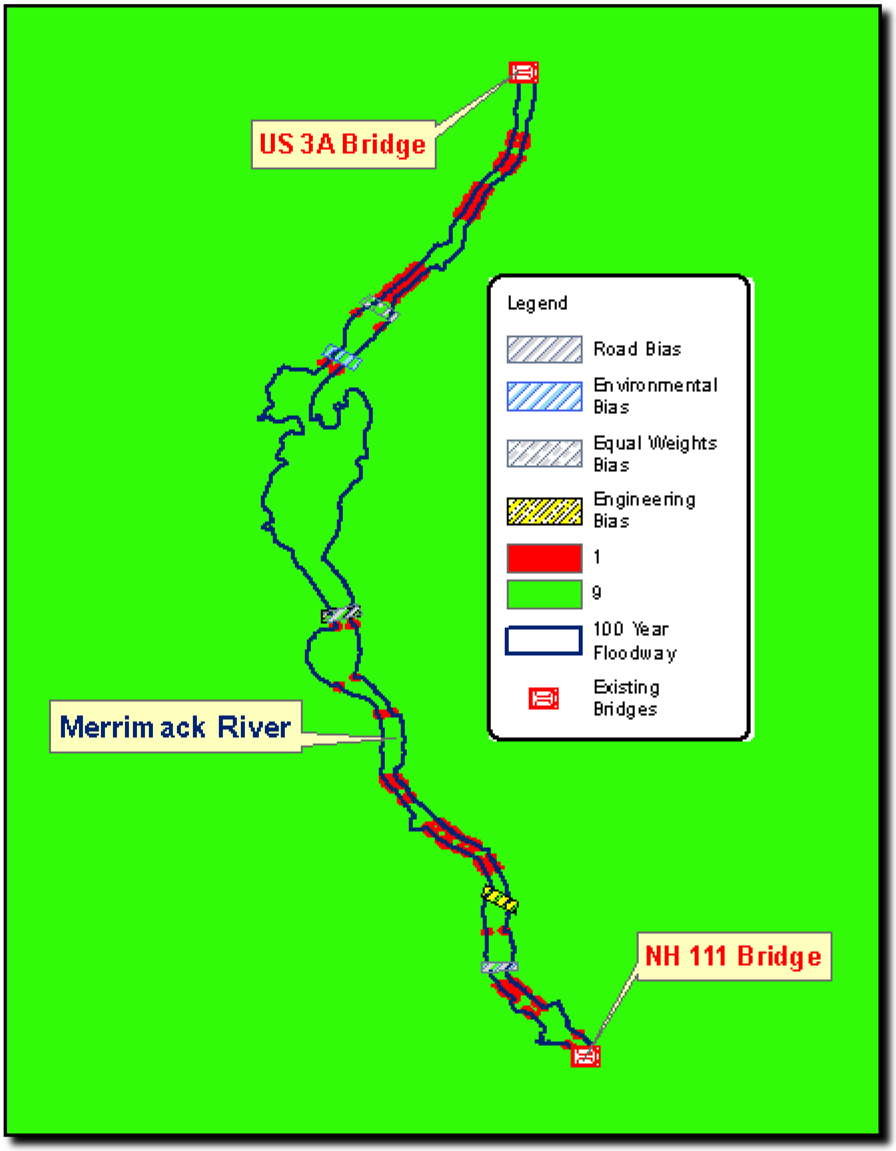

Figure 31: 100 Year Floodway and 1% Slope Criteria Check

6.2 Future Site Suitability Analysis

The site suitability analysis performed in this thesis used specific criteria to formulate results. Additional criteria could be added and assessed to add a higher resolution to the areas deemed as suitable. Avoiding sensitive areas such as habitats for endangered species can be added. Proximity to public facilities such as hospitals, fire houses and police stations seems relevant to helping those who protect and serve get to where they are needed in the most judicious route possible.

Engineering thresholds and criteria for construction are complex and take into account a multitude of parameters to ensure the success, safety and longevity of a span across a river. Capacity constraints, width of the bridge surface and number of lanes feeding the span are examples of potential criteria that could be used in future suitability analyses. Experts in the engineering field would need to advise on critical criteria to ensure the needed objectives are being realized.

Additionally, the methodology used in the thesis only accounts for travel across the river by automobile. Many commuters or travelers will utilize the bridge on foot or bicycle. Future rail networks may expand across the Massachusetts border into New Hampshire and need a bridge to cross the river. All three non-vehicular modes of travel require transportation networks that differ from motorized vehicles. Incorporating criteria to better accommodate different types of transportation would increase the scope of overall user suitability.

Increasing the types of land covers that were examined would improve the suitability assessment. Classification such as depth of bedrock, soil type or high fall level (rapids) in the river could impact the ability to build the bridge abutments, lowering or improving construction suitability. Wildlife habitats or nesting sites could be considered as low suitability land cover while rock out croppings could be considered a natural area of higher suitability.

Future site suitability analysis could incorporate all the additions discussed plus any other criteria identified by public officials, engineers, users or other individuals or groups involved in the planning and research phase of the bridge construction. The possibilities are endless as the weighted overlay model is a flexible tool able to accommodate any specific criterion with data to support it.

6.3 Conclusion and Opportunities for Future Work

This thesis has demonstrated how, by incorporating different criteria into the spatial analysis process, a varied set of results may be formulated. Alternative approaches taken to solve the same problem showed that there is no one absolute correct location for a new bridge across the Merrimack River, but only suitable alternatives based on different criteria. Determining the criteria has been found to be the most crucial step in the site suitability analysis. Detailed research and planning needs to be accomplished to refine and amalgamate the criteria to ensure a future bridge location will indeed serve the all the needs of the intended users.

While the conclusions formulated here may be more helpful in ascertaining a more suitable bridge location across the Merrimack, it also demonstrates that continued analysis and up-to-date data can benefit the analysis process and overall result. Since the criteria are so important to the site suitability process, the data that is used to perform the spatial analysis under the constraints of each criterion needs to be the latest and most accurate as possible. Errors in the data can reverberate through the analysis and be detrimental to the end result.

The NRPC will continue their work towards planning and constructing a new span across the Merrimack River. Funding, permitting, political and public support and environmental concerns will all be challenges that will need to be addressed and overcome. There is a definite need for a bridge crossing in the region north of the Taylor Falls Bridge. Site suitability analysis can point to favorable locations, but it will come down to the will of the people of southern NH whether the results of this study or any future spatial analysis will ever be utilized to aid in actual bridge construction.

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APPENDIX A: IMAGES OF ALTERNATIVE NRPC BRIDGE BUILDING SITES

Figure A-1: NRPC Alternative #1 Bridge Building Site (Source: NRPC 2003)

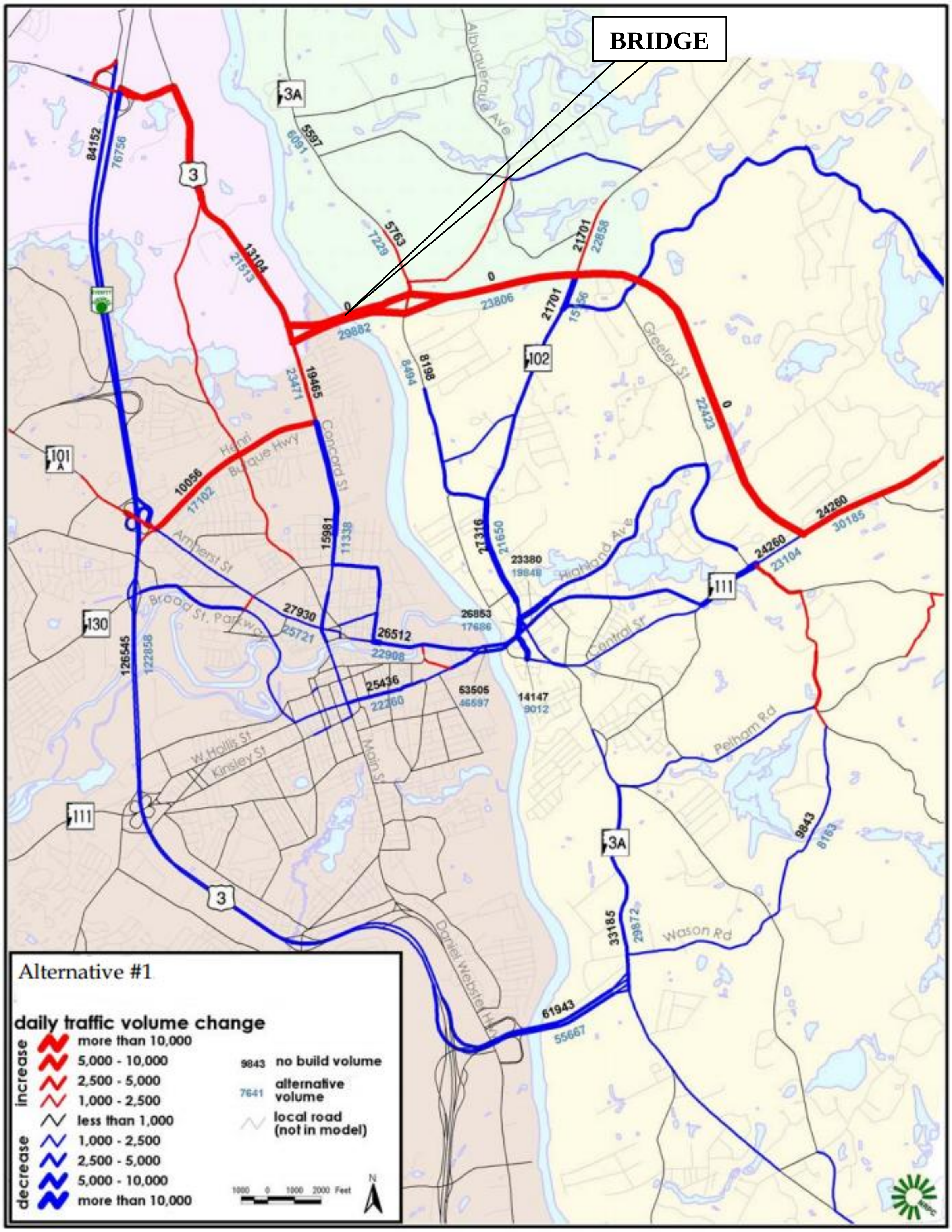

Figure A-2: NRPC Alternative #2 Bridge Building Site (Source: NRPC 2003)

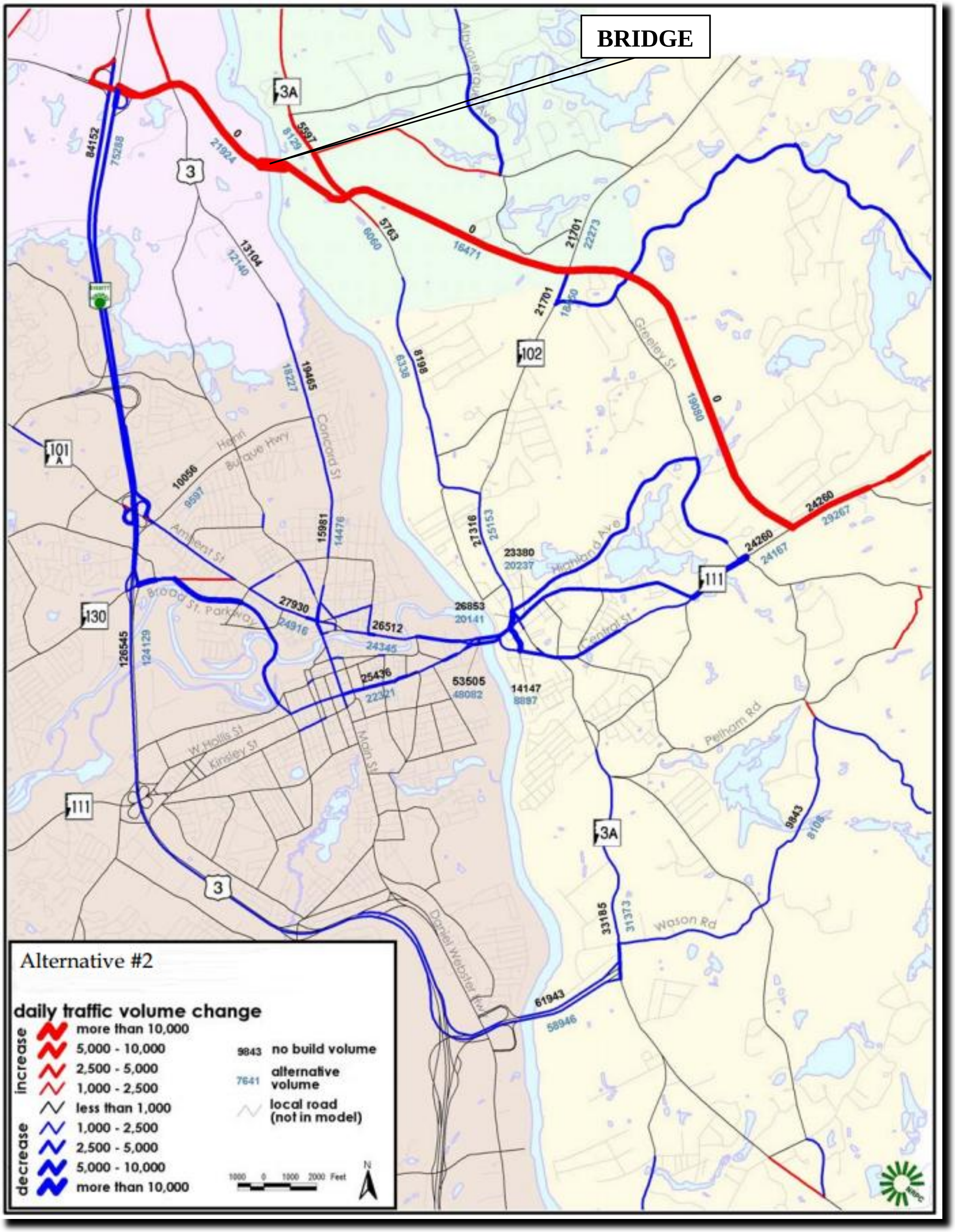

Figure A-3: NRPC Alternative #3 Bridge Building Site (Source: NRPC 2003)