MODELING WETLAND CONNECTIVITY AND VULNERABILITY TO WETLAND-CORRIDOR LOSS

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MAHABUB ALAM

Dr. Timothy C. Matisziw, Thesis Supervisor
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The undersigned, appointed by the dean of the Graduate School,
have examined the Thesis entitled

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WETLAND-CORRIDOR LOSS

Presented by Mahabub Alam
a candidate for the degree of master of science
and hereby certify that, in their opinion, it is worthy of acceptance.

Dr. Timothy C. Matisziw

Dr. Kathleen M. Trauth

Dr. Enos C. Inniss

Dr. Raymond D. Semlitsch

DEDICATION

I take this opportunity to thank my family and friends for their love and support. I specially want to thank my parents for their encouragement, love and support throughout my life.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

MODELING WETLAND CONNECTIVITY AND VULNERABILITY TO WETLAND-CORRIDOR LOSS

Mahabub Alam

Dr. Timothy C. Matisziw, Thesis Supervisor

ABSTRACT

Wetland systems involve a complex range of important biological, chemical, and hydrologic interactions among individual wetlands which contribute to ecological health. Modification of the landscape due to anthropogenic development has a direct impact on the connectivity supporting these interactions as well as the ecology of a region. It is thus important for individuals and agencies involved in the management and protection of wetland systems to understand the baseline condition of wetlands, supported interactions, and how potential land use and infrastructure modifications may change the strength of underlying connectivity. This baseline connectivity should, therefore, be rigorously defined, accommodating considerations of different types of connectivity and measurement systems. To better understand these issues, a framework is proposed for representing and reasoning about the connectivity of aquatic resources. In particular, a corridor-based representation of connectivity and network-based optimization methods have been developed and implemented in a geographic information system to establish a baseline level of connectivity and to model the effect of potential landscape changes. The developed framework is applied to a wetland system in Missouri to demonstrate the tradeoff between proposed mitigation options and ease of ensuring sustained system

connectivity. More broadly, this type of connectivity analysis can be used to inform many types of planning decisions such as those considering alternative courses of development, prioritization of wetland management/protection resources as well as those addressing policy or regulatory matters.

CHAPTER 1

INTRODUCTION

1.1 Definition of Wetland

The term “wetland” first entered the popular vocabulary following its use in the publication ‘*Wetlands of the United States*’ by Shaw and Fredine (1956). Prior to this publication, wetlands were typically referenced by a wide variety of terms such as, bogs, fens, swamps, marshes, etc. (Mitsch and Gosselink, 2007). While the term has been around for quite a while, there is still no consensus on the set of characteristics that define a wetland given the tremendous range of hydrologic conditions that are found on the earth. Generally speaking, wetlands can be found in terrestrial and aquatic ecosystems, ranging from forest to ocean. Over the years, different agencies and organizations have attempted to formally define wetlands according to their management mandates.

The United States Army Corps of Engineers (USACE), Natural Resources Conservation Services (NRCS), United States Environmental Protection Agency (USEPA) and United States Fish and Wildlife Service (USFWS) are the four federal agencies responsible for defining wetlands and enforcing wetland regulations. As such, their definitions are most often referenced. The most commonly used wetland definition by USFWS comes from Cowardin et al. (1979):

> “. . . in general terms, wetlands are lands transitional between terrestrial and an aquatic system where the water table is usually at or near the surface or the land is covered by shallow water. For purpose of this classification,

> wetland must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly un-drained hydric soil; and (3) the substrate is non-soil, is saturated with water or covered by shallow water at some time during the growing season of each year." (Cowardin, 1979, p. 9)

The regulatory definition of wetlands was established in Section 404 of the 1977 U.S. Army Corps of Engineers' (USACEs') Clean Water Act (CWA, 1977). It was amended in 1986 (CWA, 1986) and again in 1993 (CWA, 1993) for the implementation of a dredge-and-fill permit system:

"Wetlands are those areas that are inundated or saturated at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated conditions. Wetlands generally include swamps, marshes, bogs and similar areas" (CWA, 1986). The USACE defines wetlands according to some general diagnostic environmental characteristics:

> a) "Vegetation: The prevalent vegetation consists of macrophytes that are typically adapted to areas having specific hydrologic and soil conditions. Hydrophytic species, due to morphological, physiological, and/or reproductive adaptation(s), have the ability to grow, effectively compete, reproduce, and/or persist in anaerobic soil conditions.
>
> b) Soils: Soils are present and have been classified as hydric, or they possess characteristics that are associated with reducing soil conditions.
>
> c) Hydrology: The area is inundated either permanently or periodically at mean water depths ≤ 6.6 feet, or the soil is saturated to the surface at some time during the growing season of the prevalent vegetation." (USACE 1987).

Finally, a technical approach exists which includes the three USACE indicators just mentioned making a positive wetland determination possible. There are, however, a few exceptions (USACE, 1987). Evidence of a minimum of one positive wetland indicator (out of the three indicators above) from each parameter must be found in order to make a positive wetland determination (USACE, 1987).

This definition has been considered as legal definition for several years. The legal definition was strengthened by several cases and court rulings. The wetland definition puts new weight to navigable waters to identify “isolated” wetlands due to a Supreme Court decision in 2001. The water bodies that do not have a significant nexus to navigable water or no readily identifiable surface connection to a larger body of water are called isolated wetlands (Downing et al., 2003). Some wetlands might not have any surface water connection with navigable waters, designating them as isolated wetland, but there might be hydrological connections and/or biological connections. Wetland connections have thus become an important factor in defining wetland systems.

1.2 **Wetland Vulnerability and Protection**

When settlers arrived in North America from 1600-1650, nearly 127 million acres of wetlands are believed to have been in existence. Since then, almost 50% of those wetlands have been lost given development of the landscape and lack of protection. In the state of Missouri, approximately 4.8 million acres of wetlands are believed to have existed during its early settlement as opposed to the 10 percent now remaining (Epperson, 1992). This change is most evident in the southeast part of the state of Missouri, where 2.4 million wild-acres of once forested lowlands have been reduced to less than 60,000 acres, around 2 percent of its original extent (MDC, 2012a). Realizing the cons of wetland losses from North America, President Bush, The National Governors Association and a number of states have embraced no-net-loss wetlands policies (Epperson, 1992). In Missouri, formal wetland conservation planning began with financial assistance from USEPA in 1990. The Missouri Department of Conservation web site (MDC, 2012b) predicts that thousands of acres of wetland will be lost from this continent each year if wetlands are not adequately protected.

Wetlands and streams carry out vital functions to maintain the overall balance of nature. Wetlands are home to countless species central to the ecosystem (MDC, 2012b). The presence of vital nutrients in wetlands nurtures a tremendous diversity of flora and fauna. This diverse range of vegetation is an important part of the food chain that attracts invertebrates, amphibians, reptiles, mammals, resident and migratory waterfowl, shore birds, song birds, etc. Amphibians and also some other species complete their life cycle moving from one wetland to another. Proximity of wetlands hence plays a vital ecological role. Wetlands also serve to help manage water quality and protect areas from flooding and pollution. Wetlands can trap storm water reducing the flow of water into streams decreasing sediment load. Microorganisms and plants in wetlands digest excess nutrients and also some other pollutants. In periods of rain, wetland plants intercept water, reducing soil erosion and flooding as well as run off. High runoff is directly related to flooding and soil erosion. Wetlands can store floodwaters and maintain surface water flow during dry periods (MDNR web site, 2012). However, watershed areas control the hydrology. Chemical particles and micro-organism can flow with water from one wetland to another in a watershed. Thus, it is very likely that physical and chemical connections exist among wetlands in a watershed. Wetlands within a watershed filter out toxins and improve water quality. On the other hand, wetlands replaced by impermeable surface areas can result in increased runoff. To protect wetlands and the range of environmental interactions they support, a clear understanding of these potential interactions is needed. Moreover environmental lawmakers and regulators can be better informed on how to reduce potential degradation of these important features. Wetland management is essential to safeguarding aquatic resources with the help of environmental laws.

1.3 **Wetland Connectivity**

The term connectivity refers to the presence of paths of movement among objects or landscape features. The costs associated with connectivity also known as resistance or impedance refers to the effort required to traverse a particular path.

Connectivity among wetlands can have a direct impact on the health of wetlands, streams, and associate ecosystems. Sometimes protection of only wetlands and terrestrial areas are not enough to protect wetland dependent animals and also to conserve some other important physical and chemical exchanges. Surface water and groundwater connections in a wetland system maintain energy balance and also maintain flow of other chemical components and microorganisms. Particularly with respect to amphibians, long term evaluations of metapopulation dynamics have found that the suitability of wetlands to amphibians also depends on the intermediate land use matrix (Compton et al., 2007; Bauer et al., 2010). Maintaining landscapes suitable for amphibians or other species, however, is becoming increasingly difficult with increasing anthropogenic developments. Thus understanding of the wetland connectivity is very important when it comes to protecting ecology.

The framework of my thesis considers three main types of connectivity between wetlands: a) biological connectivity – corresponding to species' perception of proximity (Taylor et al., 1993; Semlitsch et al., 2008); b) hydrological connectivity - the surface water or groundwater interaction between aquatic resources (Cabezas et al., 2011); and c) chemical connectivity – chemical mobility between wetlands or among water resources (Likens and Bormann, 1995). One type of connectivity may facilitate or perhaps threaten another type of connectivity. For instance, good surface water connections benefit fish species but threaten other species such as amphibians and similar types of micro-organisms because of increased access for predators. Similarly, hydrological connectivity is essential for maintaining water quality, but it can also facilitate pollution.

1.4 **Geographical Information Science**

Geographic information refers to any type of information that can be referenced to a location(s) on the earth's surface. Geographic information can be very detailed (e.g., tracking a species location every second) or it can be presented in a very aggregate form (e.g. one location for a species each day). The technology for collecting, manipulating, analyzing, and visualizing geographic information is called geographic information science. There are three types of technologies commonly applied to record positional information and to detect changes in landuse/landcover: 1) global positioning system, 2) remote sensing, and 3) geographic information systems. Geographic Information Systems (GIS) software allows environmental data to be stored, analyzed, manipulated and visualized (Nuckols et al., 2004). GIS is a useful tool for making information usable for planners and decision makers with powerful analysis and visualization capabilities.

The main attraction of GIS is it can provide an efficient method of managing complex data and information that have a spatial context (Stanley et al., 2005). The most commonly used data models for representing geographic features and activities in a GIS are the vector and raster data models.

1.4.1 The Vector Data Model

Points, lines, and polygons objects are the three basic geometric primitives used to represent features in the vector data model (Ogden et al., 2001). Networks are a way of representing connections among different features using vector primitives (Figure 1). In this sense, points (also known as nodes) are often used to represent the location of features such as wetlands. Whenever a direct relationship exists between a pair of points, a line or arc is used to indicate the presence of these relationships taken together. A set of nodes that are connected in some way via a set of arcs form a graph or network. Arcs in a network can be directed (i.e., only can be used in one direction like a one-way road) or they can be undirected, where movement can take place in either direction. Network arcs and nodes can also be attributed in a variety of ways with characteristics such as cost, traffic volume, capacities, etc.

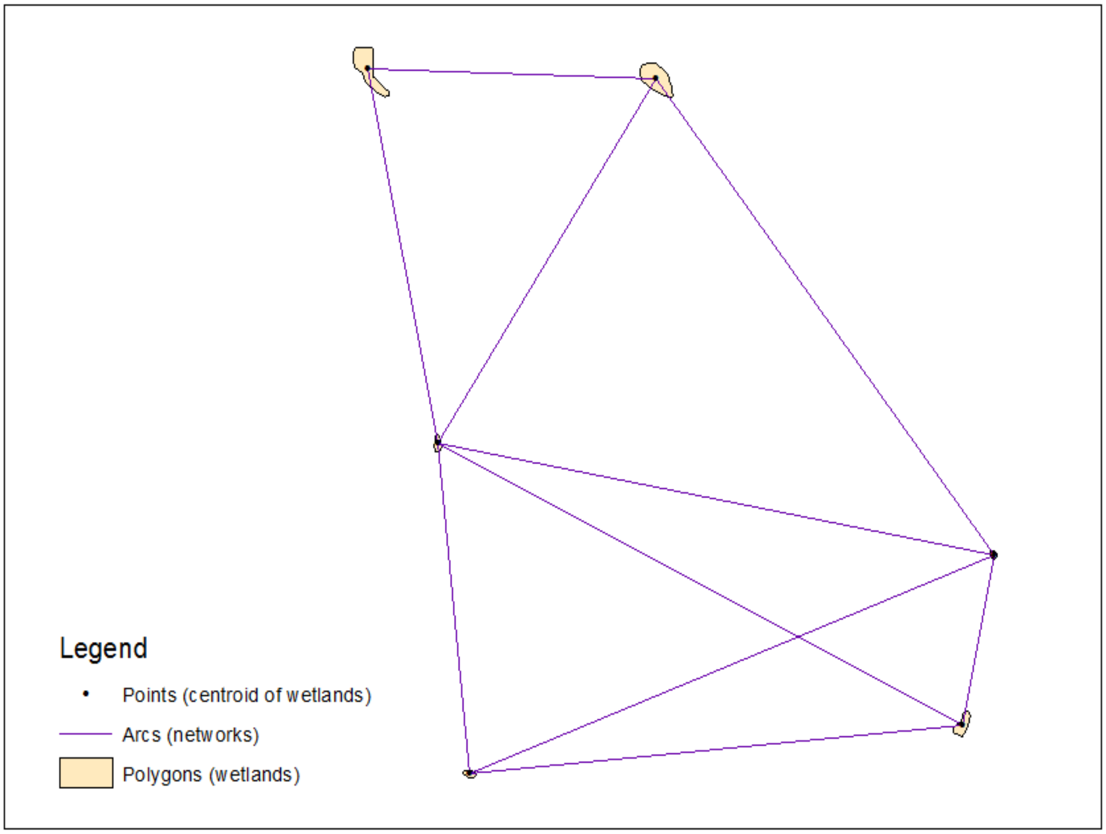

Figure 1: Example network representation of a wetland system

1.4.2 The Raster Data Model

The raster data structure differs from the discrete geometries used in the vector data model in that it is comprised of systematically spaced grid cells of uniform size which serve as the basic unit of analysis. Typically, raster cells are square, but could theoretically be of any other shape that is able to fully tessellate a plane without leaving holes in the covered region, e.g., triangle, rectangle, or hexagon (GeoVITe, 2010). Table 1 lists some of the advantages and disadvantages of vector and raster data models.

GIS presents an advantage over other computer-based analysis platforms such as CAD, given that features in different data layers are geographically referenced and can be queried within and between other data layers. Thus, GIS is a strong tool for spatial analysis because of the combined thematic attributes which contain geometrical and topological information (GeoVITe, 2010). While a base GIS system can provide many toolkits for analysis, arguably the most important strength is that it provides tools that can be used to develop new analysis techniques.

Table 1: Advantages and disadvantages of raster and vector data models

Data structure	Advantages	Disadvantages
Raster	(a) easy to produce (b) easy workflow and analysis (c) represents continuous features	(a) hard to represent objects less than cell size (b) finer resolution generates huge data (c) highly generalized representation of discrete features (d) limited interactivity and more primitive analysis algorithm
Vector	(a) simple discrete geometry that means less data (b) easy to edit (c) logical data structure (d) attributes are combined with objects (e) preserve source extent or scale after utilizing different rule and (f) many types of geographical analysis techniques supported	(a) Spatial analysis, filtering or any change inside a single polygon or line is not possible (b) continuous data is difficult to represent (c) lots of manual editing may be necessary (d) uncertainty modeling is difficult

1.5 **Thesis Goals and Organization**

The primary objective of this thesis is to model connectivity within wetland systems and to develop an analysis framework for understanding and reasoning about how different scenarios of landuse/landcover change may impact wetland connectivity. Another objective is to explore prospects for providing recommendations about how to improve system connectivity or to mitigate threats to system interactions.

Chapter 2 reviews relevant literature on the role of wetlands, connectivity and approaches for its analysis. Chapter 3 presents a methodology for modeling wetland connectivity, assessing the impact of potential landscape changes, and proposing mitigation measures. Chapter 4 applies the proposed framework to evaluate biological and hydrological connectivity in a watershed in Missouri. Chapter 5 presents analysis results, discussion and possible future directions for research. Chapter 6 provides concluding remarks.

Chapter 2

LITERATURE REVIEW

2.1 Wetlands and Wetland Systems

The meaning of the term “wetland” depends on the context in which it is used. For instance, wetland scientists are more often interested in wetland functions and their interaction with the environment. On the other hand, wetland mangers are more concerned about jurisdiction or regulatory definitions used to protect wetlands. Wetland definition becomes more comprehensive day by day and includes related sciences. This chapter will cover how definitions of wetlands have changed focusing on different parameters from the mid twentieth century (Table 2). While these definitions do exhibit some similarities, marked and even contradictory differences can also be found.

Table 2: Formal wetland definitions

Title	Source	Targeted group	Focus
Early U.S. Definition: Circular 39 Definition	USFWS (1956)	Wetland scientist and regulatory both	Wetland vegetation
U.S. Fish and Wildlife Service Definition	USFWS (1979)	More scientific than regulatory	Vegetation, hydrology and soil
Canadian Wetland Definitions	National Wetlands Working Group (1988)	Official definition of wetlands in Canada	Wet soils, hydrophytic vegetation and various biological activity
U.S. National Academy of Sciences Definition	National Research Council (1995)	Wetland scientist and regulatory both	Hydric soils, hydrophytic vegetation
An International Definition	The International Union for the Conservation of Nature and Natural Resources (1991)	Wetland scientist	Water depth

In 1995, a formal definition of wetlands was proposed by the National Research Council (NRC, 1995).

> "A wetland is an ecosystem that depends on constant or recurrent, shallow inundation or saturation at or near the surface of the substrate. The minimum essential characteristics of a wetland are recurrent, sustained inundation or saturation at or near the surface and the presence of physical, chemical, and biological features reflective of recurrent, sustained inundation or saturation. Common diagnostic features of wetlands are hydric soils and hydrophytic vegetation. These features will be present except where specific physiochemical, biotic, or anthropogenic factors have removed them or prevented their development." (NRC, 1995).

This is the most comprehensive scientific definition put forth in recent times. Although it used the terms "hydric soils" and "hydrophytic vegetation" as did the early USFWS definition, these terms are used as "common diagnostic features" rather than absolute necessities in designating a wetland.

In the mid-1970s, the United States needed specific wetland definitions that would close legal loopholes. Two such definitions were developed by USACE and NRCS for regulatory purposes. USACE (1977) adopted the definition for "dredge-and-fill" permit program as part of the Clean Water Act (CWA) (1977), and NRCS (1985) proposed another one for protecting wetland under the swampbuster provision of the 1985 Food Security Act (Glaser, 1986).

The CWA wetland definition (1977) is mainly based on vegetative characteristics whereas the Food Security Act (1985) definition places more emphasis on hydric soils. The legal definition of wetland has been debated in the courts in several cases. One notable case is “Rapanos vs. United States” where the issue was whether land discharged by a developer was isolated from navigable waters. At last Justice Kennedy concluded that if a water body has “significant nexus” with navigable water, it should be under CWA regulation. This ruling came from Solid Waste Agency of Northern Cook County (SWANCC) vs. Army Corps of Engineers, 531 U. S. 159, 167, 172, but Kennedy did not consider all the parameters necessary to determine that the lands in question had the requisite nexus. SWANCC helped to establish a framework for wetland definition. Focusing on the goals and purposes of CWA, Congress enacted the law to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters," 33 U. S. C. §1251(a), and it pursued that objective by restricting dumping and filling in "waters of the United States," §§1311(a), 1362(12). After those circumstances not only wetlands but also wetland systems came to the forefront for wetland analysis. Since then water and ecological scientists have been trying to identify and define the physical, chemical and biological nexus between navigable waters and isolated wetlands in different ways (Downing et al., 2003).

A wetland system is an ecosystem based on wetlands. A single wetland cannot exist ecologically without interaction of neighboring wetlands (Compton et al., 2007). Surrounding land use can have a significant impact on the water quality and ecological health of a wetland while considering the interactions of wetland system (Bauer et al., 2010). Wetlands balance eco-hydrology mainly based on a watershed. Ecological integrity of a wetland system supports and maintains a balance within adaptive communities of organisms having a species composition, diversity and functional organization (Karr and Dudley, 1981). The objective of the CWA is also to maintain and restore the chemical, physical and biological integrity of nation's waters (USEPA, 1998). Thus it is important to understand and manage wetlands as a system instead of a single wetland.

2.1.1 Biological Considerations

Maintaining the biological diversity of wetland systems is a very important goal for wetland management. Safeguarding the biodiversity of a wetland may lead to protecting the entire ecosystem. Often, the health of a wetland system is assessed based on an evaluation of a set of biological indicators. For example, biological indicators could be the presence of certain types of birds, reptiles, amphibians, turtles or other species (Cosentino and Phillips, 2011; Sawyer et al., 2011). Of all species, wetland dependent amphibians seem to be the best indicator because their habitat spans both wetland and terrestrial landscapes. They are a very good indication of energy flow between water body and terrestrial lands (Lowe et al., 2006; Whiles et al., 2006). Some researchers have suggested that amphibian decline is related to large-scale spatial and temporal ecosystem effects given loss or alteration of required habitats (Rothermel, 2004; Semlitsch et al., 2007). Some of this research is based on studies of a single species (Malone et al., 2008; Semlitsch et al., 2008; Gu et al., 2011) while others are based on a group of species (Beier et al., 2009; Schalk and Luhring, 2010). In grouped species studies, some of the groups are composed of the same type of animals and some of them are comprised of different types of animals. Beier et al. (2009) developed a GIS-based methodology for generating possible landscape corridors for puma, badger, fox, deer, squirrel, rat, mouse and owl. Using raster data and analysis tools, they examined the characteristics of the considered animals, performed a suitability analysis to determine the cost of traversing the landscape, and provided a visualization of the raster corridor. Over the range of these animals, few overlapping corridors were found (Beier et al., 2009). There are many controversies regarding animal perceptions, and expert opinions on the cost of traversing landscape matrix can vary widely. Lots of landscape cost parameters must be considered for even a single species (Rittenhouse and Semlitsch, 2009). Furthermore, each parameter thought to be associated with the cost of movement has some kind of uncertainty as to how it actually affects each species (Sawyer et al., 2011).

The cost of traversing intermediate landcover and assessing land use for amphibians can be based on their tendency to desiccate/dehydrate, lose energy, and die when moving through different types of matrix habitats (Cairo and Zalba, 2007; Church et al., 2007; Schalk and Luhring, 2010; Cosentino et al., 2011). Proximity to certain type of land uses can have a negative impact on amphibian movement. For instance, locations within 900 m of roads and within 2000 m of croplands are known to provide a lower quality environment for amphibians (Romero, 2010). Juvenile salamanders such as *Siren lacertina* and *Amphibia means* can only travel between wetlands as far as 0.7 km and 0.6 km, respectively (Snodgrass et al., 1999). Thus the movement characteristics of different amphibian species with different ages will vary. The distances travelled by adults have been found to range from 142 – 289 m whereas juveniles travel 245 m to 2,830 m (Semlitsch et al., 2008; Cosentino and Phillips, 2011). Travel distances have been observed for a variety of species; however, some uncertainty always exists as to the risks associated with traveling across any landscape.

2.1.2 Hydrologic Considerations

Hydrologic connections among wetlands are very important, both in maintaining water quality and in regulating pollution. Watershed delineation is a very important component when the focus is to find surface water hydrological connectivity. In a watershed, almost all the streams and wetlands are in some way connected in the absence of any barriers. Hydrologic connections can arise due to surface water flow, groundwater movement or both. Surface water connections can be perennial, ephemeral or intermittent based on their duration.

Amoros et al. (2002) discus two different types of hydrological connectivity: 1) horizontal connectivity (e.g. surface water flows) and, 2) vertical connectivity (e.g. surface water groundwater flow interaction). To characterize surface water and groundwater connectivity, temperature dynamics and elevation change can be used (Arscott et al., 2001). Micro-organisms movement may also depend on hydrology; for instance, temporary aquatic terrain may help amphibians to travel easily from one wetland to another (Schalk and Luhring, 2010). Temporary changes in surface conditions, such as those caused by storm water drainage, can provide the aquatic pathways bridging wetlands. In this sense hydrologic connectivity may be critical for biologic connectivity (Schalk and Luhring, 2010). However, the exact relationship between hydrologic processes and biologic processes still need to be more completely defined (Kurtz et al., 2007).

2.1.3 Chemical Considerations

Chemical connections are closely related to hydrological connections. Chemicals are transported from one place to another, mostly along with fluid media, in the environment. The movement of chemicals to wetlands can be influenced by many factors such as surface water and groundwater hydrology, air, etc. Some state departments overseeing water resources employ hydro-chemical monitoring gauge stations (e.g. Missouri Department of Natural Resources (MDNR), United States Department of Agriculture (USDA), and (MDNR, 2009). Water quality measurement for traditional chemical components and physical measurements cannot measure degrees of biological integrity properly. There are some other factors aside from traditional chemical and physical measurements (such as, pollutants in plants) that could help explain biological connectivity of a wetland system more clearly (Samecka-Cymerman et al., 2010). It is still uncertain what kind of chemicals can be evaluated to assess this connectivity, and moreover, one cannot always find the same chemicals everywhere. However, testing of the chemical composition of wetland vegetation has been used to evaluate chemical connectivity (Samecka-Cymerman et al., 2010).

The EPA developed an analysis tool, Better Assessment Science Integrating Point & Non-point Sources (BASINS), which is a multi-purpose environmental analysis system that integrates a geographical information system (GIS), national watershed data, and state-of-the-art environmental assessment and modeling tools into one convenient package (Whittemore and Beebe, 2000). Another tool, Hydrological Simulation Program - FORTRAN (HSPF) was developed to estimate nutrient loads and other delivery from watershed areas; calculate contributions from point, nonpoint, and atmospheric sources; and provide a means of evaluating impacts of alternative management strategies to reduce nutrient loads and improve water quality conditions (Donigian and Love, 2002). The combined use of BASINS and HSPF could be potentially used to characterize and identify chemical connectivity (Diaz-Ramirez et al., 2010; USEPA, 2000). HSPF is currently being used for watershed studies with similar objectives in Minnesota, Washington State, Oregon, Australia, Kentucky, South Carolina, Nevada, and Florida (Diaz-Ramirez et al., 2010). Donigian and Love (2002) developed a framework for quantifying the chemical input of point and non-point sources and loadings to the stream from watersheds. This model also evaluated the potential for nutrient load reduction from various Best Management Practices (BMPs) which considered implementation levels under both current and future growth scenarios (Donigian and Love, 2002).

2.2 **Wetland Delineation**

The primarily wetland database in the United States is National Wetland Inventory (NWI), an open source GIS database, that stores each wetland as a polygon (USFWS, 1979). The NWI wetland GIS data was digitized from a 1:24,000 scales raster data (Cowardin et al., 1959). The NWI wetland GIS data distinguished the wetlands and attributed wetland type and other wetland characteristics (e.g., wetland area, wetland perimeter, etc.) according to the wetland classification of Cowardin et al. (1959) (Table

3). The limitations of cell size may influence the size and shape of smaller wetlands. In the NWI, field verifications of the digitized wetlands were performed by local, state, and/or federal agencies. The main NWI products are 1:24,000 scale maps. Different types of wetland have different times of photography shots appropriate to make NWI GIS data (Table 4). Although the NWI attempts to record wetlands of all types, some estimate that around 50% of wetlands might not have been accurately digitized digitizing from low-level infra-red aerial photography (Baldwin and deMaynadier, 2009).

Table 3: Wetland inventory features descriptions

Wetland type	Map Code	Cowardin et al. (1959) classification	Wetland definition
Freshwater- Forested and Shrub wetland	PFO, PSS	Palustrine forested and/or Palustrine shrub	Forested swamp or wetland shrub bog or wetland
Freshwater Emergent wetland	PEM	Palustrine emergent	Herbaceous march, fen, swale and wet meadow
Freshwater pond	PUB, PAB	Palustrine unconsolidated bottom, Palustrine aquatic bed	Pond
Estuarine and Marine wetland	E2, M2	Estuarine intertidal and Marine intertidal wetland	Vegetated and non-vegetated brackish and saltwater marsh, shrubs, beach, bar, shoal or flat
Riverine wetland	R	Riverine wetland and deep-water	River or stream channel
Lakes	L	Lacustrine wetland and deep-water	Lake or reservoir basin
Estuarine and Marine Deep-water	E1, M1	Estuarine and Marine subtidal deep-water	Open water estuary, bay, sound, open ocean
Other Freshwater wetland	Misc. types	Palustrine wetland	Farmed wetland, saline seep and other miscellaneous wetland

The boundaries of water bodies are dynamic and they fluctuate over time (Mitsch and Gosselink, 2007). Mitsch and Gosselink (2007) explain the delineation process of National Wetland Inventory (NWI). The NWI delineation methodology involves: a) collection of the best possible aerial photography; b) digitizing wetlands according to soil and vegetation’s color hue; c) conducting field evaluations, and d) cross checking with soil survey data (Meyer, 2002). Early spring is considered to be a good time for aerial photography for overall wetland delineation. This is because wetland basins at this time are generally full without ice or snow and prior to leaf development (Mitsch and Gosselink, 2007). Even in the dry season, the silt, clay, and other fine materials in wetland basins can hold more moisture, resulting in the distinctive dark color hue. Vegetation type is another indicator of wetland and wetland's boundary. The growth pattern of vegetation in a wetland is generally denser, more crowded, or more concentrated than that of the drier non-wetland, exhibiting a higher degree of lushness, vigor, or intensity (Mitsch and Gosselink, 2007).

Physiographic position, when viewed in a magnified stereoscopic image, can be associated with the above features to make wetland location and delineation easier. Outside boundaries of wetlands are delineated on the aerial photograph by determining where the transition zone enters the upland. Some transition zones are abrupt and very evident, while others are gradual and subtle. The subtle transition zones may require ground trothing to correlate field conditions with the aerial photography and to mentally establish the point at which the transition zone becomes a non-wetland (Mitsch and Gosselink, 2007).

Prairie potholes are glacially formed wetlands characteristic of the Upper Midwest (North Dakota, South Dakota, western Minnesota, and northeastern Montana). This region is known for its wide-ranging rainfall patterns. Wetlands here may experience marked change in plant species composition from year to year (Mitsch and Gosselink, 2007). For example, wetland basins can transition from cattail marshes to tilled cropland depending on the water conditions. In the dry season, the landward limits of prairie potholes are difficult to identify, as these drier edges are often tilled and cultivated at this time. Wetland delineation is best accomplished using aerial photography acquired when the basins are filled with water. Recognizing this need, the NWI (2003) waited until spring to conduct aerial photography based on when the prairie pothole basins were full. It took several years to acquire all of the aerial photographs, but this area-specific coverage proved invaluable (Drazkowski, 2004).

Table 4: Acquisition period for NWI aerial photography

Type of wetlands	Delineation	Suitable time for aerial photography
Coastal Salt Marshes	The border line between water ward and land ward identified by vegetation/trees non-tolerance of salts or brackish water. It can be interpreted any time of the year. Here the limitation is to identify lower coastal marshes that can be flooded by daily tide and higher coastal marshes less often than daily tidal flood.	Suitable any time of the year
Prairie Potholes	This type of wetlands could vary significantly from year to year. Even these areas can be turned into crop fields. During dry season, the dry edge of the wetlands is generally occupied by crops. Thus the best time for aerial photographs and delineating is spring when wetlands basins become full of water.	Most suitable in spring season
Forested Wetlands	Evergreen forests make it difficult to identify saturated soils or moist soils because of their canopy cover throughout the year. In this case wetlands and upland delineation is only possible by collateral data and field checking.	Difficult any time of the year. Needs field checking and collateral boundary data
	Deciduous forested wetland identification becomes difficult at the summer season because of full leaf growth. Accordingly, early spring is the best time for forested wetlands delineation when the wetlands are free of ice and snow, and trees leaves are not yet fully grown	Most suitable in early spring
Seasonal wetlands in the arid west	Perennial marshes are generally easy to identify. Intermittent and ephemeral wetlands create difficulties. Again, the best time for observing these wetlands is spring.	Most suitable in spring
Rain forest Wetlands	Southern Alaska, Hawaii, Puerto Rico, and the Olympic Peninsula in Washington State have rain forests that are extremely difficult to recognize from aerial photograph. For Puerto Rico islands, there is no proper aerial photograph for higher elevations due to the density of rain forests.	Difficult any time of year
Alaskan Moist and Wet Tundra	It is difficult to differentiate bordering moist tundra from flood plain terraces because all the area is dominated with shrubs and small plants.	Difficult any time of year

2.3 **Statutes Regarding Wetlands**

Two types of regulations or laws regulate water bodies in United States. One type of regulation protects water bodies or wetlands, and the other type maintains water quality. The United States started to regulate wetlands in 1972 through the CWA. Jurisdictional wetlands regulated by the CWA of USACE under Section 404, "must exhibit all three characteristics: hydrology, hydrophytes, and hydric soils" (USACE, 1987). It is important to understand that some areas that function as wetlands ecologically exhibit only one or two of these three characteristics; hence, they do not currently qualify as USACE jurisdictional wetlands, and thus activities in these wetlands are not regulated under the Section 404 program. Such wetlands, however, may perform valuable functions.

The federal policies adopted "No Net Loss" in1989, meaning if any action for the development of mankind, as well as unavoidable occurrences which destroy wetlands, the impact must be mitigated through development of new wetlands to compensate for the loss of wetlands (Whigham, 1999). The goal of 'No Net Loss' covered the combination of many agencies goals, such as Department of the Interior, Department of Agriculture, EPA, and United States Army Corp of Engineers (USACE) (Mitsch and Gosselink, 2007).

To maintain or improve water quality for designated uses, there is a pollution control program called water quality standards (WQS) for the regulatory water bodies. The term, "designated uses" means the surface water should be of such quality that it can be used for swimming and fishing purposes safely. This WQS set some criteria and has suitable policies to reach a goal of target water quality. The complete process of meeting water quality standards mandated by CWA (1977) is accomplished as follows: Firstly, establish water quality standards that are consistent with the statutory goals of the CWA approved by state departments. Then, water bodies are monitored to determine whether the water quality standards are met, in which case anti-degradation policies and programs are employed to keep the water quality at acceptable levels. Finally, ambient monitoring is also needed to ensure that this is the case. If the water body does not meet WQS, a strategy needs to be developed to meet these standards. The most common type of strategy is the development of a Total Maximum Daily Load (TMDL). TMDLs determine what level of pollutant load would be consistent with meeting WQS. TMDLs also allocate acceptable loads among sources of the relevant pollutants. Best Management Practices (BMPs) program would help to protect degradation of the water quality.

The CWA (1977) works to reduce direct pollutant discharges into waterways, finance municipal wastewater treatment facilities, and manage polluted runoff. These tools are designed to achieve the broader goal of restoring and maintaining the chemical, physical, and biological integrity of the nation's waters so that they can support "the protection and propagation of fish, shellfish, and wildlife and recreation in and on the water" (USEPA Water Quality Handbook, 1983).

2.4 **Wetland Conservation Planning**

The state of Missouri is especially concerned with protecting its remaining wetlands (approximately 458,000 acres) and restoring other priority areas (Dahl, 1990). The MDNR was selected to coordinate wetland protection activities in 1990 (USEPA, 2011). MDNR involved a wide range of public and private representative, state representatives, federal representative, and legislative representative to participate in a Wetlands Advisory Council (WAC). WAC developed a statewide strategy for wetland protection and management through a consensus building process. WAC continued to build its state wetland program by using the strategy for guidance. In the document entitled “Wetland goals and recommendations for the state of Missouri,” WAC promoted the short term goal to, “Achieve no overall net loss of the state’s remaining wetland resource base by the year 1995” and the long-term goal to “Increase the quantity and quality of Missouri’s wetland resource base considering acreage functions and values by the year 2000.” (Epperson, 1992). With the help of subsequent WPDGs, MDNR added outreach to the conservation plan. MDNR formed a technical advisory council, developed wetland water quality standards as well as mitigation banking procedures (USEPA, 2011).

The Missouri WAC again advocated in the document entitled “*Missouri Wetlands: A Vanishing Resource*” the same short and long term goals as well as recommendations stating that more research is needed to better understand threats to existing wetland systems and justify the protection of wetland resources against these threats as well as identify how changes to wetland systems can be monitored (Epperson, 1992).

2.5 **Representing and Measuring System Connectivity**

Network modeling is a powerful way to analyze the spatial relationships among landscape features (Matisziw and Murray, 2009). But hydrological, chemical, and biological relationships and interactions can be very complex and require careful representation. In this sense, the connection between landscape features is often viewed as occurring within an area or corridor, rather than in a very well-defined trail (Beier et al., 2009; Sawyer et al., 2011). Thus, any network connection (or arc) can possibly be characterized or attributed with a wide range of qualities found in its corridors. Again, GIS provides a powerful set of tools for analysis and manipulation of geographic information that can comprise landscape corridors. Two types of geographic representations have been used to assess landscape connectivity: a) the raster data model, and b) the vector data model. Both of these data models have a number of advantages and disadvantages for their utility in representing corridors as listed in Table 5.

Raster corridors can be generated by transforming raster layers to cost surfaces, through which shortest paths conforming to certain distance restrictions can be found. This type of corridor can range from a simple shortest path or contiguous set of raster cells between two features to a larger area encapsulating many alternative paths between the features. In Figure 2 for example, if the minimum cost path from a cell to feature '1' plus the minimum cost from the cell to feature '2' is less than some limit on likely path length, then the cell could be considered part of the corridor. This type of analysis is a tool available in many GIS applications, such as ArcGIS for generating a minimum cost path (Figure 3a) or a minimum cost corridor (Figure 3b) (ArcGIS, 2011). Cell size is a limitation of raster data model, and because of that limitation, a raster corridor may overgeneralize characteristics of the landscape (Figure 4a). For instance, if any two wetland places are 20 m apart and the raster cell size is 30 m it might not recognize the corridor between the two wetlands. Figure 4a shows the zigzag boundaries of raster corridor. For ease of analysis and representation, the conversion of raster corridor to a vector (polygon) corridor makes boundary smooth again as in Figure 4b. Raster corridor always shows the whole wetland perimeter as shared edge with the corridor. The issue for this corridor raster data model is that it cannot derive the proper shared edge geometrically for capacity calculation like the vector corridor of Figure 4c.

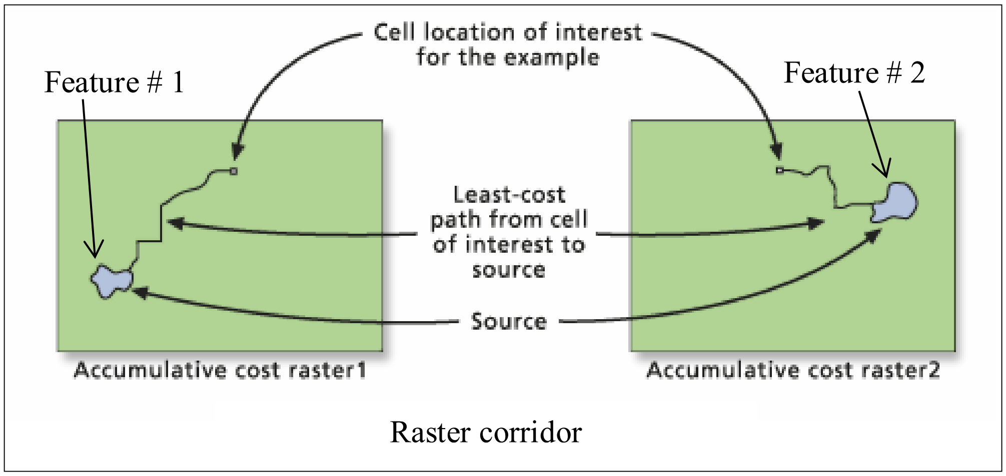

Figure 2: Raster corridor generation (source: ArcGIS, 2011)

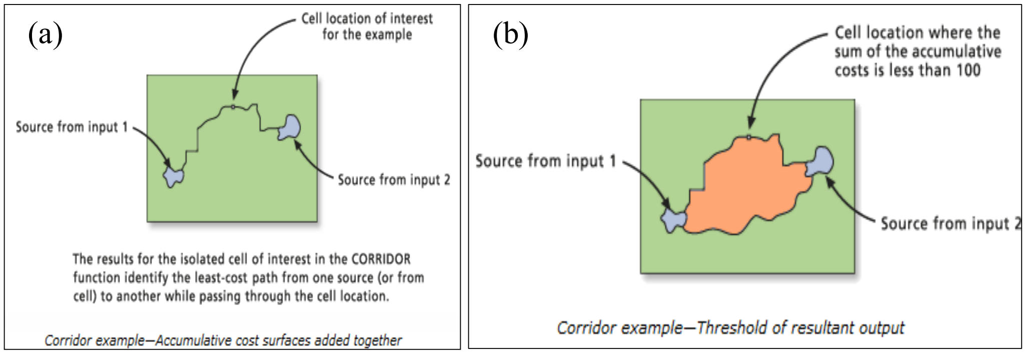

Figure 3: Raster accumulated path/corridor between two features (source: ArcGIS, 2011)

Instead of generating a corridor based on a set of raster cells that could fall along a least-cost path between two features, the vector data model (e.g., using polygon/lines) can also be used to define landscape corridors. Spatial modeling to find corridor and/or minimum path to characterize landscape connectivity has been approached in many different ways (Beier et al., 2009; Sawyer et al., 2011). Doyle et al. (2005), Matisziw et al. (2007) and Murray et al. (2007) used vector polyline networks to represent connections between Internet routers. However, it is hard to represent certain linear paths for animal movement. Some researchers have used a certain distance buffer area of a line path to represent animal movement corridors (Beier et al., 2009; Bauer et al., 2010; Sawyer et al., 2011).

Table 5: Comparison of vector and raster corridors

Factors	Vector corridor analysis	Raster corridor
Time	Vector corridor process is more time consuming because it has to come through number of ArcGIS functions.	Raster corridor model is less time consuming. There is already a built-in corridor function available in ArcGIS 10.
Accuracy	The output is a polygon of defined area.	This is a swath of range that contains a range of minimum path values.
Capacity calculation	It can create capacity. Here capacity means the arc of intersection between	The feature area is also included in the raster corridor making it very difficult to

	one feature and another proximate feature's buffer.	quantify capacity.
Flexibility	For a same maximum distance the corridor size and shape is same.	It can change corridor size using the distance limit or slicing the corridor.
Cell size	Independent of cell size.	Depends on cell size.
Suitable corridor	Based on only Euclidian distance.	Based on Euclidian distance including some other parameters that influence amphibian dispersal and migration.
Incorporate intermediate land values	Cannot do map algebra using the cost of intermediate land matrix.	Capable of doing map algebra using the cost of intermediate land matrix.

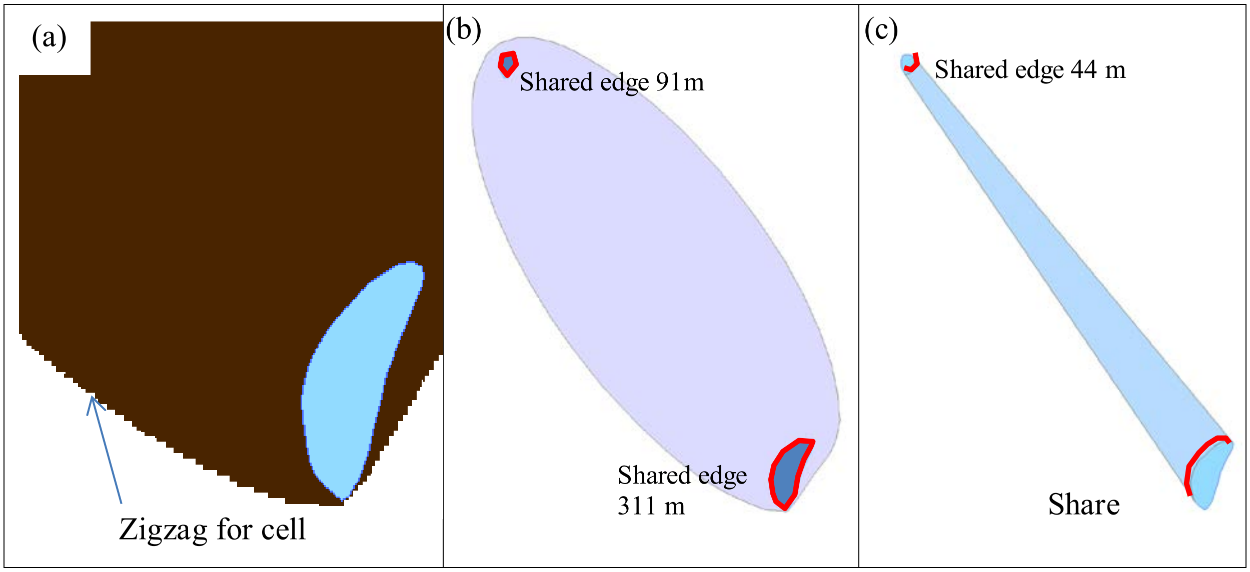

Figure 4: Comparison of corridors from raster and vector data models, a) a part of raster corridor data model, b) shared edges of raster corridor and wetlands, c) shared edges of vector corridor and wetlands

2.5.1 Biological Interaction

Biological connectivity is also known as habitat or functional connectivity in some literature (Schalk and Luhring, 2010; Ribeiro et al., 2011; Sawyer et al., 2011). Landscape connectivity is very important to the biological connectivity when considering amphibians (Ribeiro et al. 2011). Most of the literature represents habitat connectivity using the raster corridor approach because it is computationally convenient and can incorporate numerous geographic layers of data in the construction of movement costs (Beier et al. 2009; Sawyer et al. 2011).

The nature of amphibian movement in wetland systems is dependent on the intervening habitat matrix (Compton et al., 2007; Bauer et al., 2010). Amphibian movement depends on many factors such as surface roughness and weather condition (e.g. temperature, humidity, precipitation, etc.). The resistance of land use can be quantified based on tendency to desiccate/dehydrate, energy loss, and chances of mortality while moving across the landscape (Cairo and Zalba, 2007; Church et al., 2007; Schalk and Luhring, 2010; Cosentino et al., 2011). The effect of landscape variables can vary depending upon species and location. Even within a species, these effects can vary based on different age groups and sex. Thus it is difficult to find an exact cost matrix for a group of animals, even for a single species. Most research has focused on assessing the resistivity of landscape parameters (i.e., road, slope, etc.) on the movement of different species (Whiles et al., 2006; Ribeiro et al., 2011). Very few of these studies have considered more than five parameters, although Compton et al. (2007) and Bauer et al. (2010) consider more than 10 landscape parameters (but none related to climatic parameters). The following gives parameters that could impact amphibians' movement.

Wetland area

Larger wetland areas can be beneficial in a sense that a larger perimeter and terrestrial area would provide greater habitat for amphibians. However, larger wetlands are most likely perennial (water in all season), and usually also sustain population of fish or other species that prey on amphibians. Previous researchers have provided evidence that larger bodies of perennial water typically contain lower numbers of amphibians (Gu et al., 2011).

Euclidean distance

Euclidean distance is that measured along a straight line distance between two points using the Pythagorean formula. This Euclidean distance between two wetlands is thought to be one of the primary factors influencing amphibian colonization and extinction (Ricketts, 2001; Calabrese and Fagan, 2004). Distance limitations for amphibians can vary over the lifecycle of individuals. In the case of the Tiger salamander, juveniles are known to move greater distances than adults which are generally likely to stay in their breeding ponds (Church et al., 2007). The maximum dispersal distance also varies based on species (Table 6). For instance, Tiger Salamander (*Ambystoma tigrinum*) dispersal distances range from 245 m to 2,830 m (Cosentino and Phillips, 2011) while that of the Wood Frog (*Rana Sylvatica*) is over 1,000 m (Calhoun et al., 2005). Traveling from one habitat to another can come at the expense of dehydration and loss of energy. This dehydration increases their risk of mortality or chances of predation, in return resulting in more isolation or fragmentation of a wetland system (Rohr and Madison, 2003).

Table 6: Amphibian movement potential

Distance (m)	Remarks	Reference
600	Significant ecological effect of roads on plants and animals, including amphibians	Forman and Deblinger (2000)
100 – 3,000	Forest cover and amphibian presence in this range	Hecner and M’Closkey (1997); Knutson et al. (1999); Lehtinen et al. (1999); Guerry and Hunter (2002); Houlahan et al. (2000); Trenham and Shaffer (2005)
125	Adults of a variety of amphibians move up to this distance from breeding ponds	Preisser et al. (2001)
670	Juvenile Ambystoma, sp. Salamanders, dispersed up to this distance	
> 1,000	Wood frog (Rana sylvatica) data from juvenile dispersal rather than resident adult migration	Gordon (1968); Berven and Grudzien (1990); Gamble et al. (2007); Calhoun et al. (2005)
5 - 50	Spotted Salamanders and American toads can traverse this distance in grass field from forest edge	Rothermel et al. (2004)
“long distances”	Red-spotted newts may last seven years in which they may travel long distances from the natal pond	Gill et al. (1978); Forester and Lykens (1991)
451 (mean dispersal distance)	Amphibians (Tiger Salamander)	Cosentino et al. (2011 a)
245 (median nearest-neighbor distance); 36-2,830 (range)	Amphibians (Tiger Salamander)	Cosentino et al. (2011 b)
900	Amphibians, proximity of roads can negatively impact	Romero et al. (2010)
2,100	Amphibians, proximity of crops field can negatively impact	Romero et al. (2010)
> 100	Breeding and post-breeding habitat are connected by overland migrations	Semlitsch and Bodie (2003)

Effects of slope

Landscape slope is thought to have a significant impact on amphibian movement and the rate of successful colonization (Randall et al., 2006). The ability to overcome a slope gradient depends on the species of interest. The spatial configuration of wetlands with respect to elevation gradients has been observed to affect the distribution of Siren and Amphiuma within a landscape (Snodgrass et al., 1999). In particular, steeper slopes have been found to impede their movement. Amphibians can move upslope or downslope within a certain slope limit. However, the exact impact of slope on amphibian movement is still a matter of ongoing research.

Desiccation rate (moisture of the intermediate path)

Dry habitats are harmful to amphibians. Amphibians dehydrate in dry surface areas which causes energy loss and a tendency to disperse from one place to another. Some amphibians are thought to have the capability to detect restrictions (e.g., <50m, (Rothermel et al., 2004)) while others cannot (Rohr and Madison, 2003). For instance, spotted salamanders (*Ambystoma maculatum*) and efts (*Notophthalmus viridescens*) have olfactory capabilities to sense such changes in landscape parameters, while small-mouthed salamanders do not have these particular abilities (Rohr and Madison, 2003; Malone et al., 2008).

Fish occupancy

Wetlands occupied by fish are known to negatively affect amphibian populations. Fish occupancy has a greater impact on colonization and extinction than hydroperiod, vegetation cover and canopy cover (Consentino et al., 2011). Usually fish occupancy is more prevalent in perennial wetlands or streams. Fish generally eat larvae of amphibians, presenting a significant factor to amphibian survival. Thus, wetlands populated with fish are not a suitable breeding habitat.

Effect of roads

Roads are a significant barrier to amphibian dispersal. First, roads are typically dry surfaces that can desiccate and degrade energy levels. Temperatures on exposed road surfaces can be quite extreme on sunny days, such that areas within 900 m of some roads can negatively affect amphibians. Road mortality due to vehicle movement is also a noticeable threat to amphibian colonization. Three primary parameters associated with road mortality of amphibians or reduction of amphibian movement: a) road width, b) traffic volume, and c) road surface material and temperature on sunny days (Clevenger et al., 2003). Additionally, season is another factor that is related to road-mortality. The largest number of road kill happens in July (Clevenger et al., 2003, Langen et al., 2007). Bridges or culverts can function as safe corridors in a move from one side of a road to another. Mild stream flow in dry seasons and the shade provided by culverts or bridges could be helpful to amphibian populations. However, bridges and culverts can also be good locations for predators, e.g., raccoons, cats, opossum, etc. After rain, increased water currents around bridges/culverts can cause injury and death to amphibians. Moreover, the bridges and culverts are typically built based on hydrologic principles and infrastructure needs and thus, they might not necessarily occur in the path of amphibian movement.

Effects of climate and land use

Climate is a significant factor in the dispersal and migration of amphibians. Higher air temperature and less humidity in soil surface are also good reasons for body desiccation (Cosentino et al., 2011). Amphibians usually move twice a year. Amphibians have a body surface area-volume ratio that causes more dehydration through skin (Rohr and Madison, 2003; Semlitsch et al., 2008). This desiccation also depends on temperature, humidity, and the surface area of different types of land uses.

Amphibian movement potential through crop fields can vary based on the type of crop and the time of year. Forest and soybean fields lessen the decrease of body mass, but corn and prairie crops are more apt to decrease the body mass (Consentino et al., 2011). Soybean fields create more shadow and increase humidity to the underneath soil surface which might be suitable for amphibians (Cosentino et al., 2011). Usually crops such as amaranth, buckwheat, pearl millet, soybean, and sunflowers are planted in June and harvested in October. Again winter crops such as canola and wheat are planted in September and October and harvested in mid-June to early July in the United States. Sometimes agricultural lands are occupied with a combination of crops such as a combination of amaranth, buckwheat, sunflower and pearl millet (Pullins et al., 1997). Most crop lands restrict dispersal potential in some way, except those planted with soybeans. When a combination of soybeans and pasture or soybeans and crops are available, most amphibians are thought to prefer traveling through soybean fields or ecotone (transition zone between soybean fields and pasture) as their path of dispersal (Cosentino et al., 2011). After planting, soybeans create more restrictions than a bare field. Also, other aspects of the farming process (such as spraying pesticides, plowing, etc.) can pose risks to amphibians (Clark et al., 2009).

In ecology or wetland management, network analysis has been widely used to model and evaluate spatial systems (Cabeza and Moilanen, 2001). Murphy et al. (2010) used a network-based gravity model showing genetic flow as a function of three basic components: distance between sites, production/attraction (e.g. at-site landscape process), and resistance (e.g. between-site landscape process). The hypothesized productivity is limited by breeding site characteristics such as the introduction of predatory fish and inherent site productivity. For some species, network connectivity is thought to be negatively correlated with predation, while positively correlated with gene flow for other species (Murphy et al., 2010). Most of the habitat connectivity models use the negative effect of predation and positive effect of site productivity, including bottleneck tests that support the presence of source–sink dynamics (Rothermel, 2004). Ribeiro et al. (2010) examine the correlation of structural network (geographic relation) representation of habitat with functional connectivity (biologic interaction) based on amphibian persistence. Their geography-based network illustrated how spatial structural network can reflect amphibians' biodiversity pattern (Ribeiro et al., 2011).

2.5.2 Hydrological Connectivity

Surface water connectivity can be determined from aerial photography or Digital Elevation Model (DEM). Sub-surface or groundwater connectivity and representation can be more challenging to determine than surface water connectivity. Cabezas et al (2011) utilized water level, river discharge and temperature to define/quantify connectivity between a river channel and different types of riparian wetlands. Their study also characterized surface water, groundwater and their connections with a hysteresis diagram to characterize each wetland connection in different seasons. Hydrologic connectivity refers to the exchange of mass, energy, and organisms between wetlands. The hydrologic path could be variable in size based on season or time of year as well as the direction of water flow. The hydrological parameters that influence ecological system are discussed below.

Contributing area to wetland or stream

The portions of the landscape diverting runoff to a wetland or stream are referred to as the contributing areas. These areas are hydrologically connected to the wetland at least after precipitation. Schalk and Luhring (2010) noted that their study area generally contained a number of ephemeral streams within the wetland which helped amphibian dispersal or migration. However, they only studied the two most aquatic species out of a large number of amphibians.

Streams/Flow path

Streams are necessary for some stream breeding amphibians and also sometimes helpful to dispersal (Lowe et al., 2006; Whiles et al., 2006). Ephemeral or intermittent streams may facilitate amphibians (salamander) colonization (Schalk and Luhring, 2010). Some amphibians rely on the streams created during flood events (Schalk and Luhring, 2010). In contrast, perennial streams contain predators that usually have negative impacts on amphibians and the flow of flood related streams always distracts amphibians. The resistance also depends on the direction of movement and depth of water in the stream. If the direction of movement is along the stream then it might be helpful to movement, but if it is in reverse direction of the flow then it could be difficult to overcome the flow and slope. Whether amphibians will move in an upstream or downstream direction depends on their body condition too. Here, body condition refers to growth rate and productivity, which are positively auto-correlated through time in an individual's movement (Lowe et al., 2006).

Groundwater and precipitation

Groundwater level and groundwater-surface water exchange areas can be important environments for amphibians. Diminishing streams lose a significant amount of water to the subsurface through bed rock openings. In contrast, gaining streams add a significant amount of water from subsurface to surface streams. Another groundwater-surface water exchange is springs that have natural opening from the groundwater to surface. All of them maintain soil moisture that is related to amphibian breeding and movement. If the groundwater level is not far below the earth surface and there is no impervious rock between the surface and groundwater, soil moisture is preserved and amphibian movement is facilitated. Accordingly, larger distances between groundwater and soil surface with impervious rock in between the two surfaces makes soil dry and unsuitable for amphibians. Rain is also an important hydrologic factor to make a suitable environment for frogs and salamanders. After rain, when habitats are wet, is the most suitable time for amphibian dispersal (Cairo and Zalba, 2007).

Soil/Bed rock and elevation

The permeability of soil and the depth of bed rock underneath soil surface are important to conservation of soil moisture. Impermeable soils are not suitable because they usually cannot hold moisture which can dehydrate amphibians during dispersal (Rohr and Madison, 2003). Bed rock near soil surface helps to hold soil moisture which is suitable. Elevation is thought to be another influential factor in amphibian movement (Snodgrass et al., 1999). Elevation is considered mainly from wetland centroid to nearest downstream. Length of flow path from wetland centroid is also important for analysis (Romero et al., 2009).

Bed slope

A stream's bed slope or channel influences water flow or current. High current or water flow kills larvae and also distracts amphibian from their direction of movement (Lowe et al., 2006). No significant research is available on the effect of stream water flow on amphibian habitat fragmentation.

2.5.3 Chemical Connections

Determining whether two wetlands are connected chemically (e.g. share common chemical traits) is important in efforts to monitor and mitigate threats to wetland health. For instance, sites for locating Best Management Practices (BMPs) for repairing, and protecting wetland function can be better identified given knowledge of chemical connectivity among aquatic resources. Some research has explored the representation of chemical connectivity from statistical analysis of different chemical components at different geographical locations (Rentch et al., 2008). Wetland water contains lots of chemicals that can serve as good indicators of chemical connectivity, e.g., calcium, magnesium, ammonia, bi-carbonate (H-HCO3) pH, alkalinity, conductivity, etc. (Kurtz et al., 2007).

The combined use of BASINS for watershed system analysis and Hydrologic Simulation Program-Fortran (HSPF) for evaluating impact on water quality might provide a good way of characterizing and representing chemical connectivity (USEPA, 2000). Some limitations of the HSPF approach are the extensive data requirements (e.g., hourly rainfall), model hydraulics limited to non-tidal freshwater systems and unidirectional flow, simplified representation of urban drainage systems (e.g., culverts, pipes, CSOs), and an absence of comprehensive parameter estimation guidance (CWEMF, 2002).

Chemical characteristics such as low conductivity (12.0–15.0 mS), slight acidity (pH of 5.0–6.0), high dissolved oxygen content (80–90% saturation), and moderate midday summer temperatures (13.0–17.08C) are suitable for amphibian breeding and wandering (Likens and Bormann, 1995). Currently chemical data for all the wetlands are not freely available. The Department of Natural Resources (DNR) in Missouri maintains chemical data sampling stations only on historical wetlands and streams. Amphibians are very much related to water and their skin is semi-permeable. Thus, acidity or alkalinity of water may play a big role in their health (Likens and Bormann, 1995).

Also, since amphibians usually breed near water, it is important that their larvae have a good food supply. Thus, high levels of Total Suspended Solid (TSS) in the water may present an obstacle to the larvae in seeking food.

Finally, current research has not clearly identified the impact of nitrogen and phosphorus on amphibian health or fragmentation/isolation. However, too much nitrogen and phosphorus may cause death of larvae (Earl and Whiteman, 2010).

2.6 Network Analysis and Vulnerability Assessment

Network analysis can provide a tremendous number of insights to many types of geographical problems (Matisziw and Murray, 2009). Network vulnerability assessment is one important component of network planning and management (Wood, 1993). A network is constructed with arcs and nodes. Disruption of node and/or arcs may impede network flow (e.g., connectivity, flow capacity, etc.). Several approaches exist for assessing vulnerability to the loss of arcs and nodes including the mathematical programming approach as well as scenario-specific, strategy-specific, and simulation approaches. Matisziw et al. (2009) and Murray et al. (2008) provide detailed discussion of these approaches and their limitations. These methods have been applied in a range of contexts such as transportation systems, Internet systems, habitat systems, etc. In particular, mathematical programming approaches are especially valuable given their ability to identify scenarios of arc/node loss most severely affecting network performance (Church et al., 2004; Matisziw et al., 2007). On the other hand, scenario-specific and simulation approaches can be used to characterize other scenarios of interest (Matisziw et al., 2009). A crucial part of network vulnerability analysis is how the network is defined to represent current system conditions. In a habitat system, the capabilities of organisms to interact are generally used to define the network. Habitat interactions are too dynamic to result in a long-term management decision (Drechsler, 2005). From the planning point of view, we must characterize the range of connectivity and understand the impact of node and/or arc loss on a whole network to be effective.

Network disruption models are one form of modeling that can be used to assess network vulnerability to arc and/or node loss. Murray et al. (2007) demonstrate the use of a flow disruption model for modeling the effects of node loss on network performance. In particular, their model is structured to maximize disruption to network performance given that *p* nodes are permitted to be lost. This model was used to identify which node/nodes would impact most and/or least flow in an Internet system (Murray et al., 2007). Similarly, Matisziw et al. (2007) introduced a network vulnerability model capable of maximizing network disruption and provided the ability to interdict network arcs. They presented a linear-integer optimization approach which can be used to find a cut-set of arcs that maximizes or minimizes connectivity loss (Matisziw et al., 2007). Matisziw et al. (2009) also demonstrated how the impacts of connectivity loss or change can vary based on different network configurations. While all these network disruption models can be constructed to interdict nodes or arcs, many other network disruption models are available that can address other modeling objectives and planning constraints (Wood, 1993).

There are several ways of assessing the impact of network vulnerability. Mathematical programming is one way of assessing the impact of network disruption, and it is popular to find the maximum and minimum bounds (Salmeron et al., 2004). Another way of doing this is to simulate different scenarios of disruption to explore the range of impacts that may arise. For instance, Matisziw et al. (2009) simulated scenarios of node loss by removing a set of nodes and re-calculating the characteristics of the network. The characteristics/parameter of a network changed by the scenario of node loss could involve things like connectivity, capacity, flow, etc. In a habitat network, the performance of a system can be measured in a number of ways, such as:

Maximum flow: Maximum flow is a summation of minimum flow (bottle neck) of every possible path between a pair of nodes (Fulkerson et al., 1956). For example in Figure 5, the possible paths between node 2 and 1 are: a) 2-3-1, b) 2-3-4-1, c) 2-4-1. For path (a), minimum flow is $min\ (161, 44) = 44$; for path (b), the minimum flow is $min\ (227, 184, 44) = 44$ which is already occupied by path (a) for the 4-1 arc; for (c) min, $(227, 78) = 78$. Thus, according to the maximum flow theory, the maximum flow between node 2 and 1 is $(44 + 78) = 122$.

The maximum flow for this network is the summation of the maximum flows between all possible pairs of nodes or habitats.

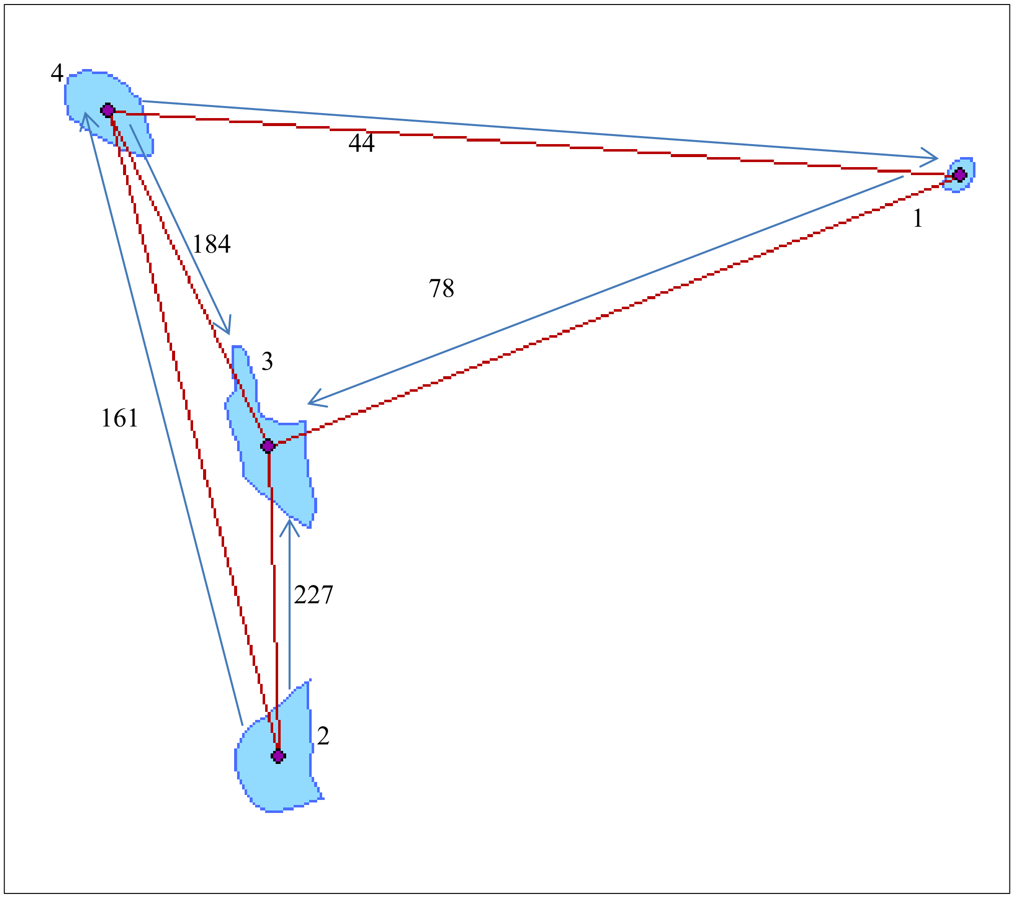

Figure 5: An example network

Sum of Capacity: Another measure of network performance is the total capacity of all network arcs of a network that is functional. In the network shown in Figure 5, the sum of the capacity is *695* (*161+227+78+184+44*).

Connectivity: Connectivity refers to the availability of a path between two nodes in a network. The most common way to measure connectivity is to find the shortest path or least cost path between a pair of nodes (Daskin et al., 1995). If a path can be found between a pair of nodes, they can be considered to be connected; otherwise, connectivity does not exist. Since a multitude of paths can exist between a pair of nodes, often only a subset of possible paths are considered when evaluating connectivity. For example, the k-shortest paths or paths conforming to a specific cost threshold can be used to represent realistic prospects for network movement. For instance,

in Figure 5, node *2* and node *3* have only one path containing one arc (arc 2-3) when it is 1 step paths, but when it is 2 step paths, then it has another path containing 2 arcs (arc 2-4 and arc 4-3).

2.7 **Wetland Mitigation Options**

There are many circumstances when a new site needs to be selected to augment an existing network. For example, business expansion can require identifying a location for a headquarters for a large company or siting a local switching center for a telephone company (Church and Murray, 2009). A new site could be point-based (i.e., a facility building), line-based (e.g., utility corridor, bus route, etc.), or area-based (e.g., recreation area, natural reserve, etc.). There are many ways to determine an optimal location for siting a new facility (such as 1-center problem, geometric median, etc.) that account for the spatial relationship of the new site with areas in need of service (and the relative levels of demand for the service existing at those areas). In particular, Weber (1909) describes a model for siting a new facility in order to minimize transportation costs, where transportation cost can be interpreted as a function of distance. The new facility site fulfills the demands of existing locations at the lowest cost. The demand could be anything representing need for a service (Church and Murray, 2009). From a management point of view, it is important to find or understand potential benefits associated with a new facility. In a wetland system, a new facility can be a wetland or wetland corridor. Applying Weber's (1909) problem in this case could then provide insight on where a new wetland could be sited such that its location complements and strengthens connectivity best in a wetland system. Identifying a new wetland site that minimizes distance to other proximate wetlands would allow planners to make better decisions in efforts to mitigate damage to wetland systems. The Weber formula can also be extended for siting multiple facility locations. The multisource Weber problem deals with locating multiple facilities concurrently in a continuous plane, minimizing the total distance (transportation cost), while satisfying the demand at each service location (Brimberg et al., 1998).

White and Fennessy (2005) performed a suitability analysis for wetland restoration potential at the watershed scale. In their analysis, AHP was utilized by comparing pairwise criteria of land use/land cover to derive standardized factors for a wetland location analysis. The parameters used for standardization of factors were: a) stream order, b) overland flow length, c) saturation index (without permeability), d) saturation index (with permeability), e) land use type, and f) use attainment. Utilizing GIS and available data, White and Fennessy (2005) identified and prioritized wetland restoration sites. Another type of GIS suitability analysis for mitigation site selection was done by Lonkhuyzen et al. (2004). In their study, suitability was assessed for potential wetland areas based on an index of hydrology, soil, historic condition, adjacent vegetation, vegetation cover, and land use. Several studies detail the desirable characteristics of mitigation wetlands but very few provide details on prospects for identification of potential mitigation sites for enhancing ecological characteristics of a region and species behavior (Van Lonkhuyzen et al., 2004; White and Fennessy, 2005; Hunter et al., 2012).

In Missouri, since the beginning of the USACE Section 404 regulatory permitting process in 1982, the Missouri Department of Transportation (MoDOT) has been responsible for constructing wetlands to compensate for those lost due to their activities (MoDOT, 2012). Since the beginning of the U.S. Army Corps of Engineers (COE) Section 404 regulatory permitting process in 2008, MoDOT has constructed approximately 69 wetland sites, totaling over 600 acres (excluding mitigation bank sites). Most of the sites are located within MoDOT's right-of-way (ROW) or immediately adjacent to ROW (MoDOT, 2012). Generally, MoDOT must monitor these sites for up to five years following their completion to ensure their success before the COE will formally grant a release. Once these sites are released, MoDOT typically retains them in its realty inventory (MoDOT, 2012). The ultimate intent is to hand over these properties to a trust or non-profit organization so that they can perform any long-term maintenance and protection (MoDOT, 2012).

Wetland mitigation is a part of regulatory action where selecting a location for wetland construction is a significant issue. There is disagreement as to whether constructing a new wetland is a good solution for mitigating the impact of wetland loss for development. According to Schulse (2011), if a constructed wetland can maintain all the suitable characteristics for amphibians then it is possible to construct an effective wetland. No fish, high vegetation and low slope as well as low anthropogenic disturbance are most suitable for a constructed wetland (Sexton et al., 1994; Semlitsch, 2008; Cosentino and Phillips, 2011). A constructed wetland has to maintain interaction with the local habitat network. The location of a constructed wetland depends on the types of connectivity demand of its neighbor wetlands.

Chapter 3

METHODOLOGY

3.1 Corridor Generation and Network Representation

While the raster data model has been used to generate corridors between landscape features, it may not be an effective option in other cases, as discussed earlier. In these cases, a vector network model might be a better solution for further analysis. Network analysis is more flexible and can be applied to any system that can be represented as a network. Parameters for defining an environmental system can vary widely based on location and species but a baseline network can be constructed that can be used to represent general geographic characteristics of the system. To address this goal, this thesis explores an alternative means of generating corridors using a vector representation. The resulting vector corridor representation can then be easily converted to a network for analyzing various types of geographic relationships, in particular: a) direct connectivity – movement can occur directly between two features, and b) indirect connectivity – movement between two features that necessitates traversing intervening features.

3.1.1 Vector Corridor Generation

Here, a vector corridor between two wetlands is conceptualized as a polygon or line feature that could represent the potential areas of movement between wetlands. Given any two wetland polygons, such as those available in the NWI dataset (USFWS, 2012), the possibility of a direct relationship must first be assessed (i.e., are the two wetlands within a specified distance range of one another). If a direct relationship is possible, then a corridor could exist and be modeled as a polygon feature. Consider the following notation:

$i, j =$ index for wetlands, entire set denoted as I

$S =$ range (i.e. distance within which a connection is possible)

$C_{ij} =$ vector polygon corridor between i and j

$A_i =$ polygon wetland i

$A_i' =$ buffer transformation of polygon i by range S

$L_i =$ polyline representation of A_i

$C_{ij} =$ vector polygon corridor between i and j

$P_i =$ Intersected arc of wetland i with buffer area A_j'

Using these notational conventions, the following algorithm for creating a corridor between two wetland polygons is proposed:

VECTORCORRIDOR $\{i, j, S, A_i, A_i'\}$

1. Compute the intersection T of A_i' and A_j $\left(T = A_i' \cap A_j\right)$.

2. If an intersection exists (i.e., $T \neq \{\varnothing\}$), a direct connection is possible and proceed to Step 3. If polygons i and j are not connected, go to TERMINATE VECTORCORRIDOR.
3. To get the perimeter of wetland *i* exposed to *j*, compute the intersection P_j of $A_i^{'}$ and L_j $\left(P_j = A_i^{'} \cap L_j\right)$ (P_j is also the capacity of j wetland)
4. To get the perimeter of wetland *j* exposed to *i*, compute the intersection P_i of $A_j^{'}$ and L_i $\left(P_i = A_j^{'} \cap L_i\right)$
5. The capacity of the corridor $cap_{ij} = \min(P_i, P_j)$
6. Compute the convex hull (CH_{ij}) of P_i and P_j
7. Find the union $U_{A_i A_j CH_{ij}} = CH_{ij} \cup A_i \cup A_j$
8. Select the polygon $k \in U_{A_i A_j CH_{ij}}$ where $k \cap A_i$ and $k \cap A_j$
9. The selected polygon $k = C_{ij}$ is the corridor between wetlands *i* and *j*
10. TERMINATE VECTORCORRIDOR

VECTORCORRIDOR works with any pair of wetlands to: a) identify whether a direct corridor exists and if so, b) generate a vector representation of the corridor. At the beginning, a buffer transformation of all the wetland polygons by a distance *S* is applied to create new polygons $A_i^{'}$. Next, all wetland polygons are converted to polyline objects representing the boundary L_i of each wetland (Figure 6b).

In Step 1, a buffer area A_i' of wetland polygon i intersects with all the wetlands within range *S* of the wetland; in Step 2, the algorithm checks if the buffer polygon A_i'

intersects with any other wetlands' polygon A_j (Figure 6c). If an intersection occurs, then the wetland(s) will be identified as neighbors. In Step 3, the buffer area A_i' intersects the perimeter polyline of neighbor wetlands to select the portion of the perimeter of the neighboring wetland contained within the buffer area. This intersecting portion of wetland perimeter ($\left(P_j = A_i^{'} \cap L_j\right)$) is used to represent the capacity of wetland *j* exposed to wetland *i* (Figure 6d). In Step 4, similar to Step 3, the neighboring wetland's buffer $A_j^{'}$ intersects with the polyline perimeter of wetland L_i. This is done to determine the portion of the perimeter of wetland *i* exposed to wetland *j*, representing the capacity for movement out of *i* to *j*. In Step 5, the lengths of the intersection parts of each wetland (P_i and P_j) are evaluated and the minimum length of the two perimeter parts P_i and P_j is selected to represent the capacity of that corridor (Figure 6h). In Step 6, the convex hull of the pair of intersected perimeters P_i and P_j is computed (Figure 6e). In Step 7, a union of the convex hull polygon and the two neighboring wetland polygons is created (Figure 6f). In Step 8, the polygon that touches both wetland polygons is selected as the corridor (Figure 6g).

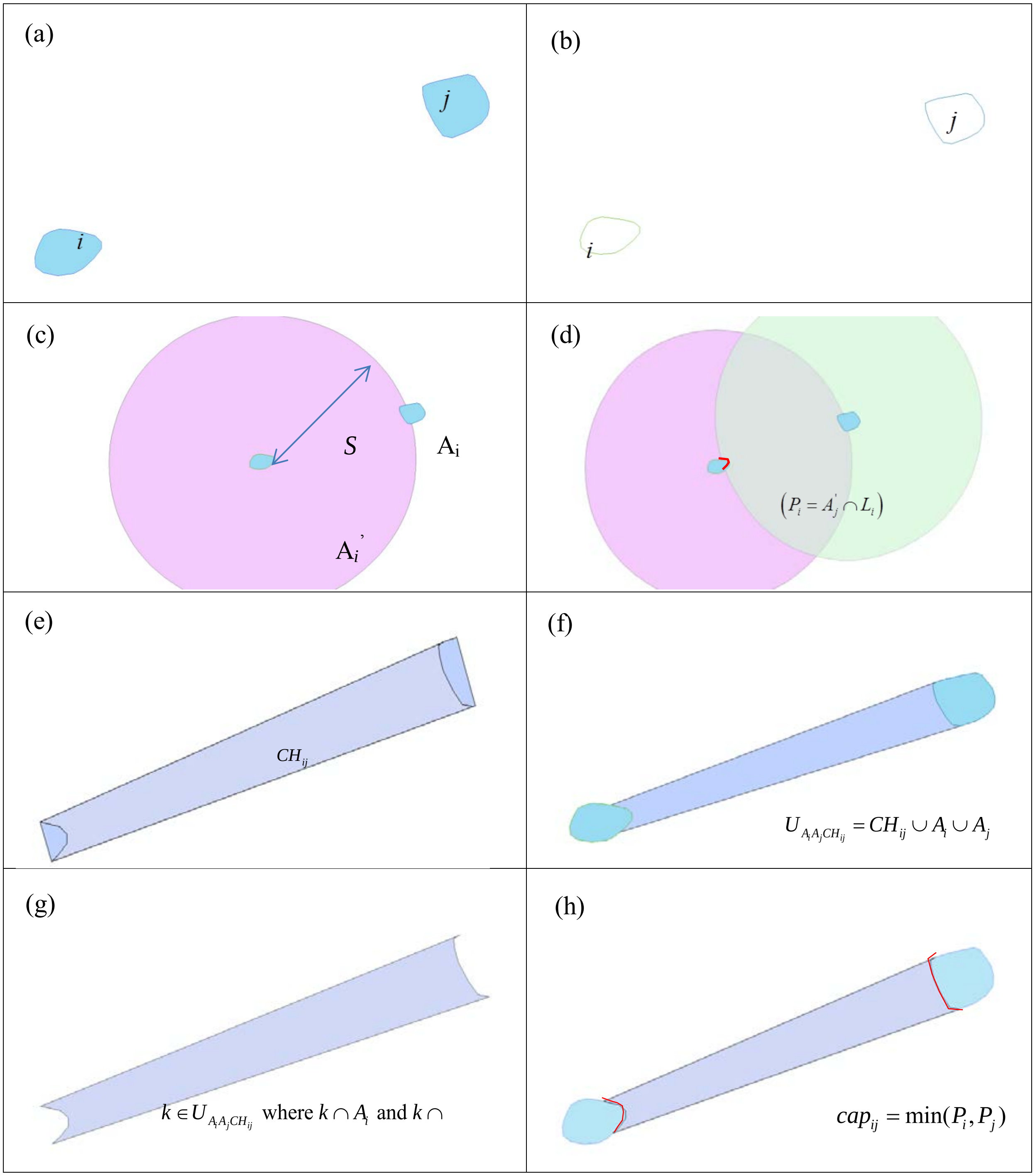

Figure 6: Vector corridor generation steps: a) a set of two polygons (wetlands), b) the perimeter of the two polygons, c) wetland buffer intersecting neighbor wetland's area, d) buffer of both wetlands intersects neighbor wetlands, e) convex hull between the intersected parts of the two wetlands, f) union of convex hull, and the two wetland polygons, g) corridor selection, h) red arcs are showing the capacity (effective length of perimeter) of the corridor.

While the algorithm is shown for assessing a corridor between two wetlands, it can be easily extended to evaluate and construct corridors between many pairs of wetland polygons.

3.1.2 Deriving a Network from the Vector Corridors

The application of network analysis is an effective tool for analyzing geospatial relationships among landscape features (Matisziw et al., 2007; Matisziw and Murray, 2009). The corridors generated in the previous section can be easily converted to a network representation to facilitate analysis of wetland systems. A network can be generated by connecting centroids (nodes) of the wetland polygons between which corridors exist. Consider the following notation:

$i, j =$ index for wetlands, entire set denoted as I

$S =$ range (i.e. distance within which a connection is possible)

$C_{ij} =$ vector polygon corridor between i and j

$G(N, A) =$ a network with N nodes and A arcs

```
1. CORRIDORNETWORK { $G(N,A), C_{ij}$ }Convert all polygons to nodes (i.e., points)
2. Add nodes to $G$
3. For each corridor $C_{ij}$, construct an arc ( $i, j$ ) between points $i$ and $j$
4. Transfer attributes (i.e., capacity) from $C_{ij}$ to arc ( $i, j$ )
```

5. Add arc (i, j) to network G

Using corridors derived in VECTORCORRIDOR, the generation of a network representation is relatively straightforward. Step 1 is to create a centroid point (node) for all the input wetland polygons. Step 2 adds all the nodes to the network G. Step 3 is to construct an arc (i, j) between two nodes of a corridor C_{ij}. Step 4 is to transfer all the attributes from corridor C_{ij} to corresponding arc (i, j). Finally, in Step 5, all of the arcs are added to the network G.

For example, the polygon of *i* and its neighbor *j* in Figure 7a are converted to centroid points *i* and *j* in Figure 7b. Next, an arc connecting these points (nodes) is generated (7b). This network is helpful for further analysis.

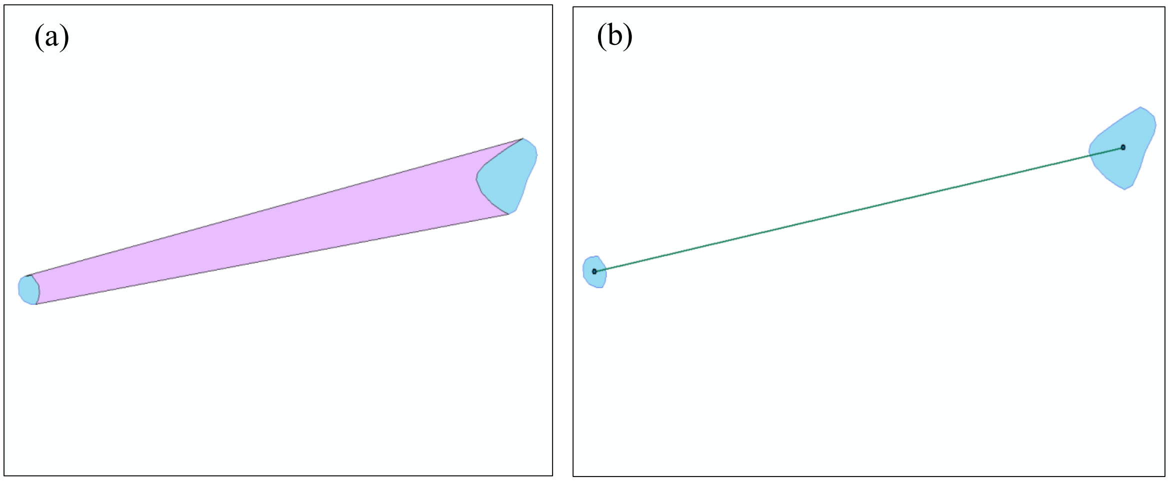

Figure 7: Conversion of vector corridor to an arc: a) polygon corridor, b) arc and nodes of a network

3.2 **Modeling System Vulnerability**

Once corridors have been generated and a network representation has been developed of a wetland system, vulnerability of the system to corridor/wetland losses can be better evaluated. There are several ways of conducting such vulnerability analyses. Keitt et al. (1997) evaluated possible scenarios of habitat loss by systematically removing individual habitat wetlands from a habitat network and computing changes. In their analysis, the impact on the network was used to assess the ecological importance of habitat loss. Later Urban and Keitt (2001) went further by removing arcs and nodes randomly from a habitat network, as well as in sequential order, based on habitat characteristics. In this thesis, systematic removal of nodes (wetlands) and arcs (corridor) is similarly assessed; however, this vulnerability model is using corridor characteristics.

3.2.1 Assessing Impact of Individual Wetland and/or Corridor Loss

The use of an incremental node removal strategy is first applied to evaluate the importance of each wetland in a habitat network.

Consider the following notation for incremental wetland/corridor loss based on corridor characteristics:

$G(N, A) =$ a network with N nodes and A arcs

```
INCREMENTALREMOVAL $\{ G(N, A) \}$
1. Select a node/arc
```

2. Remove the node/arc from $G(N, A)$ resulting in modified network(s) $G(N, A)$
3. Compute the characteristics of the modified networks relative to the original one to get the amount of change associated with removing arc/node
4. Evaluate the relative amount of change induced by each removal scenario to determine which node/arc's loss represents the largest vulnerability. $I = Vi$ the vulnerability associated with removing i

Generally speaking, as arcs/nodes are lost or damaged, then connectivity between other features is degraded. These changes in the network's ability to perform can be viewed as connectivity, flow, capacity, etc. For each scenario of arc/node loss, change in network performance induced by the loss of that arc/node can then be plotted.

3.2.1.1 An Example of Incremental Node/Arc loss

Figure 8 depicts an example wetland system containing six wetlands and six corridors. Each wetland centroid is considered as node and its connections are spatially represented as arcs/corridors. This model removes each node (wetland) one by one, starting with node '*0*' and ending with node '*5*'. For the system in Figure 8, note that node '*1*', '*3*', '*4*', and '*5*' are in a connected region/network while node '0' and '2' are in a different connected region/network.

The elimination of one wetland from a connected region doesn't have any effect on wetlands in other wetland regions. For example, removal of wetland '0' only impedes the network capacity and flow with wetland '*2*', not on wetlands in different region/network. Removal of node '*3*' will result in the loss of its three incident corridors

(corridors '*b*', '*d*', and '*e*') and degrade the network capacity from 695m to 205m (Figure 9).

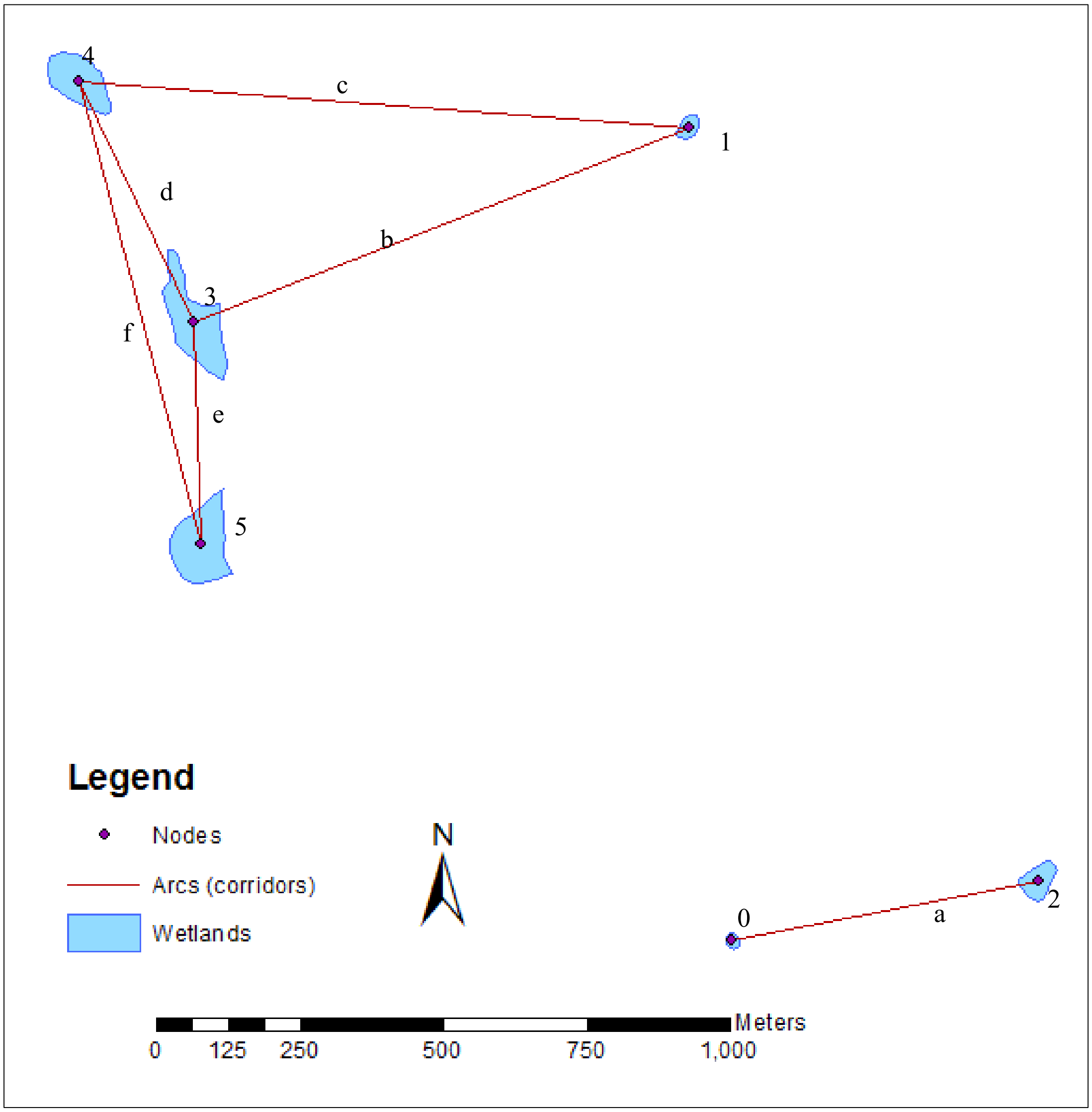

Figure 8: Example wetland system

After each node is removed from the system, several measures of network performance, such as total network capacity, total network flow, and network connectivity are computed. The relative impact of each wetland's loss can then be evaluated. For instance, Figure 9 plots the "capacity or flow lost given the removal of each wetland.

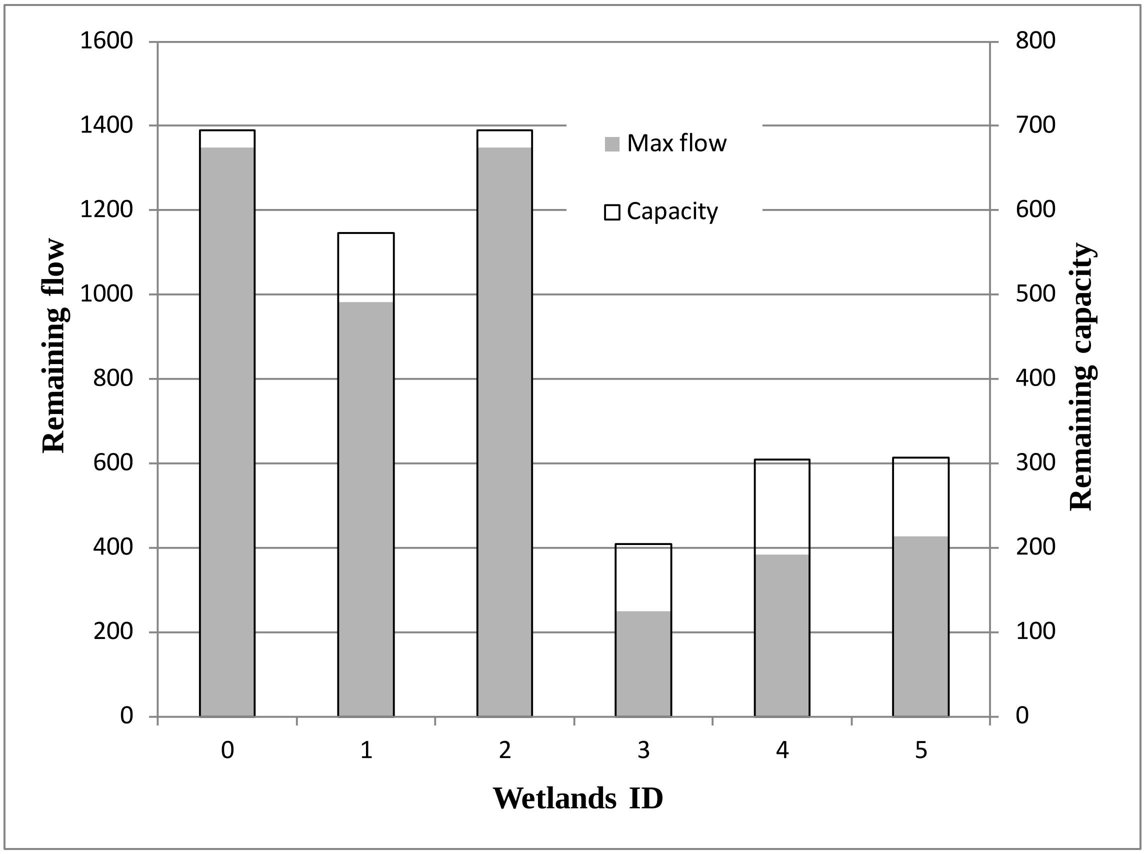

Figure 9: Wetland loss impact on the network

The impact of individual corridor losses on network performance can be assessed in a way similar to that of node loss. Next, each corridor is removed in turn, updating the network's performance characteristics (e.g., flow, capacity, etc.) at each stage. Again, elimination of corridor from a wetland region doesn't impact network performance in other regions, which is similar to the previous model. Here in this example, the impact of corridor loss is also evaluated utilizing the maximum flow and capacity parameters.

From Figure 10, it is noticed that arc ‘*a*’ creates minimum impact on the network because remaining network flow and capacity is maximum whereas arc ‘*d*’ creates maximum impact. This model computes the impact based on a network or sub-graph, the arc ‘a’ is not in the sub-graph that is computed, thus the removal of arc ‘a’ has no impact on the sub-graph.

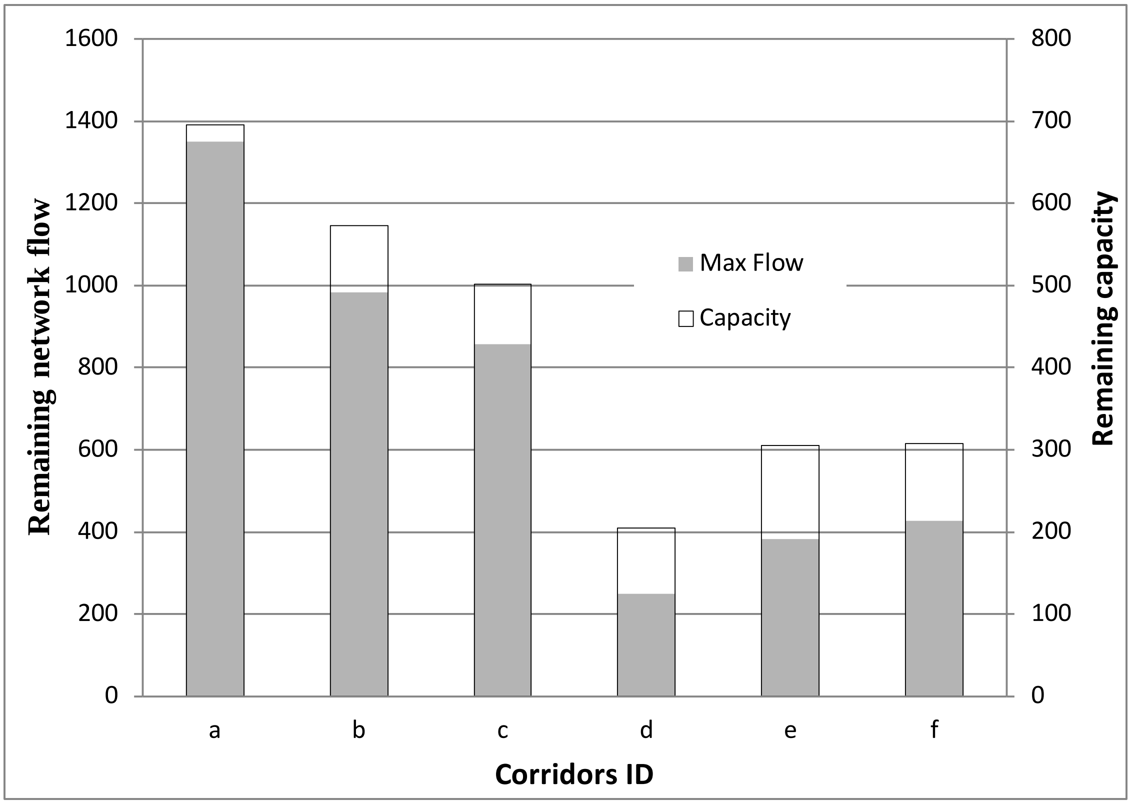

Figure 10: Impact of corridor loss on network performance

3.2.2 Modeling Simultaneous Loss of Arcs

Human development not only affects the wetlands themselves but connections among them as well. Loss of connections between elements of a system is known to affect the whole network and make it more vulnerable to threats (Doyle et al., 2005).

Damage to network arcs and nodes can affect a network's performance in many ways such as reducing capacity for movement, flow, or ability of nodes to interact. It is important for watershed management to understand the importance of these connections to the entire wetland system. However, threatening changes to wetlands and their corridors often occur. For instance, a proposed road might involve damage to several wetlands and corridors at once. In cases such as this, it is difficult to justify incremental removal techniques for measuring which wetlands and corridors may represent the largest vulnerability to the system. Instead, planners need some way to evaluate the potential impact of proposed landscape changes relative to a worst-case change of a similar magnitude (i.e., involving the same number of arcs or nodes). However, evaluating vulnerability to worst-case loss of multiple arc/nodes is not trivial and requires optimization techniques. To evaluate network vulnerability to simultaneous arc/node loss, this thesis presents an optimization approach similar to that proposed by Matisziw et al. (2007) for identifying a set of arcs, that if removed, would impact connectivity the most (or alternatively, the least). This approach was selected because it accounts for the range of disruption of arc loss that makes the network most vulnerable and because it can be combined with any other network's performance (i.e., capacity). An upper bound on connectivity loss or flow loss is useful for identifying those arcs contributing most to network vulnerability. The network vulnerability model presented herein is designed to identify the worst-case scenarios of arc/node loss for a wetland system. This model not only evaluates nodal connectivity but can also show how network capacity is affected. The objective then is to identify those arcs whose loss impacts a network's connectivity or capacity the most.

The model used here is similar to the flow interdiction model (FIM) proposed by Murray et al. (2007) and the p-cutset model (PCUP) of Matisziw et al. (2007). The main differences of the proposed model in this thesis as compared to the FIM and PCUP models are: a) the FIM model evaluated impact to flow between origin-destination nodes while the thesis model evaluates impact to network capacity and b) the FIM model modeled the loss of nodes but the thesis model focuses on the loss of arcs.

The goal of this model is to characterize and identify the importance of arcs to network connectivity and capacity.

$i, j =$ index for polygon, the whole set is denoted as I

$c =$ index of arcs, entire set denoted C

$N_{ij} =$ set of paths in between i and j polygons

$P =$ number of arcs/linkages to be lost

$\Phi_c =$ set of arcs along path c

$Q_{ij} =$ capacity of path in between i and j polygons

$$X_{ij} \begin{cases} 1 \text{ if arc between polygon } i \text{ and } j \text{ is interdicted} \\ 0 \text{ otherwise} \end{cases}$$

$$Y_c \begin{cases} 1 \text{ if interdiction doesn't impact path } c \\ o \text{ otherwise} \end{cases}$$

$$Z_{ij} \begin{cases} 1 \text{ if there is no connection between polygons } i \text{ and } j \\ 0 \text{ otherwise} \end{cases}$$

System optimization:

Maximize $\sum_i \sum_j Z_{ij}$ .... (1)

Maximize $\sum_i \sum_j Q_{ij} Z_{ij}$ .... (2)

Subject to:

$\sum_{c \in N_{ij}} Y_c + Z_{ij} \geq 1 \qquad \forall i, j$ .... (3)

$Z_{ij} \leq (1 - Y_c) \qquad \forall i, j, c \in N_{ij}$ .... (4)

$Y_c \geq (1 - \sum_{i,j \in \Phi_c} X_{ij}) \qquad \forall c, i, j \in \Phi_c$ .... (5)

$Y_c \leq (1 - X_{ij}) \qquad \forall c, i, j \in \Phi_c$ .... (6)

$\sum_{i,j} X_{ij} = p$ .... (7)

$X_{ij} = \{0,1\} \qquad \forall i, j$ .... (8)

$Y_c = \{0,1\} \qquad \forall c$ .... (9)

$Z_{ij} = \{0,1\} \qquad \forall i, j$ .... (10)

Objective (2) of the model is to maximize system capacity loss. It is accounting the capacity losses when all the paths between two nodes (*i* and *j*) are lost. Constraint (3) and

Constraint (4) track available paths between polygon *i* and *j*. Specifically, Constraint (3) is for the condition where there is no path available and no connectivity is possible. On the contrary, Constraint (4) ensures connectivity between two nodes when at least one path is available. Constraint (5) and Constraint (6) ensure that a path can only be available if no component arcs are damaged. These two Constraints work similarly as Constraints (3) and Constraint (4), as connectivity is replaced by path and path is replaced by arcs. Constraint (5) limits the number of arcs lost. Constraints (8), (9), and (10) represent the binary restrictions on the decision variables.

This vulnerability assessment model selects a set of arcs whose removal maximizes disruption to network connectivity and capacity. For example, consider three nodes 1, 2 and 3, with three linkages '*u*', '*v*' and '*w*'. Arc '*u*' is connecting with a pair of polygons 1-2; '*v*' is for the pair of polygons 2-3, and '*w*' is for the pair of polygons 1-3. Assume that arc '*v*' (2-3) is lost and that the other two linkages are in good condition. Previously there were two paths between node 2 and 3: one is 2-3 and the other one is 2-1-3. After the loss of arc (2-3), only 2-1-3 path is available. Given constraint (6) for path 2-3, $X_{2\text{-}3} = 1$, $Y_c = 0$. Again for constraint (5), Y_c can be 0 for path 2-3 or Y_c can be 1 for path 2-1-3 depending upon type of optimization (maximization or minimization). Also from constraints (3) and (4) Z_{ij} could be 0 or 1 depending on the type of optimization system. For maximization, the model always selects the value of $X_{2\text{-}3}$ and Y_c with a view to keeping Z_{ij} value maximum; for instance, selection of more Y_c=0 in the network can maximize the value of Z_{ij}.

3.3 **Siting Wetlands to Enhance Connectivity**

Another important goal in the management of wetland systems is to reduce vulnerability to wetland and corridor loss through addition of new wetlands and corridors. Wetland and corridor loss may also require constructing another new wetland for regulatory compliances. Even if the resources are available for constructing a wetland, the selection of optimized location for ecological habitat benefit is a priority for wetland managers. This thesis addresses this issue by applying the Weber Problem (Weber, 1909) to find a potential wetland location where the constructed wetland minimizes distance between other wetlands in the system. The idea here is that selecting a new wetland site that is close to other existing wetlands will enhance the potential for system connectivity. The Weber Problem can account for differing levels of importance of existing wetlands by weighting cost to the new facility site accordingly. In this thesis, the capacity of a wetland, as considered in the vector corridor algorithm in section 3.2, is utilized as a weight for existing wetlands.

Consider the following notation:

$i =$ index of wetlands

$a_i =$ demand (capacity) at wetland i

$n =$ total number of wetlands

$(X, Y) =$ selected location for new wetland

$L_i =$ index of vector polygons/arcs, entire set denoted as LI

$P =$ selected polygon to remove

SITESELECTION $\{ i \in I, Li \in LI, Rk \in RK, P) \}$

1. Select polygons $i \in I$ that have direct connection with P

2. Select $Li \in LI$ that have direct connection with P

3. Collect demands for each polygon (a_i)

4. Minimize $Z = \sum_i a_i d_i$

Here, Weiszfeld's algorithm has been used to search for an optimal new wetland site (Weiszfeld, 1937; Church and Murray 2008).

Weiszfeld's algorithm:

5. $(X^k Y^k) =$ estimated Weber point at iteration k

$$X^{k+1} = \frac{\sum_i \frac{a_i x_i}{\sqrt{(X^k - x_i)^2 + (Y^k - y_i)^2}}}{\sum_i \frac{a_i}{\sqrt{(X^k - x_i)^2 + (Y^k - y_i)^2}}}$$

$$Y^{k+1} = \frac{\sum_i \frac{a_i y_i}{\sqrt{(X^k - x_i)^2 + (Y^k - y_i)^2}}}{\sum_i \frac{a_i}{\sqrt{(X^k - x_i)^2 + (Y^k - y_i)^2}}}$$

In order to assess the prospects of siting a new wetland in a wetland system given the loss of an existing wetland, the following process is applied:

a) Select a wetland potential to remove;
b) Select the incident wetland(s) and corridor(s) that have a connection with the targeted (for removal) wetland;
c) Derive centroid points of the selected wetlands attributed with their capacities;
d) Utilize Weber's formula and weighting cost to each existing wetland with its capacity; and
e) Assess the viability of the identified site.

To illustrate the model, a small sample area is taken from a wetland network and a wetland is selected for removal which is shown in Figure 11a. It is assumed that only the wetlands that have direct connection with the targeted wetland are impacted and their capacity will be utilized to select a new location for wetland mitigation (Figure 11a).

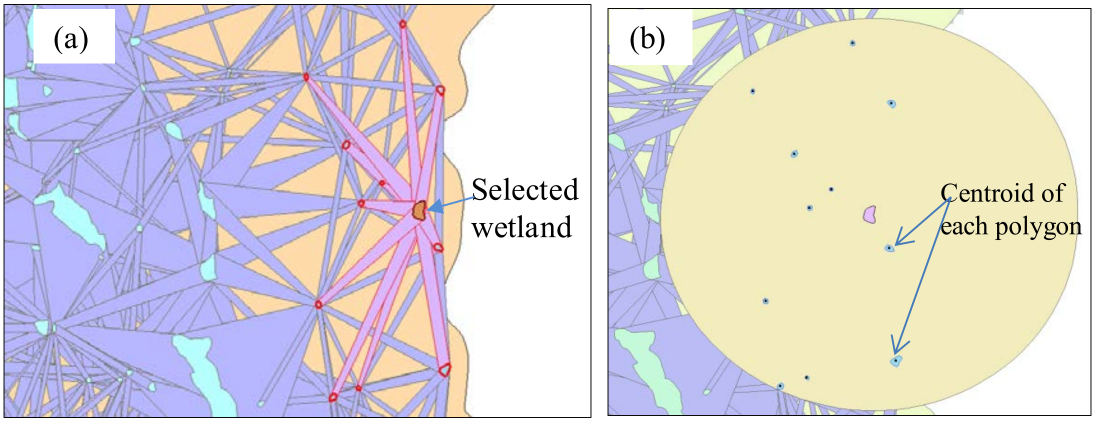

Figure 11: a) Targeted wetland for removal and associated corridors, and b) Points representating wetlands

Figure 11 shows that eleven incident wetlands have connection with the targeted wetland through 11 corridors (Figure 11a). The relative weights or demand associated with the 11 incident wetlands are shown in Table 7. The Weber Problem uses the Euclidean distance from the centroid of the targeted wetland to the neighboring wetland's centroid (Figure 11b). For designing a new wetland, the maximum capacity among all selected wetlands is considered to ensure better capacity of the network (Table 7).

Table 7: Capacity between target wetland and 11 other incident wetlands

Incident wetland ID	Capacity of wetland (Demand)
1023	43
1081	68
1091	63
1092	89
1227	39
1276	87
1333	53
1341	58
1345	50
1391	55
1400	83

3.4 **Raster Corridor Analysis**

The derivation of least-cost corridors over a cost surface is a well-known and widely used capability of raster geographic information systems (GISs). The design of wildlife corridors for maintaining or restoring connectivity through landscapes threatened by habitat loss and fragmentation is a popular concept (Crooks and Sanjayan, 2006). The most widely used approach for designing corridors is least-cost path modeling (Cushman et al., 2009; Consentino et al., 2011). Least-cost corridor models can be developed by generating a GIS raster of the potential resistance a species may face while moving through the landscape (Adriaensen et al., 2003; Beier et al., 2008). The biggest issue is the robustness of the habitat corridor that comes from the GIS tool. Beier et al. (2009) determined different corridors based on expert opinion for eight focal species and assessed the robustness of the corridor with available biological data. In their model the parameters were based on four habitat factors (land cover, topographic position, elevation, road density) and resistance values for each class within a factor (e.g., each class of land cover). It is a simpler approach in terms of the number of parameters. The raster data model becomes more complex when it deals with a greater number of parameters that can represent real cost of a surface.

There are many parameters/variables that need to be considered for a suitability analysis of species movement. The parameters/variables depend on how animals behave and their geographic location, etc. Each parameter involves some uncertainty with respect to actual animal behavior. As the number of parameters increase, the percentage of uncertainty also increases. Thus, it is necessary to reduce the number of parameters for the accuracy of calculation. It is also difficult to select a reduced number of parameters because animal movement depends on many factors, and thus nothing can be dismissed entirely. Some research has determined raster corridors focusing on a few variables. However, this can lead to uncertainties if they have missed any essential parameters. The thesis model selects parameters based on an examination of the available literature on the topic. Each parameter could be part of a suitability analysis to determine the cost layer for amphibians. An important issue is how to weigh the different parameters in order to derive a meaningful cost surface. The three popular ways to accomplish this are: a) expert opinion based, b) literature based, and c) empirical behavior based. Regardless of which method is selected, there can be conflicts based on actual animal behavior (Cushman et al., 2006).

The following table displays potential factors that may influence movement of amphibians as an example. The selected parameters and some of their cost values are collected from literature for different amphibians. For some parameters, there is a known qualitative impact on amphibians that may be important to amphibian movement but they do not have an empirical basis. Budgetary limitations are an issue in developing amphibian perception data for any type of land use. It may be costly to gather enough experts to analyze and reach consensus on these factors (e.g., stream, slope, etc.).

Compton et al. (2007) introduced a resistant-kernel model of connectivity for amphibians. This model also identified parameters and their estimated cost values for migration and dispersal. So far, no model has yet considered seasonal impacts on amphibian dispersal or migration to set different factors’ cell value for corridor derivation. Not every season impacts an animal in the same way. For instance, autumn or spring may be much more suitable for amphibian movement over a barren field, whereas summer's hot and dry conditions are likely less suitable. Table 8 incorporates different cost values for different seasons. These are not empirically based resistance cost values for any species but illustrate how corridor costs can vary for different seasons.

Table 8: Cost parameters of the three types of connectivity

Criteria	Sub-criteria	Parameters	Source	Dispersal/Migration
Biologic	Wetland area (Pond/lake, non-forested wetland, salt marsh)	Perennial		7 (AS), 6 (S)
		Ephemeral		1 (AS), 1(S)
	Slope between wetlands	More than 1:8	(MoDOT, 1994)	8 (AS/S)
		Less than 1:8		3 (AS/S)
	Road	Expressway	(Compton et al., 2007)	10 (AS/S)
		Major highway		8 (AS/S)
		Major road		6 (AS/S)
		Minor street or road		4 (AS/S)
		Unpaved road		2 (AS/S)
		Railroad		2 (AS/S)
	Land use	Urban Impervious (Urban)	(Compton et al., 2007)	6.5 (AS/S)
		Urban Vegetated (Orchard/Nursery)		2 (AS/S)
		Barren or Sparsely Vegetated (Row crop)		2.6 (AS/S)
		Row and Close-Grown Crops (Row crop)		2.6 (AS/S)
		Soybean type crop fields (Row crop)		2.6 (AS/S)
		Cool-season Grassland (Pasture)		2.3 (AS/S)
		Warm-season Grassland (Pasture)		2.3 (AS/S)
		Glade Complex (Pasture)		2.3 (AS/S)
		Eastern Red Cedar and Red Cedar-Deciduous Forest and Woodland (Forest)		1 (AS), 4 (S)
		Deciduous Woodland (Forest)		1 (AS), 4 (S)
		Deciduous Forest (Forest)		1 (AS), 4 (S)
		Shortleaf Pine-Oak Forest and Woodland (Forest)		1 (AS), 4 (S)
		Shortleaf Pine Forest and Woodland (Forest)		1 (AS), 4 (S)
		Bottomland Hardwood Forest		1 (AS), 4 (S)

		and Woodland (Forest)		
hydrologic	Groundwater	Losing stream		1 (AS/S)
		Gaining stream		3 (AS/S)
	Soil/bed rock	Pervious surface but impervious bed rock in 10 ft beneath it		1 (AS/S)
		Pervious surface with no impervious bed rock in 10 ft		3 (AS/S)
		Impervious		2 (AS), 4(S)
	Sedimentation and buffer area	Buffer area <30 ft for stream or wetlands	(TAIC, 2009)	
		Buffer area >30 ft		
	Contributing area of wetland or stream		Newly added	1 (AS), 2(S)
	Stream/flow path	1st order	(Compton et al., 2007)	1.5 (AS/S)
		2nd order		2 (AS/S)
		3rd order		6 (AS/S)
		4th order		10 (AS/S)
	Landscape slope	> 0.1	(Aslan, 2009)	3 (AS/S)
		< 0.1		1 (AS/S)
Chemical	pH	<5.0 or >9.0	(USEPA, 2012)	9 (AS/S)
		5.0 – 8.0		1 (AS/S)
	Total suspended solids	> 100 mg/L		9 (AS/S)
		< 100 mg/L		1 (AS/S)
	Chlorine	> 66 ug/L		9 (AS/S)
		< 66 ug/L		1 (AS/S)
	Nitrogen	> 10mg/L		9 (AS/S)
		< 10mg/L		1 (AS/S)
	Phosphorus	> 0.2 mg/L		9 (AS/S)
		< 0.2 mg/L		1 (AS/S)

Symbols: Summer (S)/ Autumn or Spring (AS)

The steps involved in creating a raster corridor suitability model are: 1) make sure all the collected raster layers are in the same coordinate system, i.e., geographic extent; 2) maintain a standard unit of analysis cell size (e.g., 30m X 30m) for all raster layers; 4) reclassify all the raster cells according to the above cost utility values in Table 8; 5) use map algebra to combine raster cost layers in different ways to create a final cost resistance layer; 6) create cost distance layer from each of the targeted wetlands (Figure 12b and Figure 12c); and 7) finally create a corridor based on the two cost distances (Figure 12d).

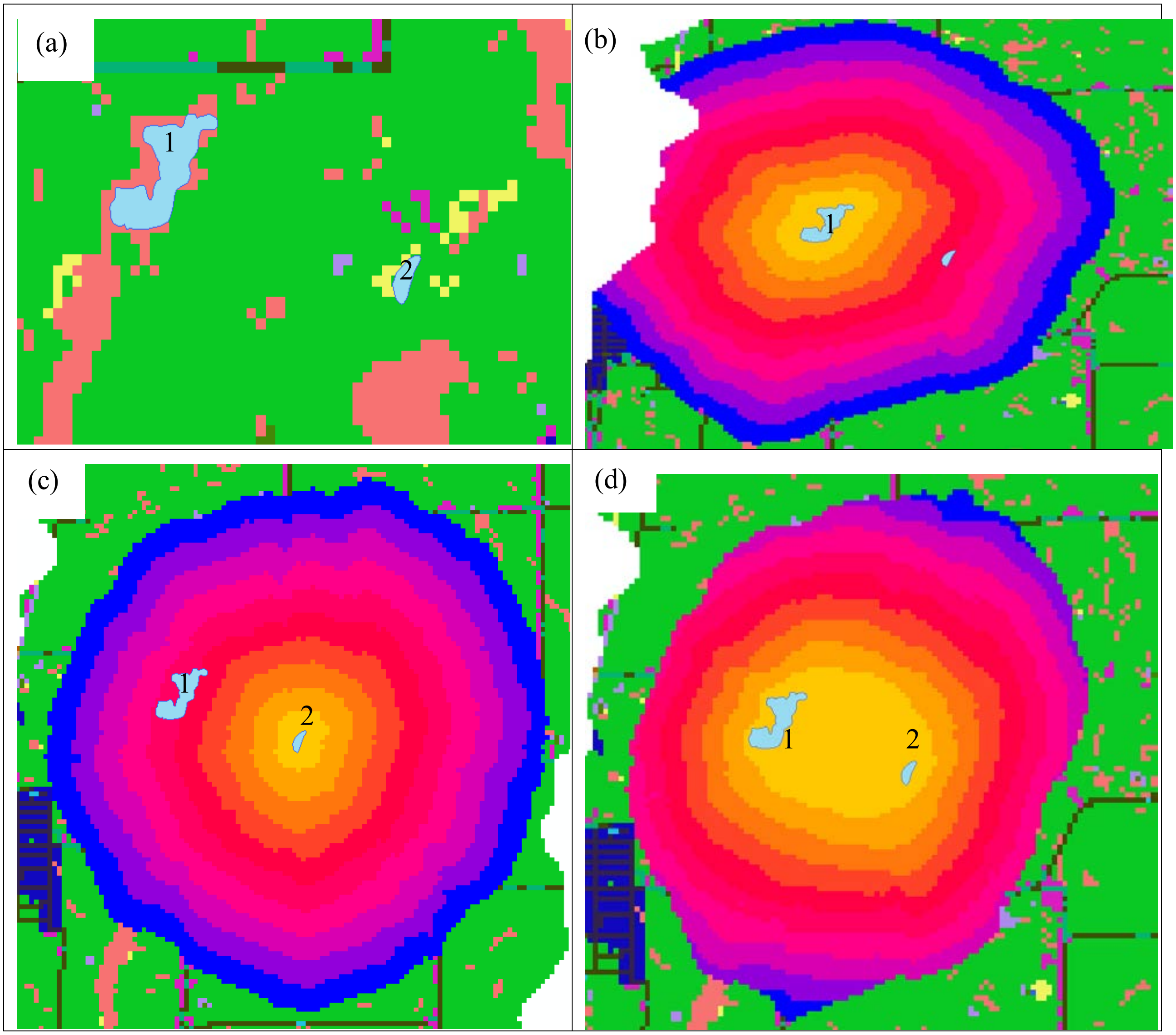

Figure 12: Steps of raster corridor creation, a) selecting pair of wetlands, b) establishing cost distance for wetland '1', c) establishing cost distance for wetland '2', and d) developing raster corridor for wetland '1' and '2'.

The cost of the factors (e.g., roads, streams, etc.) of the parameters (e.g., biological, hydrological, etc.) varies for an animal depending upon different seasons. For different seasons, determining cost follows the same steps for different values of factor's cell resistance.

3.5 **Surface Water Connectivity Visualization**

Surface water hydrology is easier to define spatially than groundwater hydrology (Kenny et al., 2008). Kenny et al. (2008) illustrated a methodology for routing overland flow through sinks and flats in interpolated raster terrain surfaces. However they did not test the interpolated raster terrain to see if their methodology works well with surface water hydrology. It is believed that the methods are equally effective at different scales when using DEMs derived from a variety of remotely sensed elevation base data sources. The surface water connectivity modeling methodology used in this thesis determines the surface water hydrologic connectivity based on elevation. It also visualizes the hydrologic connectivity (and also possible chemical connectivity) through GIS interface integrating biological connectivity. The result a user friendly and low cost approach that is easy to implement in GIS to define hydrological surface water interaction.

The steps of deriving the contributing area are: 1) create the flow direction raster data derived from DEM data model. In a raster model, flow direction follows the direction from one cell to the next steepest downward cell using a DEM (Figure 13b), 2) create the flow accumulation layer derived for each cell from the flow direction raster data (Figure 13c), 3) develop the contributing area for the lowest elevation point of each wetland (assuming centroid is the lowest elevation point of a wetland) based on flow accumulation raster data layer (Figure 13d).

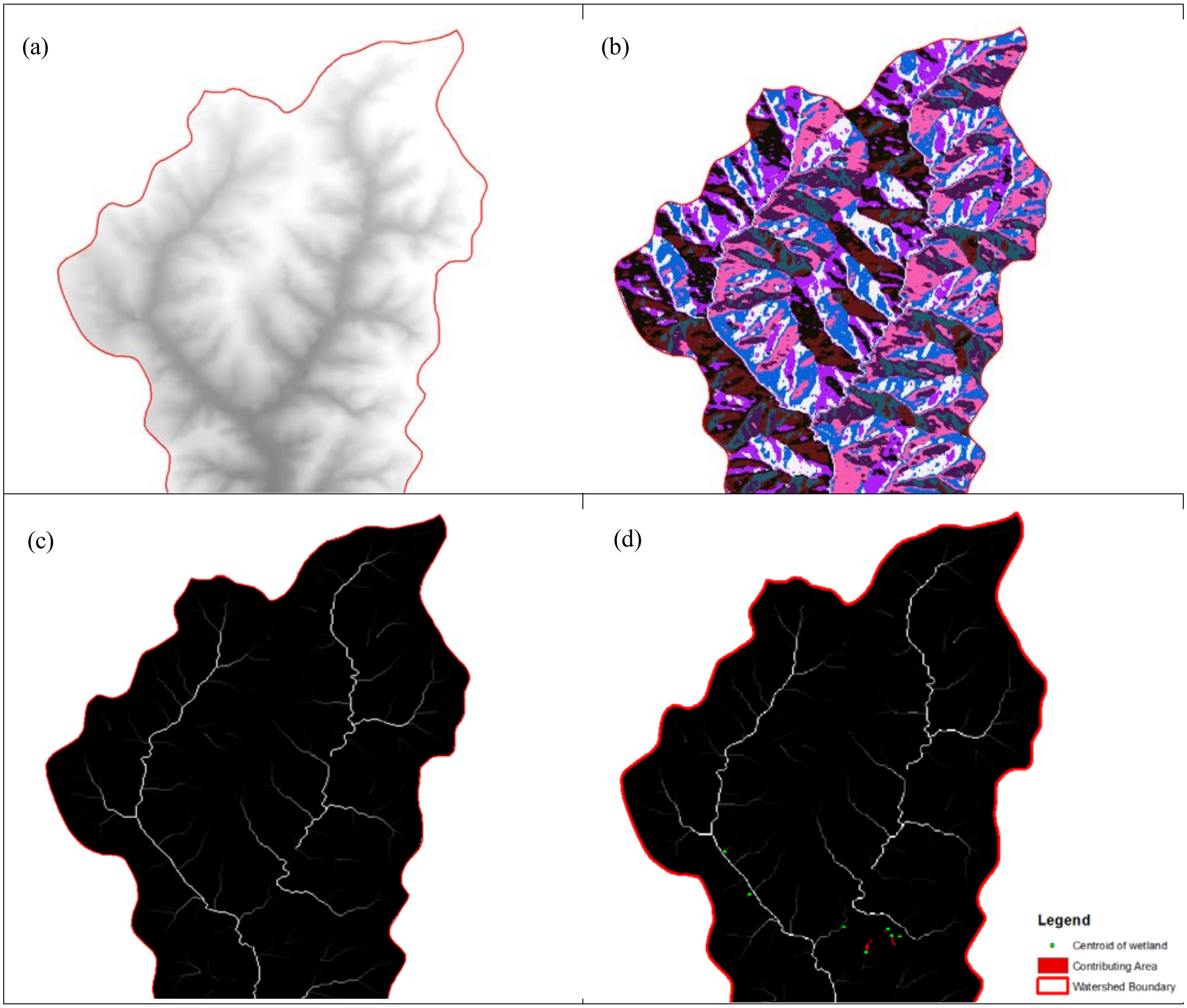

Figure 13: Surface water contributing area derivation, a) DEM of a part of a watershed, b) flow direction raster surface, c) flow accumulation layer, and d) point representation of wetland and contributing areas.

The objective is to combine hydrologic and biologic connections to provide a more detailed representation of system connectivity. If the overflow from one wetland reaches other wetland(s), their contributing areas can be considered be connected. Accepting this assumption, the GIS based approach used in this thesis computes the number of wetlands that overlap with contributing areas. If any overlapping area contains more than one wetland then they are considered to be hydrologically connected.

Chapter 4

ASSESSING WETLAND CONNECTIVITY IN MISSOURI

4.1 Modeling Wetland Connectivity

In this chapter, all the models that are described in Chapter 3 are applied to wetlands, and to their spatial interactions, on biological and hydrological connectivity. As detailed in the previous chapters, wetlands can be connected with the surrounding environment in many different ways--biologically, hydrologically, and chemically. Each type of connection can entail a multiplicity of parameters that can be used in approximating connectivity. These parameters and their relative importance can vary from place to place and from species to species, but a baseline network using a general set of parameters can help watershed managers to understand important wetland interactions. Distance is a universal parameter for any kind of spatial connectivity. To start with, distance is used in this model to construct wetland corridors and a whole wetland network. In the next section the behavioral traits of amphibians will be considered in defining a baseline measure of biologic connectivity. To illustrate this process, wetlands suitable for amphibian populations are considered in building the baseline network while others that are less suitable are not included (i.e., riverine wetlands, lakes, ponds, and some other larger water bodies that are of low value for amphibians) (Semlitsch and Bodie, 2003). Next, the movement potential of amphibians is considered. Different species of amphibians at different age levels can traverse different distances. Their average movement potential ranges between 50 – 3,000 meters (Table 6 of Chapter 2). If there is no wetland within the maximum distance range, survival is low. There is no evidence that amphibians can sense a wetland or other suitable habitat in the direction they are moving. Thus, this application assumes wetlands are ecologically connected if they are within 2,000 meters straight-line distance of each other. This distance could be changed based on other species or locations or age of individuals.

4.2 Study Area: The Muddy Creek Watershed

The application area is within the Grand River watershed, located in Linn County, MO. The Grand River has been an important 303(d) listed impaired streams since 1998 whose water quality has been greatly diminished (MDC, 2012c). The main problem of the Grand River water quality is its sediment contents. To control the sediments, it is easier to treat the upper dependent smaller watersheds. The Muddy Creek watershed is one of the important contributing sub-watersheds, for both sediment and nutrients flowing into the Grand River watershed. The Muddy creek watershed contains 17,388 acres of land area and is connected through Locust Creek to the Grand River (Figure 14). From an ecological point of view, the wetland system of this area contains federal and state listed aquatic and terrestrial species (Todd et al., 1994). This watershed contains several types of wetlands, including a) freshwater emergent wetlands, b) freshwater forested/shrub wetlands, c) riverine wetlands, and d) freshwater ponds. Land use is approximately 60% cropland, 25% pasture, 8% woodland, and 7.3% urban and other uses (USDA, 2007). Excessive sediment is the major water quality problem in the basin.

Non-point source (agricultural pollution) is also a problem for the water quality within the watershed. The condition of the aquatic habitat ranges from poor to good. The aquatic habitat issues are for excessive channelization that causes excessive sedimentation. The Muddy Creek contains 26.7 km of perennial streams, 5.6 km (21%) of which are channelized (Todd et al, 1994). In this application, wetlands in the NWI dataset (USFWS, 1979) are used. In this watershed, 486 wetlands are recorded in the NWI dataset and include 128 freshwater emergent wetlands, 83 freshwater forested/shrub wetlands, 275 freshwater ponds, and 1 riverine wetland.

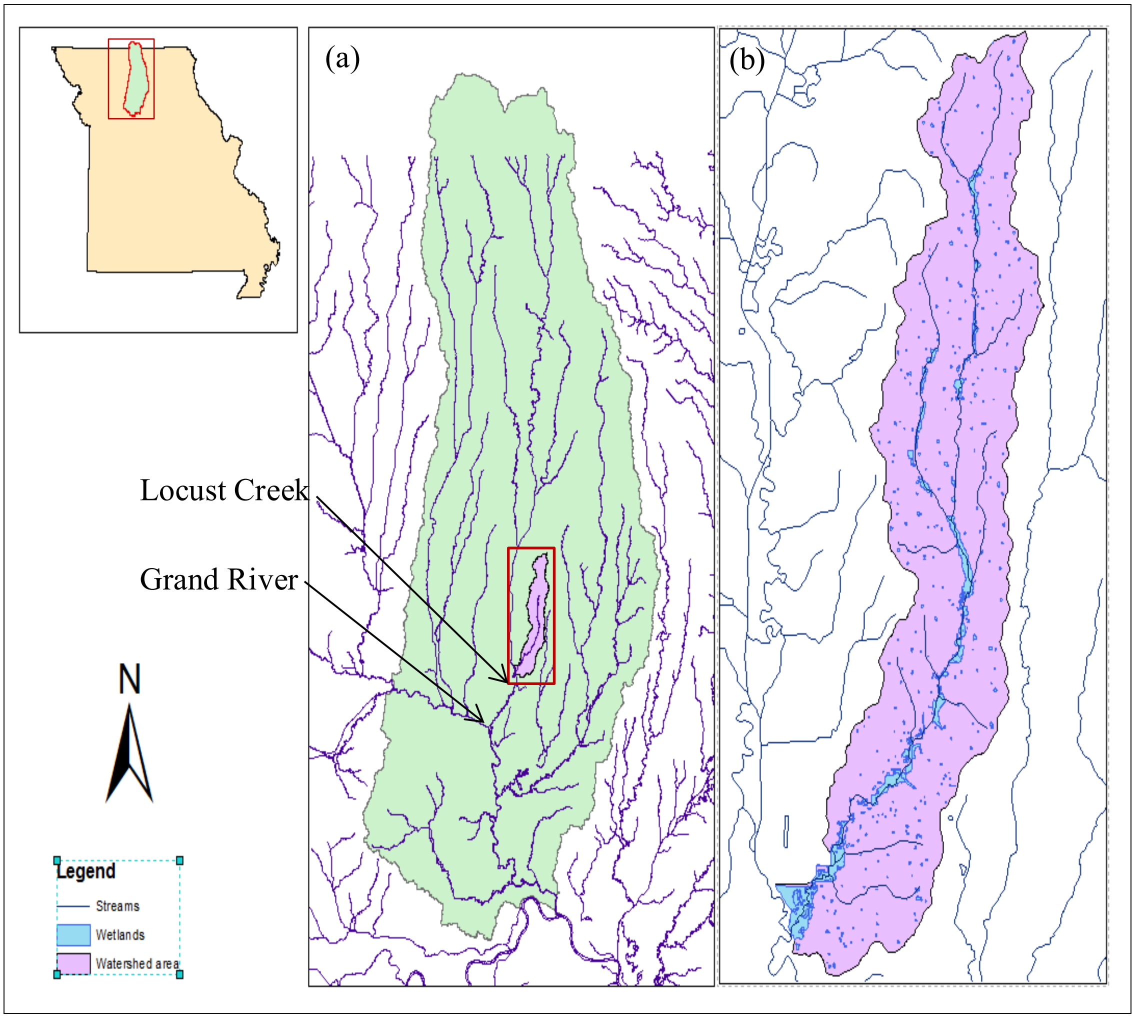

Figure 14: Location of study watersheds: a) Grand River watershed and b) Muddy Creek watershed

4.3 **Network Generation and Analysis**

For the Muddy Creek watershed, only wetland types of freshwater emergent wetlands and freshwater forested/shrub wetlands are considered as viable amphibian habitat. In total, 210 wetlands of these types were selected from the NWI dataset (USFWS, 1979) for the study site. These wetlands varied in size from 0.001 to 168 acres. Vector polygon corridors between each pair of neighboring wetlands that are within

2,000 meters of each other were then created. Again, a 2,000 meter range was used here because this number is in the range of amphibian's movement (50 – 3,000 meters see Table 6 of Chapter 2). To do this, the VECTORCORRIDOR algorithm was implemented via Python using ArcGIS 10.0 to iterate through all the wetland pairs and create the corridors. Running the python script on a Dell Optiplex 960 desktop (16 GB memory, core 2, 2.345 gHZ quad processors) required 496 minutes. The resulting polygon corridor network for wetlands of the Muddy Creek watershed is shown in Figure 15. Some possible reasons for the long computation time are: a) wetlands often have many neighboring wetlands within the distance range, and b) at least 12 ArcGIS tools are involved in creating a corridor for each wetland pair, each of which is an individual model that takes its own processing time.

In sum, 10,794 corridors are found to exist for this configuration of wetlands. The resulting corridors are attributed with several important characteristics of the corridors such as "intermediate distance", "from wetland ID", "to wetland ID", "capacity", "wetland region," etc. Here, capacity of a wetland is the shared length between the wetland and the adjacent corridor, and the capacity of a corridor means the minimum capacity of the two-neighbor wetlands capacity previously discussed (see Figure 6d of Chapter 3). Research on amphibians has indicated that they disperse randomly from a wetland's edge outward into terrestrial habitat (Rittenhouse and Semlitsch, 2009). It is thus assumed in this application that the amphibians who leave only from the shared portion of a wetland can reach their neighboring wetland. The corridor algorithm generates corridors among all the wetlands considering distance as a parameter. After the polygon corridors are generated, an arc-node network is also created as detailed in Chapter 3. The arcs in this network can then be attributed with characteristics (i.e. capacity) of the underlying polygon corridor. The resulting network is useful for further analysis because there are many algorithms and a GIS tool which have been already built for network analysis (Figure 17c).

This derived network supports two types of connections previously discussed in Chapter 3: a) when two wetlands are within 2,000 m of each other they are considered as directly connected (a one-step path), and b) when two wetlands are connected via another wetland, they are considered as indirectly connected (a two-step path). Given the configuration of wetlands selected in this application and the resulting corridors identified, 21,588 one step and 924,072 two-step paths connecting wetlands exist. Together, these 945,660 paths support connectivity between 21,588 wetland pairs. In this application, the term “wetland region” is used to refer to a group of wetlands that are directly and/or indirectly connected to each other. All the wetlands in a region will be identified by a region ID. Similarly, all the corridors between wetlands in a group region will be identified by a region ID.

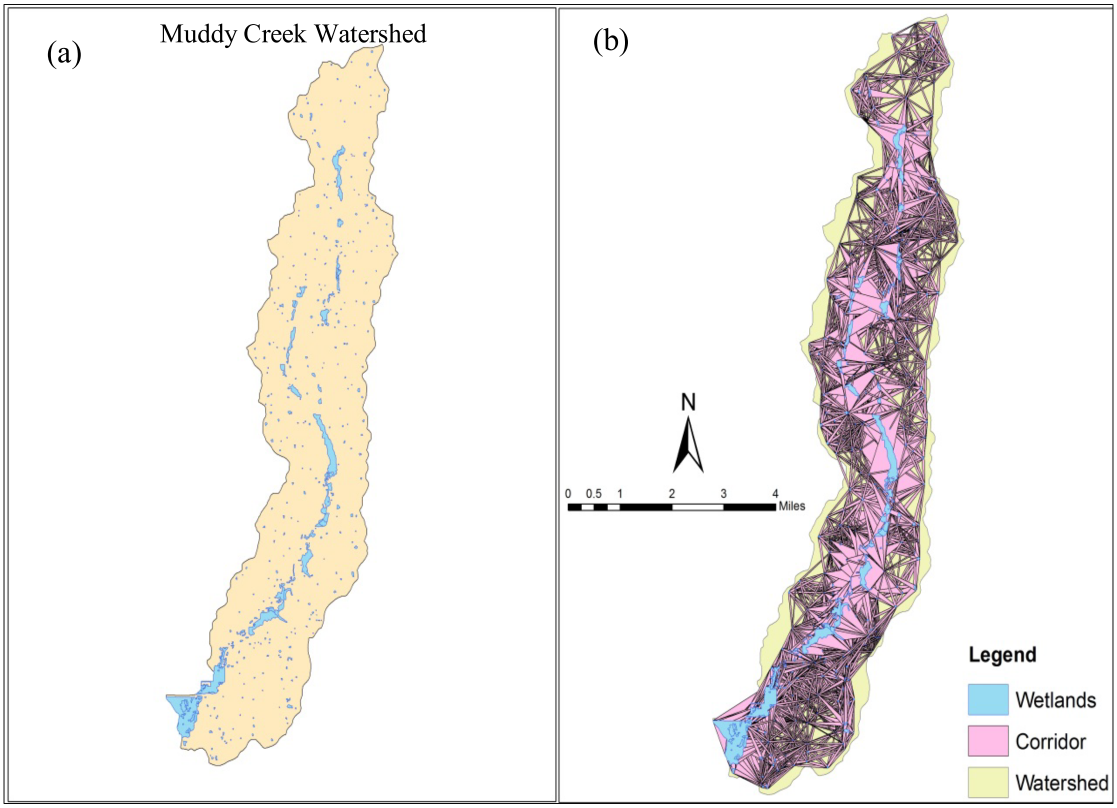

Figure 15: a) Wetlands in the Muddy Creek watershed, b) Corridors for all the wetlands

There are some issues that can arise from the vector polygon corridor implementation in a wetland system. Some major issues are: a) there are some wetlands that are completely within another wetland in the NWI dataset used, which means a wetland is completely surrounded by another wetland. In this case a corridor from an inner wetland cannot be created; b) sometime a larger wetland can be situated over a narrower corridor (Figure 16a); and c) sometimes a smaller wetland can be situated in a wider corridor. For the first issue, one possible solution can be to remove inner wetlands when setting any corridor because the inner and outer wetlands will function as a single wetland (Figure 16b). In the second situation, the direct corridor between two smaller wetlands can be eliminated and their connection can be depicted as an indirect connection through the larger wetland because in reality, the direct corridor between two smaller wetlands is a part of the indirect corridor. For the third situation, it might not be an issue, and sometimes it is helpful to have a smaller wetland in a corridor of wider wetlands.

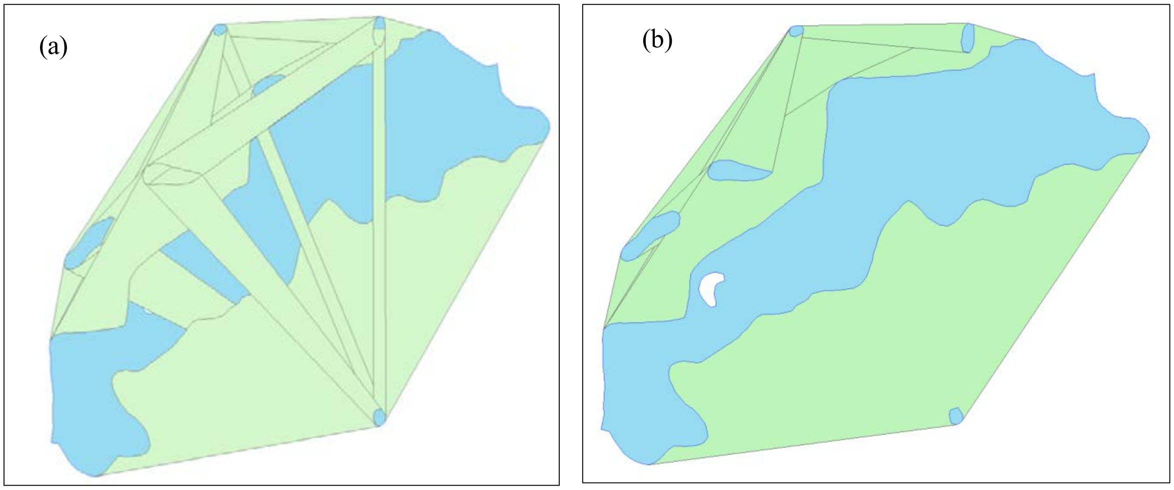

Figure 16: Handling overlapping corridors

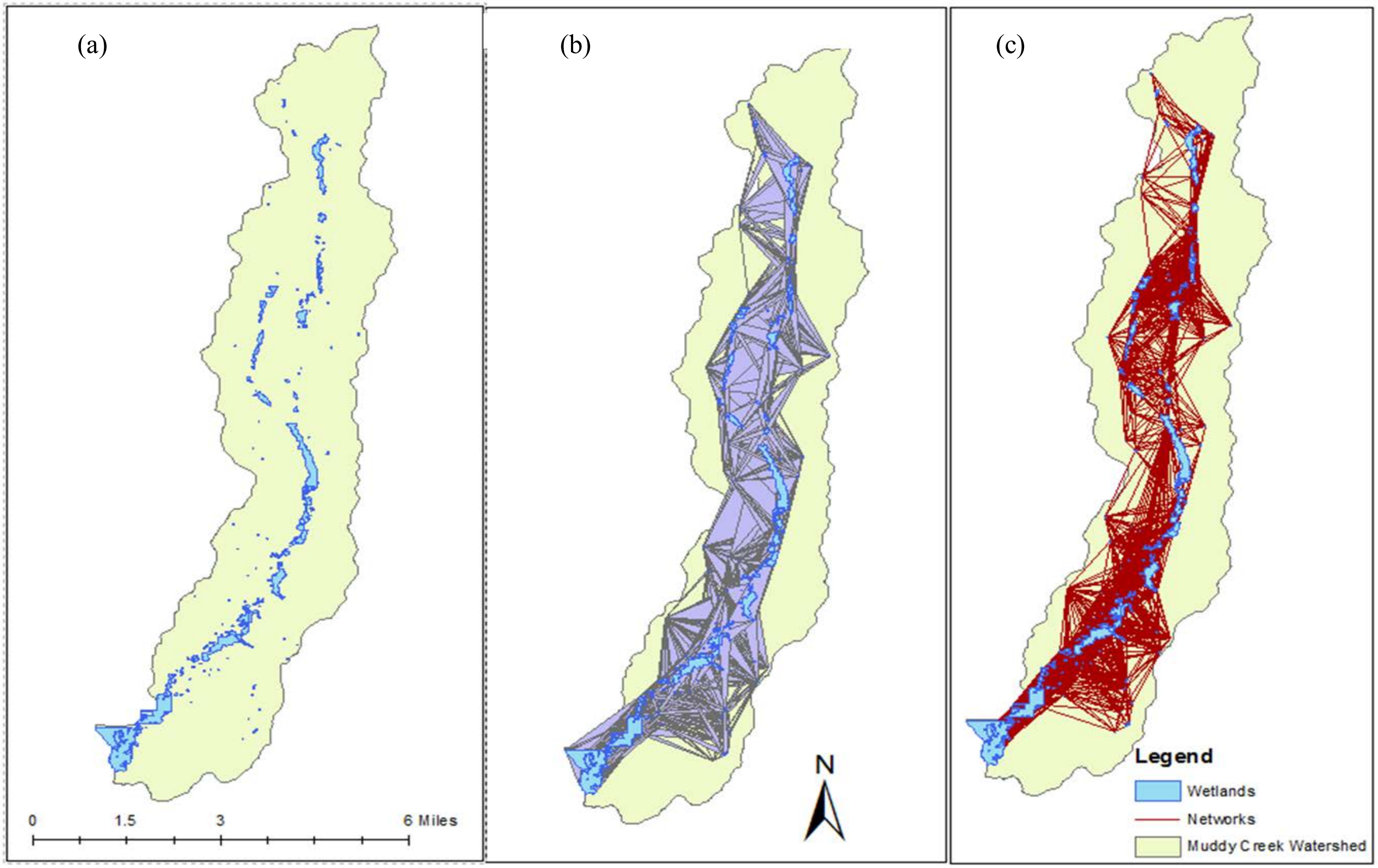

Figure 17: a) Wetlands in Muddy Creek watershed, b) vector corridors of the wetlands, and c) network

4.4 **Vulnerability to Wetland/Corridor Loss in the Muddy Creek Watershed**

Vulnerability analysis is conducted on the wetlands of Muddy Creek watershed (Figure 18). The watershed contains 486 wetlands according to the NWI wetland data (USFWS, 1979). After merging the adjacent wetlands into a single wetland, the number of wetlands becomes 388 in the watershed. The adjacent wetlands are merged because this vulnerability model is developed based on distance among the wetlands. Where there is no distance between two wetlands, there is no corridor. Technically the adjacent wetland acts as a single wetland.

To better evaluate how network size can impact vulnerability, different configurations of wetlands are considered. First all, 388 wetlands in the watershed are considered viable components of the wetland system (Figure 18a). Second, since perennial riverine wetlands and freshwater ponds are not that suitable to amphibians, because they introduce the biggest threat of fish predators, they are eliminated leaving 129 viable wetlands (Figure 18b). Finally, given that Palustrine system forested wetlands can become so dry in the summer season, this dryness might cause the area to become unsuitable as a wetland, which would increase the rate of amphibian body desiccation; hence, they were also eliminated leaving 125 viable wetlands (Figure 18c). The spatial relationship between wetlands can be conceptualized as a network based on the universal parameter ‘distance.’

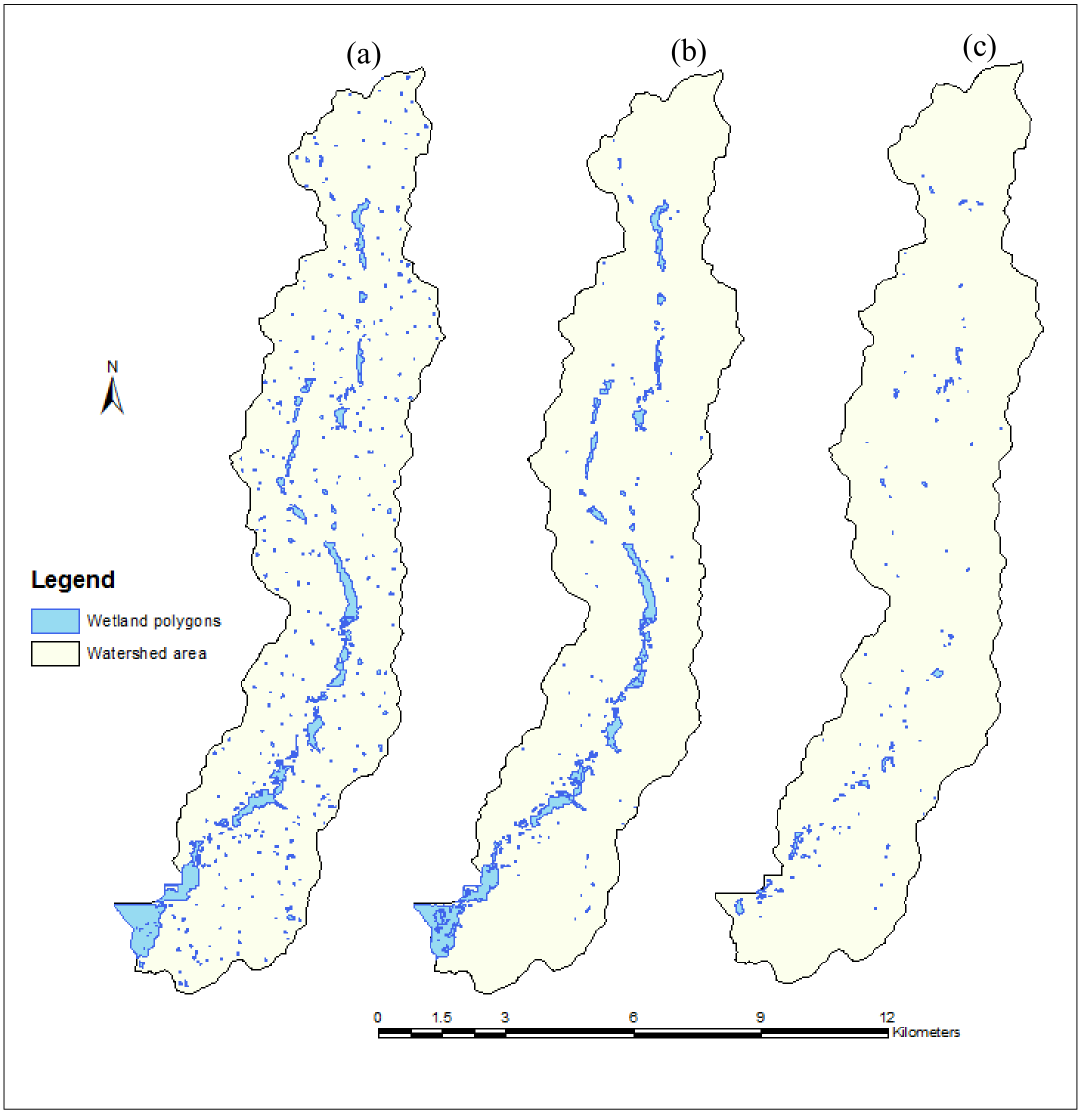

Figure 18: Muddy Creek watershed: a) all wetlands, b) no ponds and riverine wetlands, and c) no ponds, riverine and Palustrine system forested wetlands

Note that all the wetlands shown in Figure 19 are connected either directly (through single step path) or indirectly (through multiple step paths). If two wetlands are in a certain distance range (2,000 meter used here), they are considered directly connected; otherwise, they are indirectly connected (Figure 19). The number of paths and area of corridor depends on the configuration of wetlands. For the configurations in Figure 18a, 18b, and 18c, the polygon corridor network is shown in Figure 19a, 19b, and 19c, respectively.

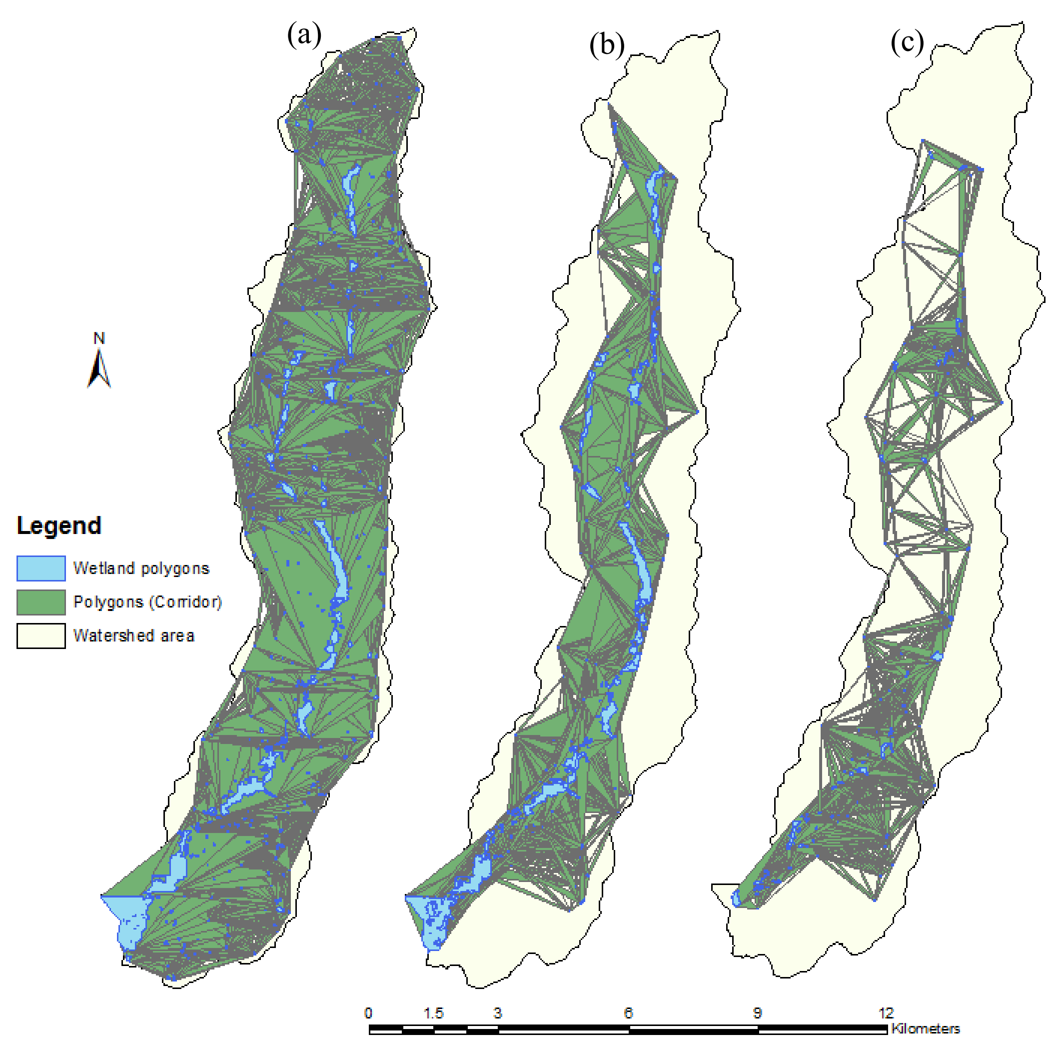

Figure 19: Vector corridors for the three wetland configurations

For subsequent analyses, the polygon corridor networks of Figure 19a, 19b, and 19c have been represented as networks of Figures 20a, 20b, and 20c respectively. Each wetland is represented by a node (centroid of the wetland) and each corridor is represented by an arc. Every arc has a starting node and an ending node. All the attributes from a polygon corridor are transferred to its corresponding arc. The different colors of the arcs (corridor) of Figure 20 represent the capacity of corridors.

In any graph, many paths of movement are possible between a pair of nodes. However, in wetland systems amphibians likely do not view all of these paths as viable options. Research on amphibians has indicated that aside from practical distance limitations on travel, amphibians likely do not make multi-step trips between wetlands. Only when considering movements representing multiple generations are multiple step paths reasonable (Semlitsch, publication pending). The distance constraint for direct connectivity has already been discussed but amphibians may have a distance constraint for indirect connectivity too. The model assumes an indirect distance constraint of 3,000 m and a maximum number of 2 arcs involved in a path (two-step path) to permit assessment of multiple generation movements.

The numbers of arcs involved in the three configurations in Figure 20a, Figure 20b, and Figure 20c are 10,794, 1,750, and 1,587 respectively. Eventually, the number of paths for one-step paths is same as the number of arcs, but the numbers of paths for two-step paths are 924,072, 83,902, and 73,572 (Table 10 in Chapter 5).

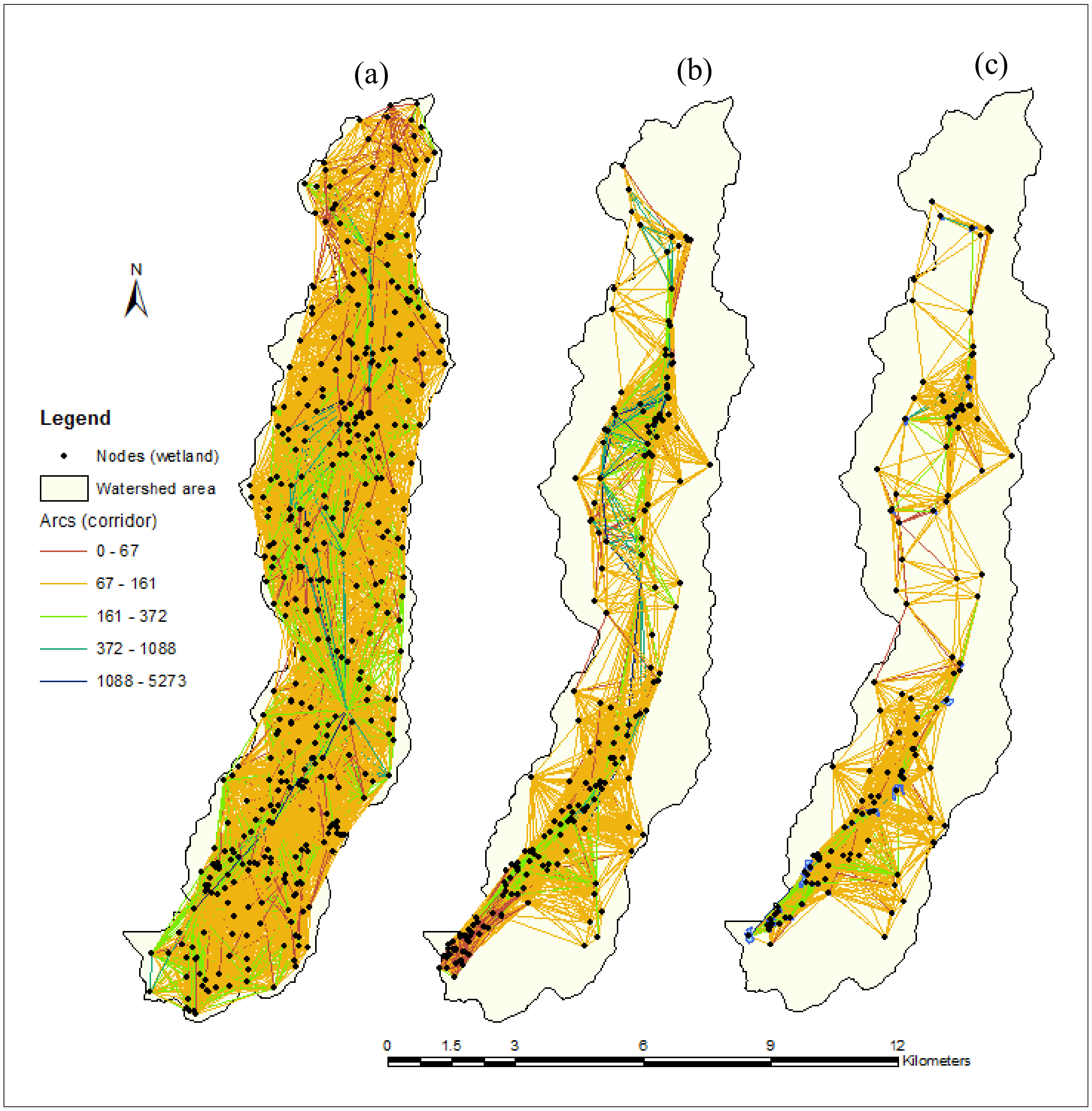

Figure 20: Networks representation for a) all the wetlands, b) no riverine wetlands and ponds, and c) no riverine wetlands, ponds, and PFOs

4.4.1 Modifications

There are numerous parameters that can affect the spatial wetland connectivity other than distance. For instance, the corridor generation approach could incorporate the impact of other landscape features (such as perennial streams, roads, etc.) and modify the connectivity accordingly. Here, one modification, the barrier effect of perennial streams is examined. All the corridors that fully overlapped with a perennial stream are considered an absolute barrier for amphibian movement and removed from the original network. Figure 21a, 21b, and 21c are the three polygon corridor network(s) created modifying perennial streams that are for the three configurations of Figure 18a, 18b and 18c respectively. Notice that in Figure 21 there are no polygon corridors left that overlap with the perennial streams. The number of wetlands for the three wetland configurations is same as before after the modification because no wetland falls over the streams. Some of the corridors can be partially overlapped with a stream but partially overlapping may not be an absolute barrier, thus those corridors are not removed. Due to the modification by stream configuration (b) and configuration (c) of the original network Figure 19b and Figure 19c becomes fragmented into three sub-graphs as shown in Figures 21b and 21c respectively. Although a stream creates an absolute barrier to configuration (a) of Figure 19a, it is not fragmented because there are enough arcs available to maintain an integrated network.

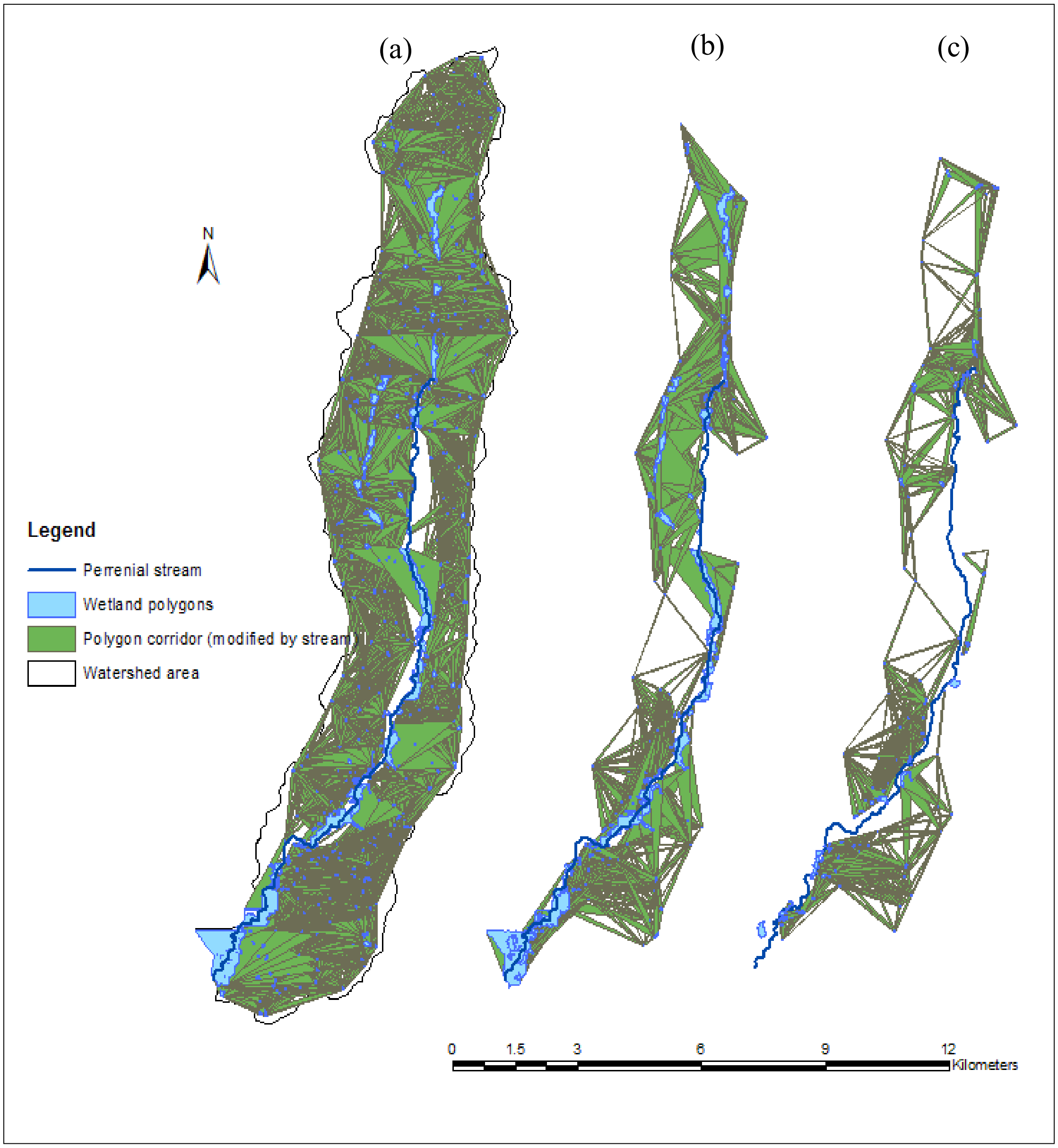

Figure 21: Vector corridors accounting for perennial streams for the three network configuration

After considering the modification due to the presence of streams, all wetland nodes remain, while any compromised arcs have been removed from the original network (Figure 22). The network optimization model discussed in Chapter 3 is then applied to each of these six network configurations. The modified network for all wetlands (Figure

22a) consists of 6,196 viable arcs while the modified networks for excluding riverine wetlands and ponds, and also PFOs in Figure 22b and 22c consist of 987 and 843 arcs respectively. The number of paths for one-step paths is reduced with the reduction of the number of arcs because, basically, they are same. The number of paths for two-step paths is also reduced to 525,561, 29,760, and 22,610 (Table 10 of Chapter 5) for the three modified configurations in Figures 22a, 22b and 22c respectively. Note that the number of path reductions in two-step paths is very high when compared to one-step paths. The vulnerability assessment model, equation *1 - 10* in Section 3.2 of Chapter 3, is set to solve for the loss of p= 1 to p=100 for each network and to ensure that damage to capacity is maximized. The number of variables and constraints are also reduced significantly for the modification that is presented in tabular form in the following chapter. This model utilizes the Gurobi 5.1 optimization solver and ArcGIS 10 for spatial data analysis, manipulation and visualization.

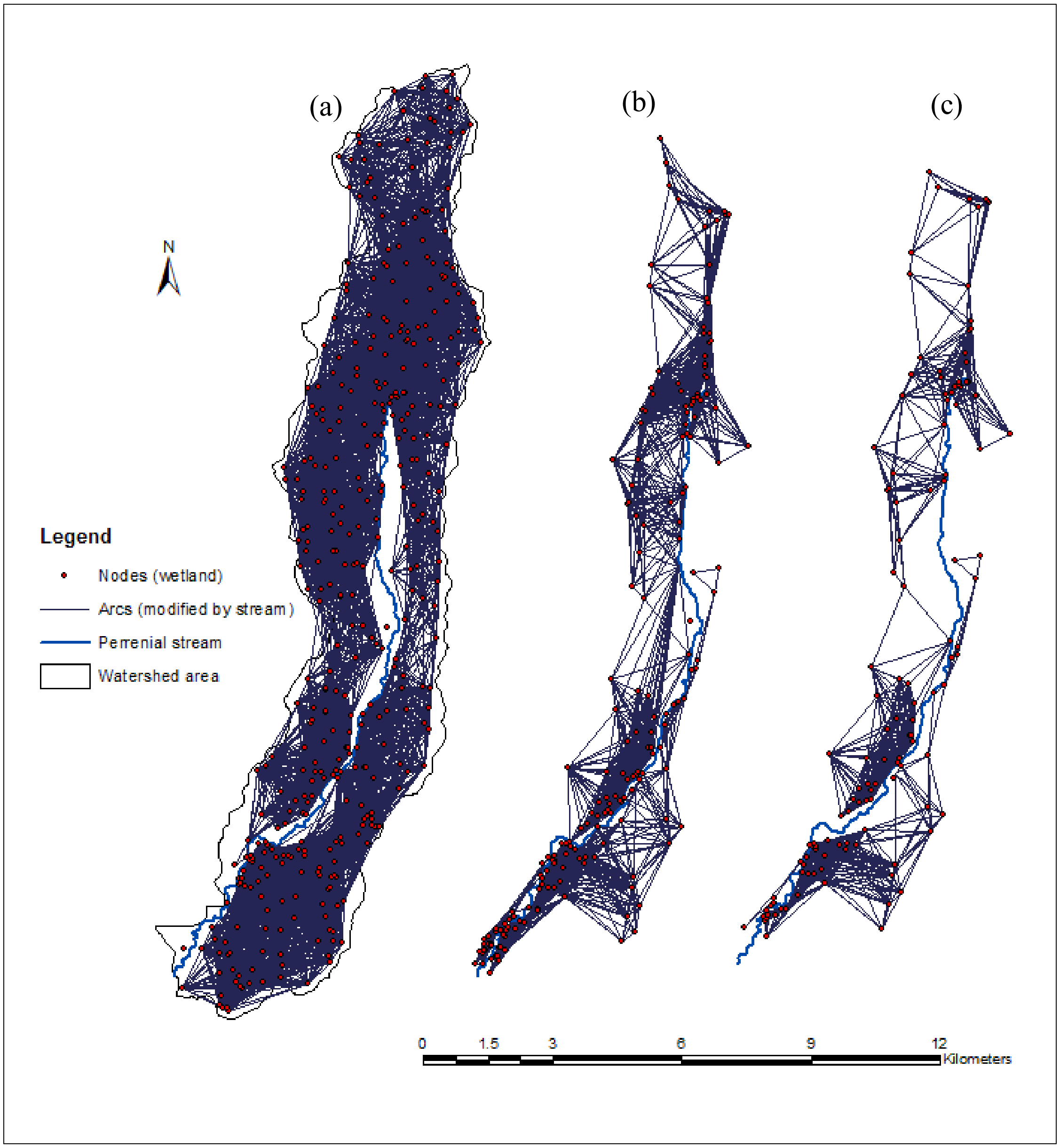

Figure 22: Modified network(s) for the three configurations

Given the addition of the modified networks, six configurations of the wetland system have now been created in order to represent possible impacts to amphibian movement.

4.5 **Cost Surface for Raster Corridor**

The raster model is also implemented in the Muddy Creek watershed. The factors for biological connectivity are implemented to derive the cost surfaces for this watershed. The cost value for each factor varies from season to season for amphibians. However, winter is not a suitable time for amphibians to move from one wetland to another. Again the cost resistance of the landscape in autumn and spring is similar in terms of precipitation in Missouri. A higher cost value means more harmful barriers for amphibian movement and a lower cost value means survival is more likely. This raster model derives a different cost raster surface from the one showing in Figure 23a for summer season and Figure 23b for autumn/spring season according to Table 8 of Chapter 3 data.

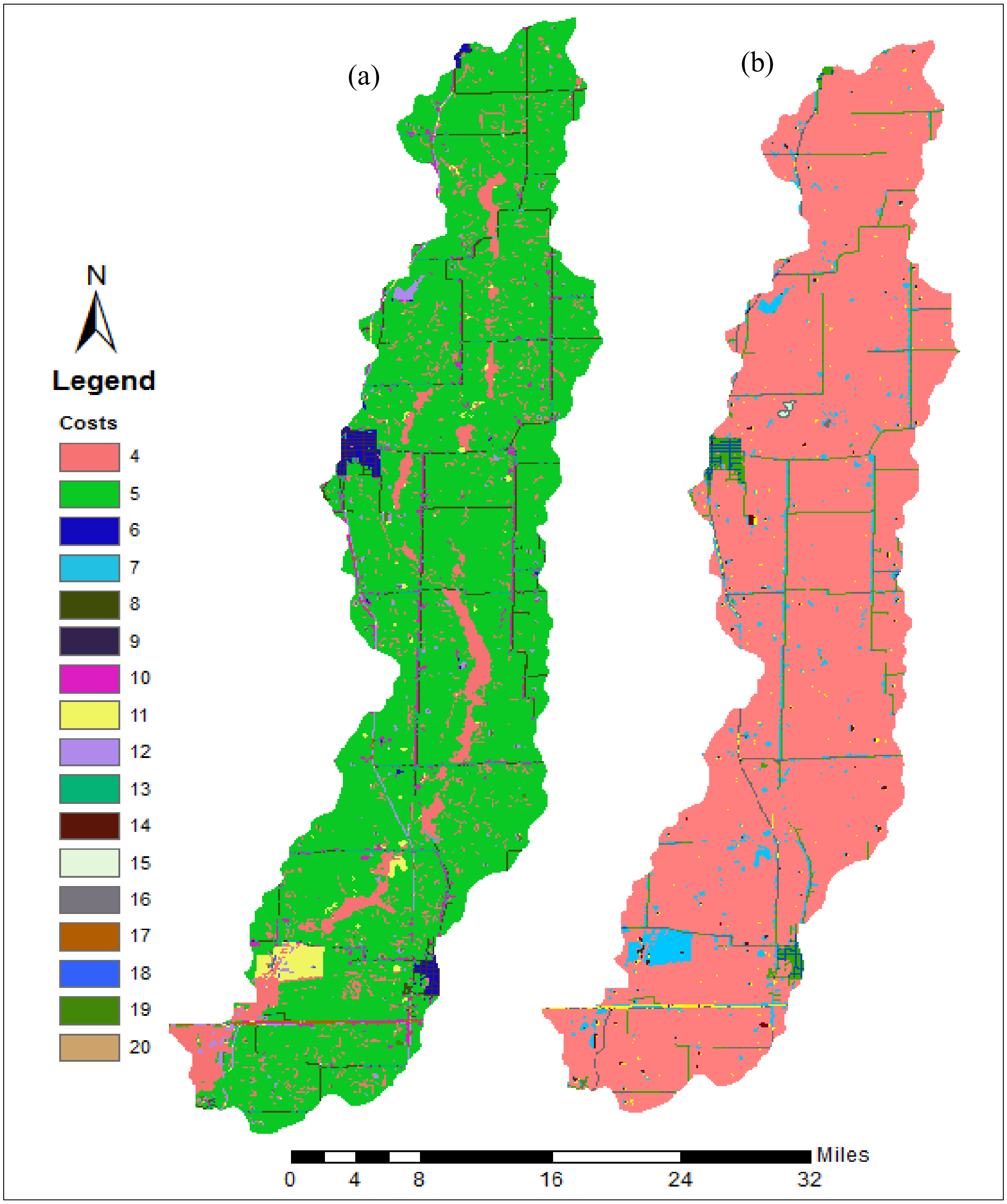

Figure 23: Cost surface for amphibian movement in a) summer season, and b) autumn/ spring season

The following example shows the raster cost corridors for the biological cost surface in two different seasons for the same wetlands. Figure 24a is for summer season and Figure 24b shows autumn/spring season between a pair of wetlands. Comparing the two corridors, we can see that corridor size in summer season (Figure 24a) is narrower than the corridor in spring or autumn (Figure 24b). This shows that resistance cost value in summer is greater than that for the spring/autumn seasons. Where the cost is greater the corridor is smaller in size.

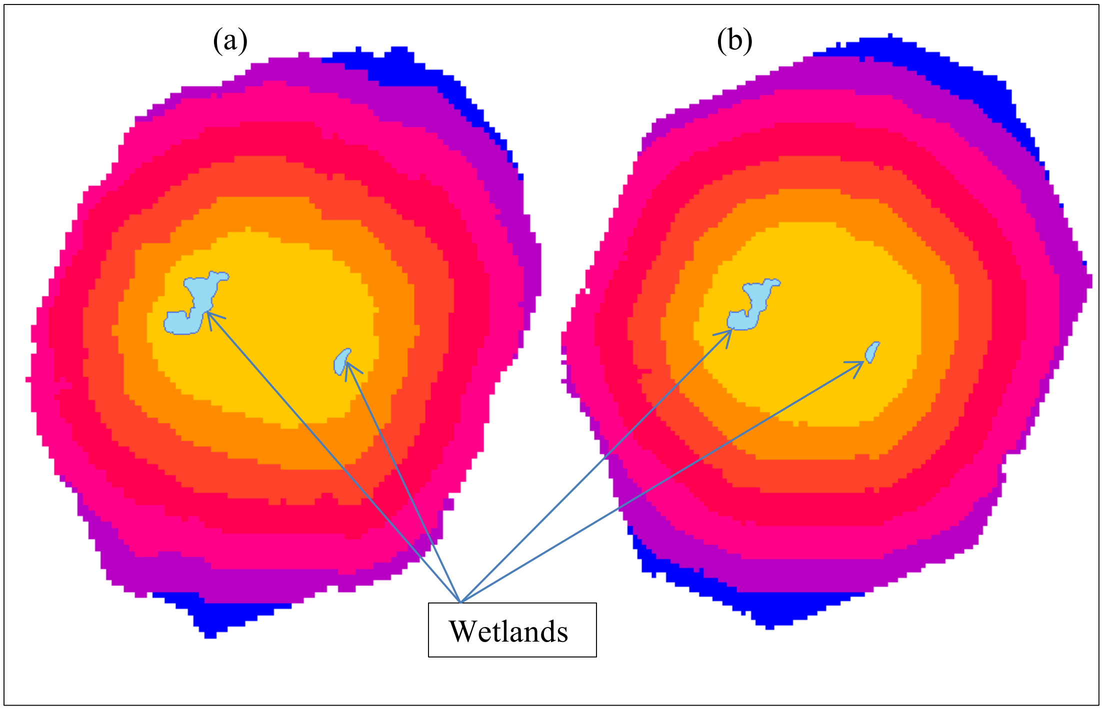

Figure 24: Raster corridor for a) summer season and b) autumn/ spring season

In this thesis, two sample wetlands are selected for visualization with a habitat corridors based on different cost surfaces in different seasons.

4.6 **Combination of Hydrological and Biological Connectivity**

ArcGIS Hydrology tools under the Spatial Analyst toolbox contain specialized tools for hydrologic analysis using the raster data model. The 10m DEM for the Muddy Creek watershed from the Missouri Spatial Data Information Service (MSDIS) website was used for analysis (Figure 25a). Using the DEM, the contributing areas for the lowest elevation points are derived and are shown in Figure 25b. There are some wetlands that contain very small contribution area (for example, one or two cells of 30X30 size) which become invisible behind the wetland points in a map. Thus the contributing area for every point is not visible in Figure 25b.

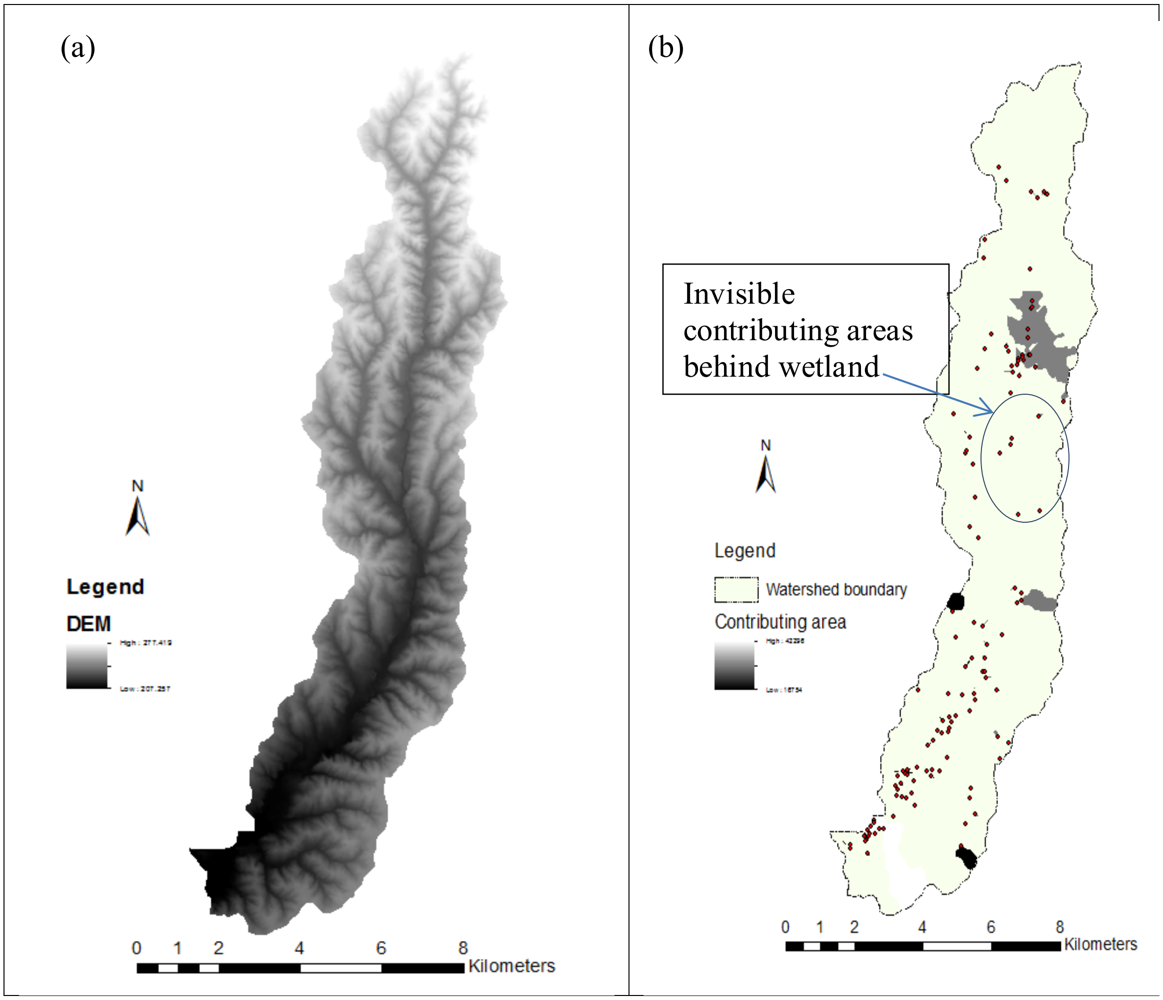

Figure 25: a) DEM for Muddy Creek watershed, b) centroid of wetlands and their contributing area

For clarity, the zoomed in picture in Figure 26b illustrates the contributing area that contains more than one wetland. It is assumed that there is a greater possibility of having strong hydrological connections when more than one wetland falls into a contributing area. Where there is a hydrologic connection, there must be a chemical connection. Here it can be shown that if the wetlands in a contributing area have biological connectivity the wetlands have hydrologic connectivity and chemical connectivity as well (Figure 26c).

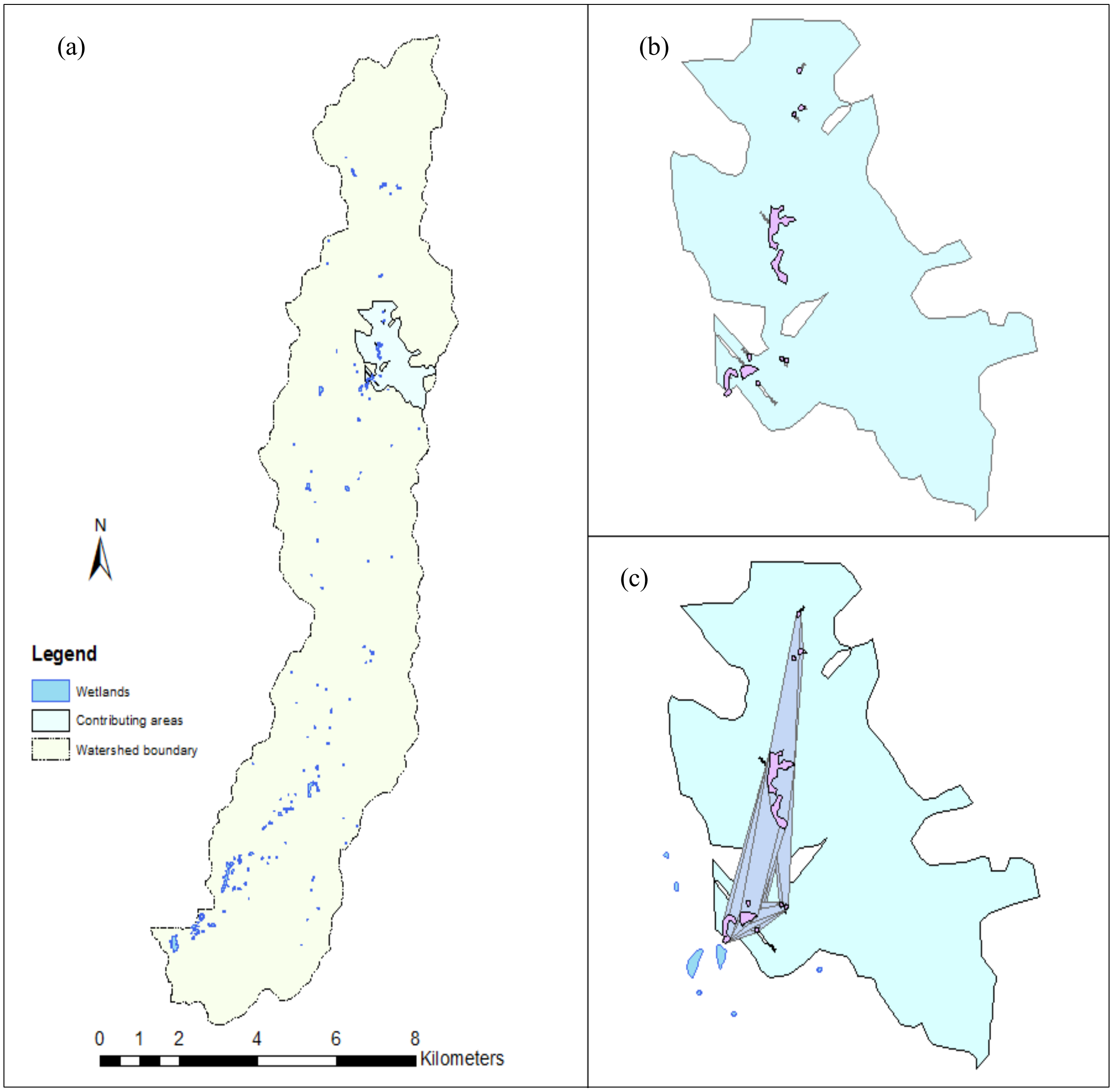

Figure 26: a) wetlands and their contributing area, b) example contributing area with overlapping wetlands, and c) vector corridors of the overlapping wetlands

Determining the lowest elevation point of a wetland is important for deriving contributing area. One easier way to find the lowest point of a wetland is to use ‘snap pour point’ tool of ArcGIS. The tool snaps points within a specified distance to the center of the accumulation layer (ArcGIS, 2011). This helps to determine the lowest point of flow within a specified distance from the center of a wetland; to ultimately derive the contributing area of surface flow. If the range of specified distance from the centroid of a wetland polygon is large enough to find the exact lowest point for that wetland, then an accurate contributing area is generated. Again, if the specified distance increases such that a lowest elevation point is projected outside of the wetland boundary, then inaccuracies in the contributing area for that wetland are introduced. However, in Figure 27a, Figure 27b, Figure 28a and Figure 28b, it can be noted that larger distance ranges result in greater contributing areas.

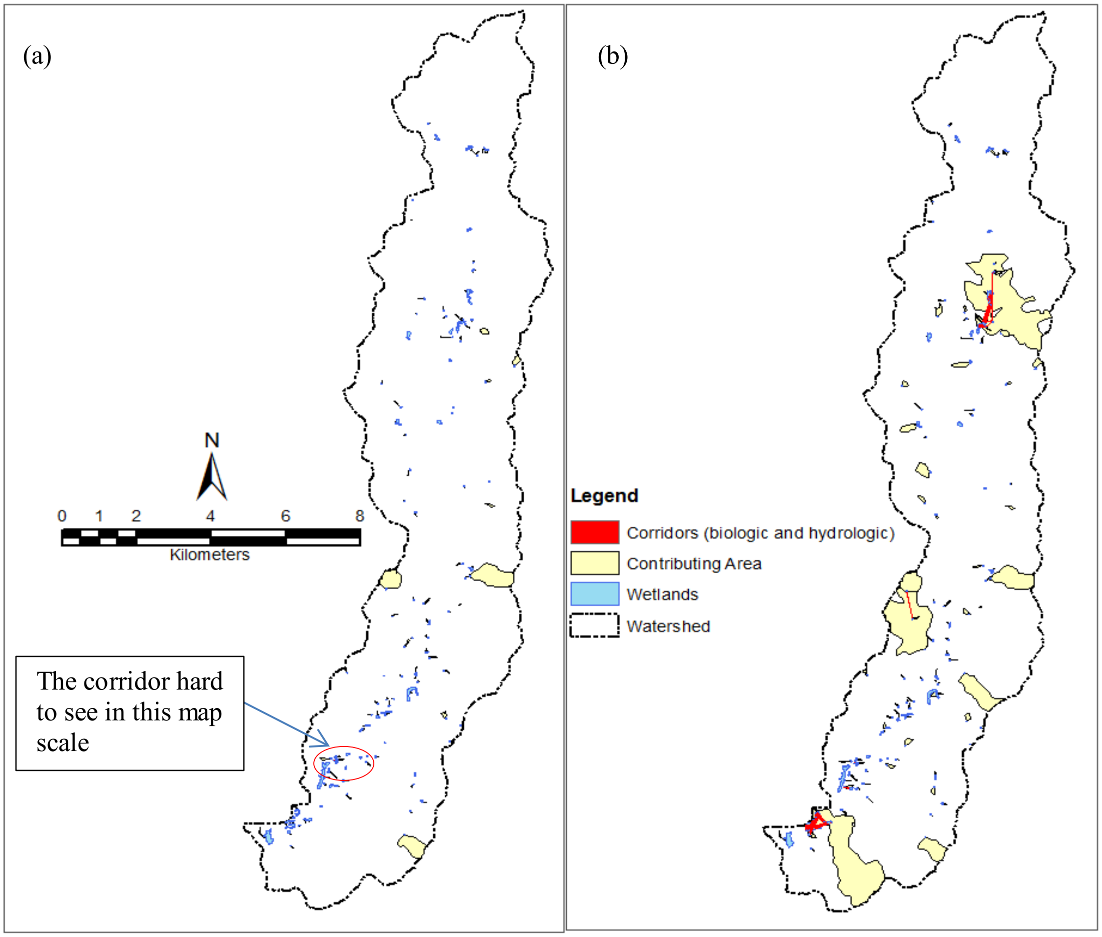

Figure 27: Biologic and hydrologic corridors considering: a) centroid of wetland as lowest elevation point, and b) area within 10m from the centroid for lowest elevation point

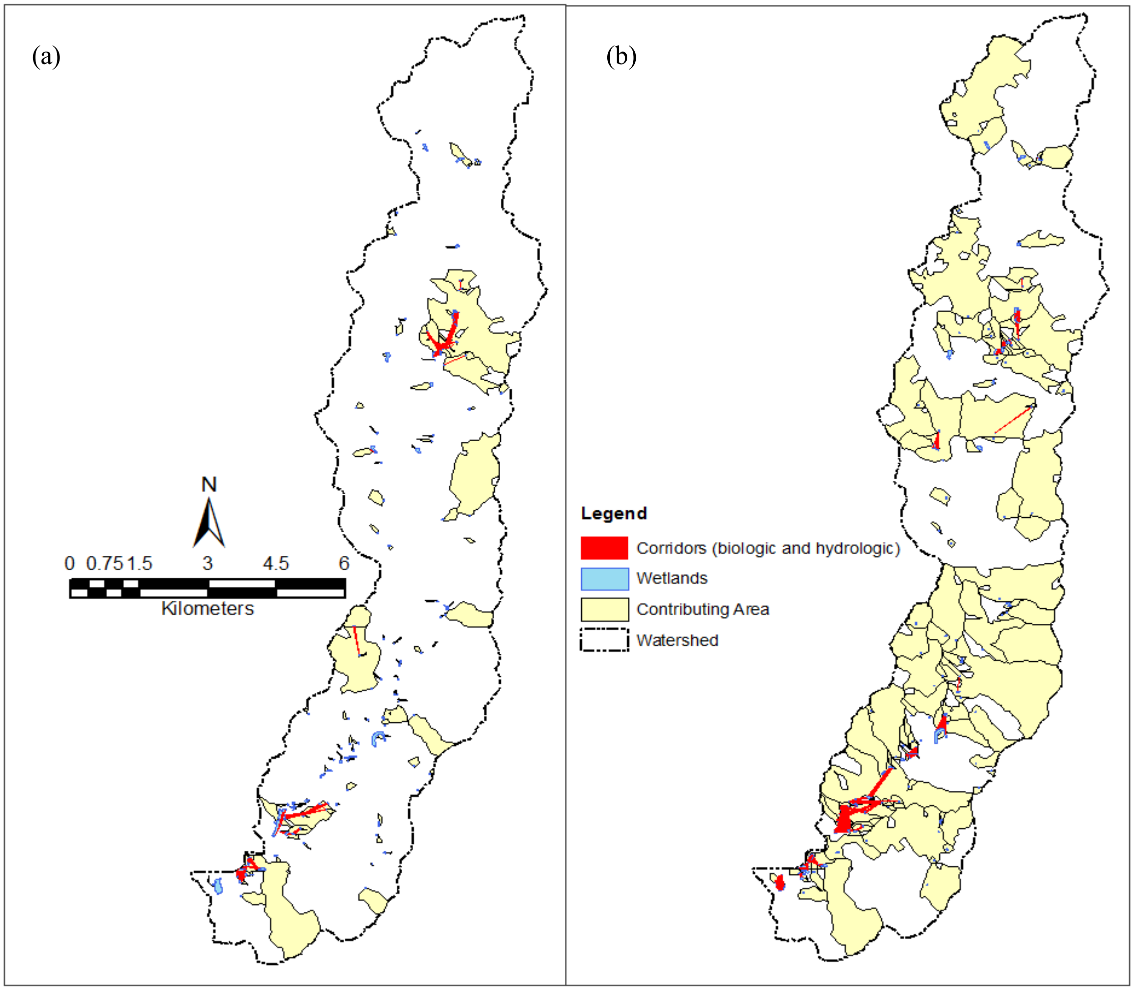

Figure 28: Biologic and hydrologic corridors considering: a) area within 20m from the centroid, and b) area within 100m of the centroid for lowest elevation point

Larger contributing areas increase the number of corridors that promote connectivity (such as biologic, hydrologic and chemical connectivity) as well (Table 9). Figure 27a (considering centroid as lowest elevated point) contains only one corridor (too small to visualize in the full map) between a pair of wetlands because all other wetlands have their own contributing area that are not overlapped with other wetlands' contributing area. While distance range flexibility incorporated for determining the lowest elevation point rather than a specific centroid point, it begins accumulating more areas for each wetland. Originally the watershed was represented as one network (Figure 20c, Chapter 3) among the wetlands (no riverine wetlands, ponds, and PFOs) considering biological parameters. However, accounting for the hydrologic parameter results in a fragmented system of subgraphs. Relative to biologic connectivity shown in Table 9, hydrologic connectivity appears to be a much sparser system.

Table 9: Hydrologic connectivity for different lowest point elevation

Type of lowest point elevation	# of subgraph (original # of subgraph)	# of corridors (original #of corridors)
Centroid	1 (1)	1 (907)
10 m snap pour point	6 (1)	20 (907)
20 m snap pour point	14 (1)	38 (907)
100 m snap pour point	33 (1)	59 (907)

The hydrologic connection of the wetlands can be unidirectional or bi-directional based on the elevation, distance, and soil condition among the wetlands. The possibility is higher of having both-way hydrologic connections, for the corridors among the wetlands in a contributing area when they are situated in the same flood plain. Here the considered wetlands have no river or stream connection; thus, all the contributing areas in the watershed area are not linked each other. Each wetland acts as a sink of its contributing area.

Chapter 5

RESULTS AND DISCUSSION

5.1 Modeling Vulnerability

The vulnerability assessment model identifies the worst-case scenarios of change to connectivity and capacity in the wetland networks for scenarios involving simultaneous loss of up to 100 corridors (arcs) for wetland configurations: a) all wetlands (Figure 20a), b) no riverine wetlands and ponds (Figure 20b), c) no riverine wetlands, ponds, and PFOs (Figure 20c), d) all wetland considering stream impact (Figure 22a), e) no riverine wetlands and ponds considering stream impact (Figure 22b), f) no riverine wetlands, ponds, and PFOs considering stream impact (Figure 22c). The first configuration (Figure 20a) contains 388 individual non-adjacent wetlands and 10,794 arcs (corridors), which constitutes the most extensive network as shown in Table 10. Being the most encompassing configuration, more paths exist as do more constraints and variables. Thus the computational time in solving the vulnerability assessment model is much higher (13 hr 12 min) than that of the other configurations (e.g., configuration (b) 1 hr 3 min, configuration (c) 48 min).

All the wetland configurations assessed by the vulnerability model tend to be affected in a similar way (i.e., an increase in number of arc losses decreases system connectivity and capacity) which is visualized in Figures 29-31. When the number of nodes and arcs is greater, the impact of increasing levels of arc loss is less. Figure 29a shows the network capacity allowing only one-step path (connectivity is more than 95%) for scenarios involving the simultaneous loss of up to 100 arcs (a), which is less than that experienced in the corresponding other two configurations in Figure 30a and Figure 31a (connectivity is less than 90%). However, the impact for two-step paths is much higher than the case where only one-step paths are considered. This is because in the case of one-step paths, an arc can be used by only a single path, while in the case of two-step paths, an arc can be used by multiple paths. Thus, when two-step paths are considered, the loss of one arc can impact multiple paths.

Each configuration is illustrated in Figure 29 to Figure 34. Of the six configurations with (a) and (b) designations, each figure represents the connectivity and capacity of the configurations, respectively.

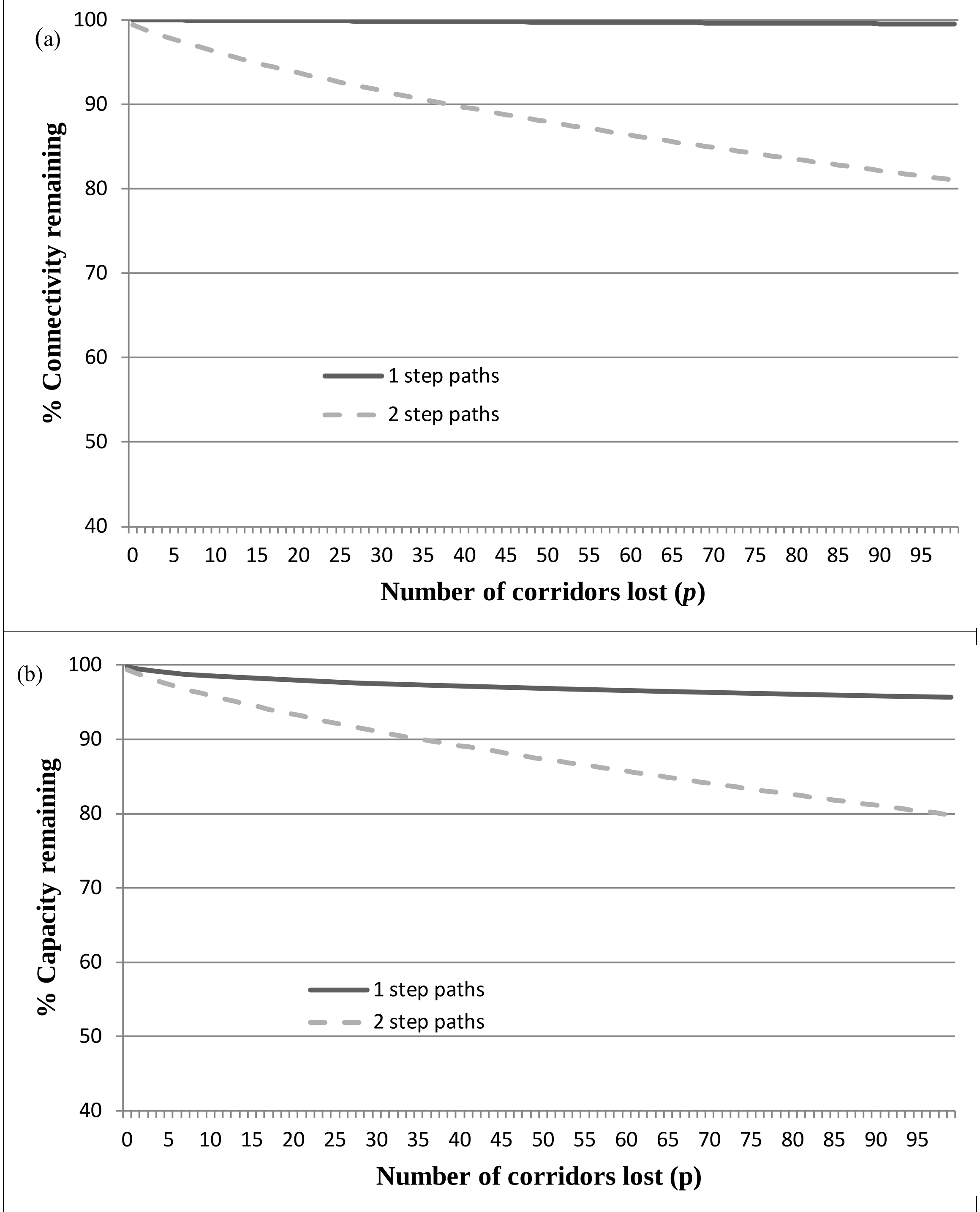

Figure 29: Impact on network due to: a) Change of connectivity for, and b) change of capacity for all wetlands

The connectivity change experienced in configuration (b) in Figure 30a and configuration (c) in Figure 31a is small for both one-step and two-step paths, because the number of nodes and arcs in the network are very close to each other. On the other hand, the capacity change experienced in configuration (b) in Figure 30b shows a greater difference than configuration (c) in Figure 31b, especially for one-step paths. System capacity not only depends on the number of node pairs that are connected, but also on the capacity of arcs (and paths). From Figure 18 of Chapter 3, one can see that a number of larger PFO wetlands are missing from configuration (b) to configuration (c). The corridors connected to those wetlands carry more capacity; thus, the loss of those corridors has a big impact on the network capacity.

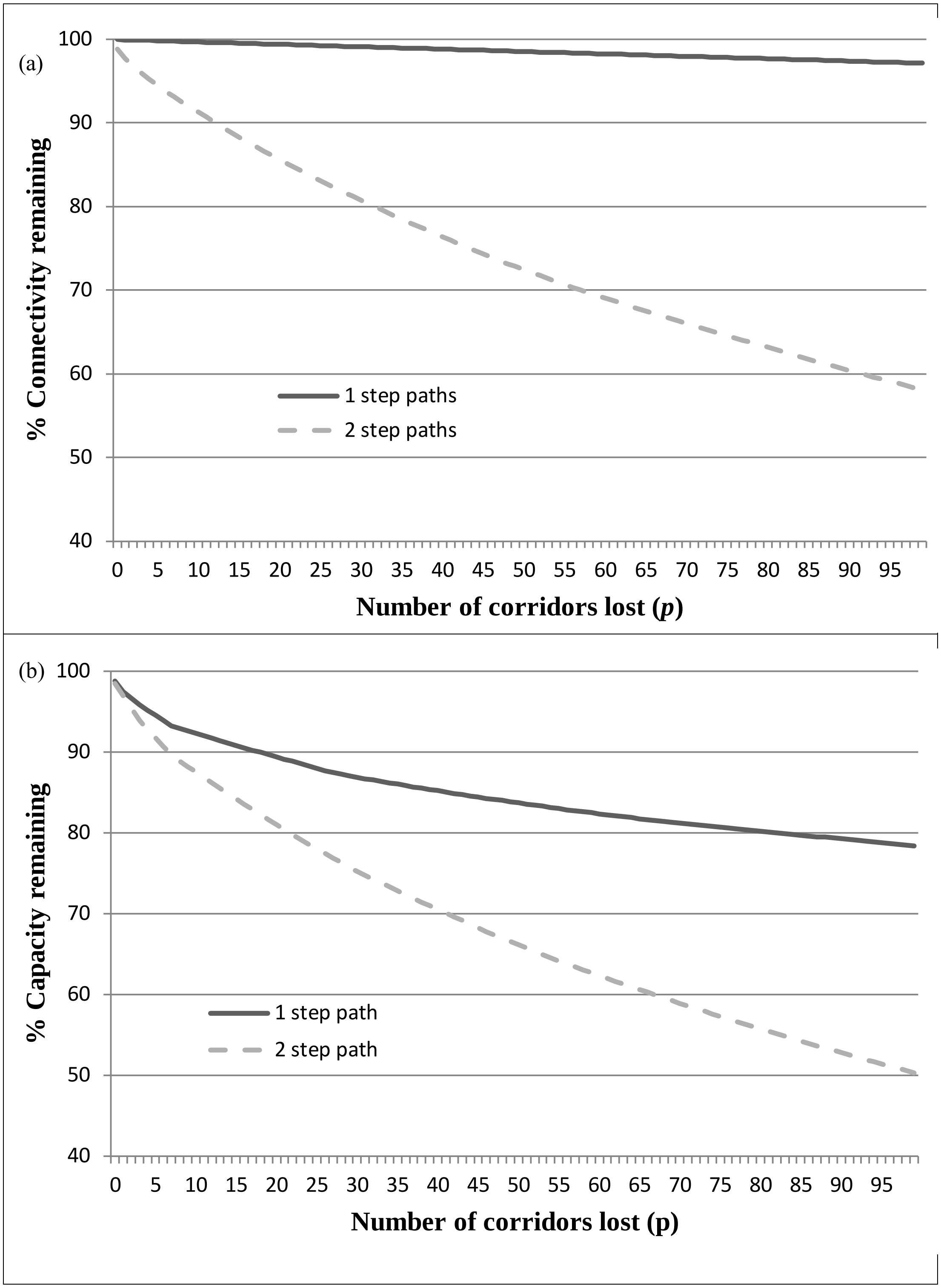

Figure 30: Impact on network due to: a) change of connectivity, and b) change of capacity, for the network excluding riverine wetlands and ponds

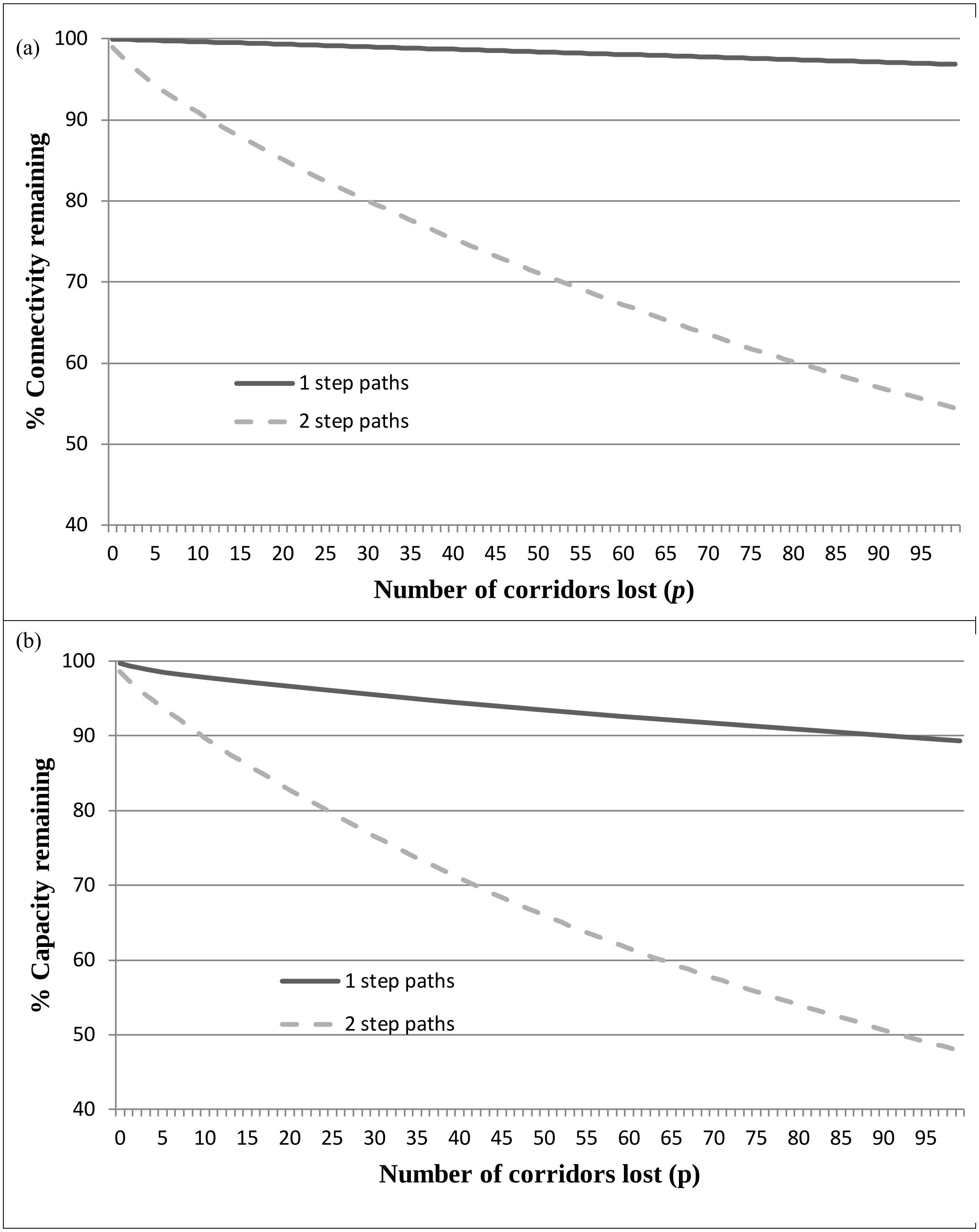

Figure 31: Impact on network due to: a) change of connectivity, and b) change of capacity, for the network excluding riverine wetlands, ponds, and PFOs

The wetland network modification by streams (Figures 22a, 22b, and 22c of Chapter 4) results in network representations with fewer viable arcs (corridors). These changes in the numbers of arcs, number of potential paths, number of variables, number of constraints, total capacity, and total connectivity due to modification are reported in Table 10.

Table 10: Summary of the maximization of connectivity and capacity loss for all the configurations and modifications

Configurations	# of wetland polygons	# of arcs (corridors)	# of constraints		# of variables		# of network(s)	# of total connectivity	Total capacity (m)	# of paths	
			1 step	2 step	1 step	2 step				1 step	2 steps
a) All wetlands	388	1,0794	86,345	537,525	64,762	290,352	1	21,588	2,442,450	21,588	924,072
b) Removing riverine wetlands and ponds	129	1,750	67,545	14,001	37,272	10,500	1	3,500	473,875	3,500	83,902
c) Removing riverine wetlands, ponds and PFOs	125	1,587	12,697	62,461	9,522	34,404	1	3,174	354,270	3,174	73,572
d) All wetlands (modified by stream)	388	6,196	63,205	343,207	47,403	18,7404	1	1,5801	1,748,798	1,5801	525,561
e) Removing riverine wetlands and ponds (modified by stream)	129	987	7,897	27,917	5,922	15,932	3	1,974	257,853	1,974	29,760
f) Removing riverine wetlands, ponds and PFOs (modified by stream)	125	843	6,705	22,141	5,028	12,746	3	1,676	172,433	1,676	22,610

The modified networks represent a system more vulnerable to arc loss as compared with the original network since it contains fewer arcs and fewer paths. The relation of connectivity and capacity for modified network(s) due to arc losses are similar to that found in the vulnerability assessments of the original networks.

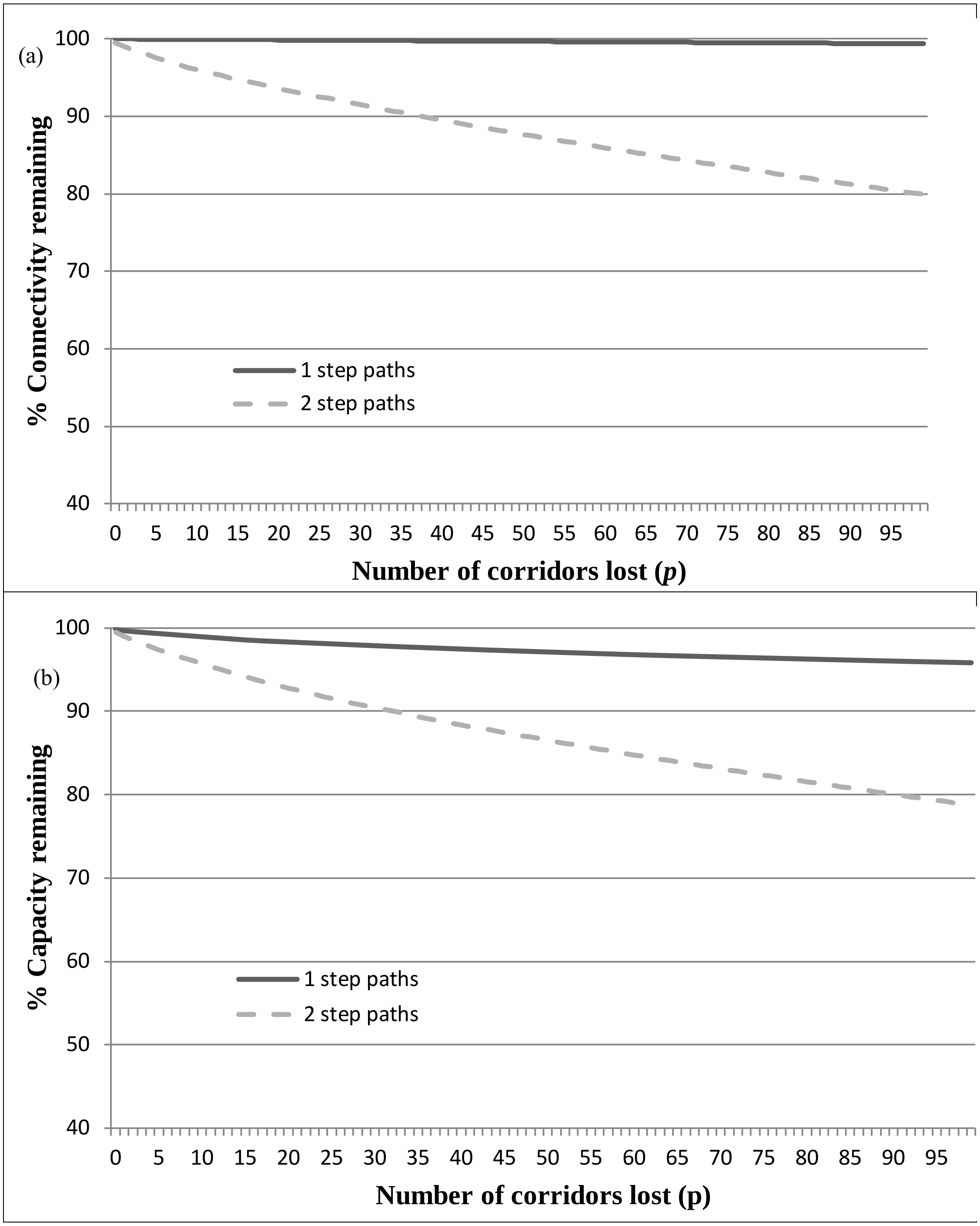

Figure 32: Impact on network for all wetlands but modified by streams due to: a) change of connectivity, and b) change of capacity

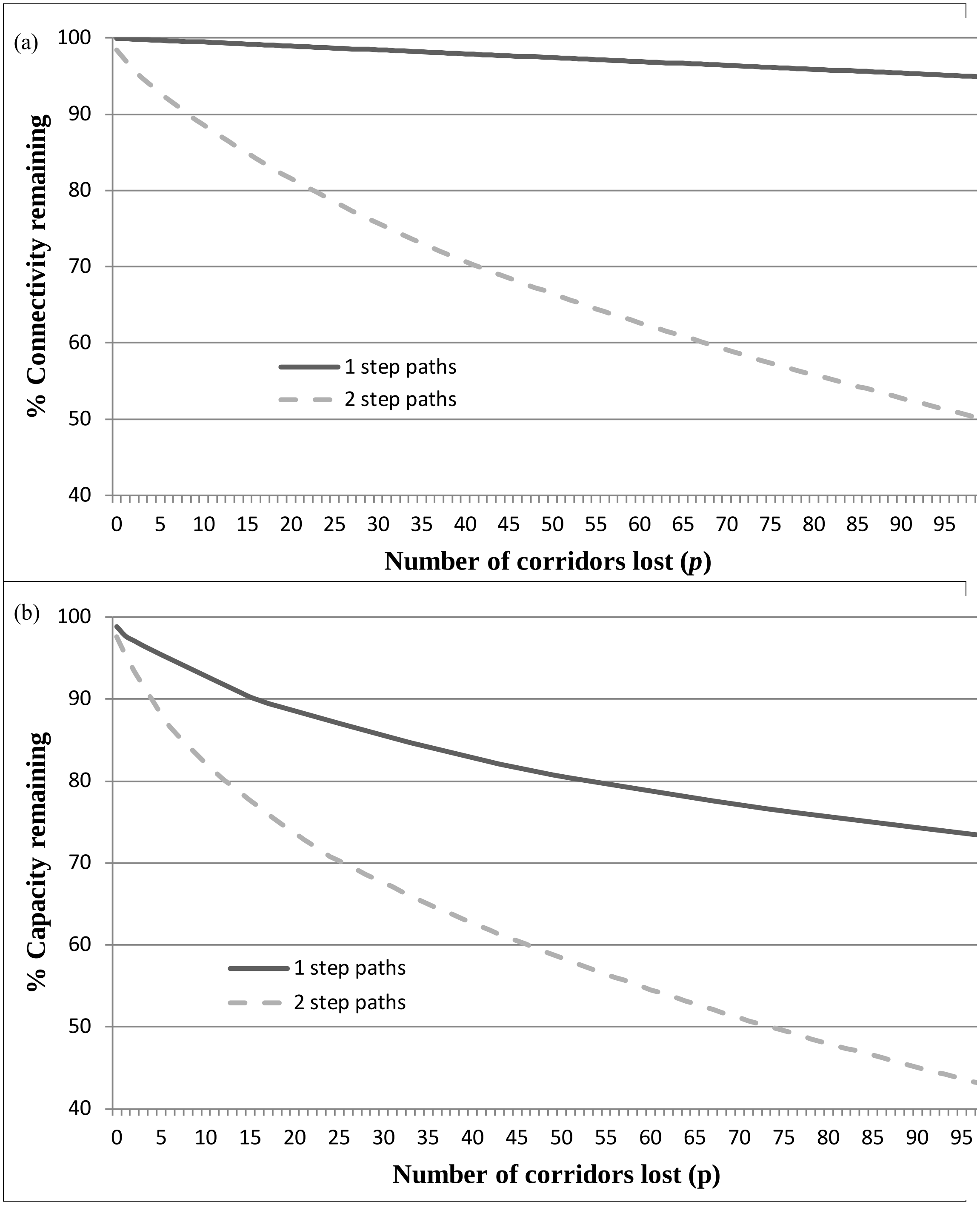

Figure 33: Impact on network excluding rivers and ponds and modified by stream due to: a) change of connectivity, and b) change of capacity

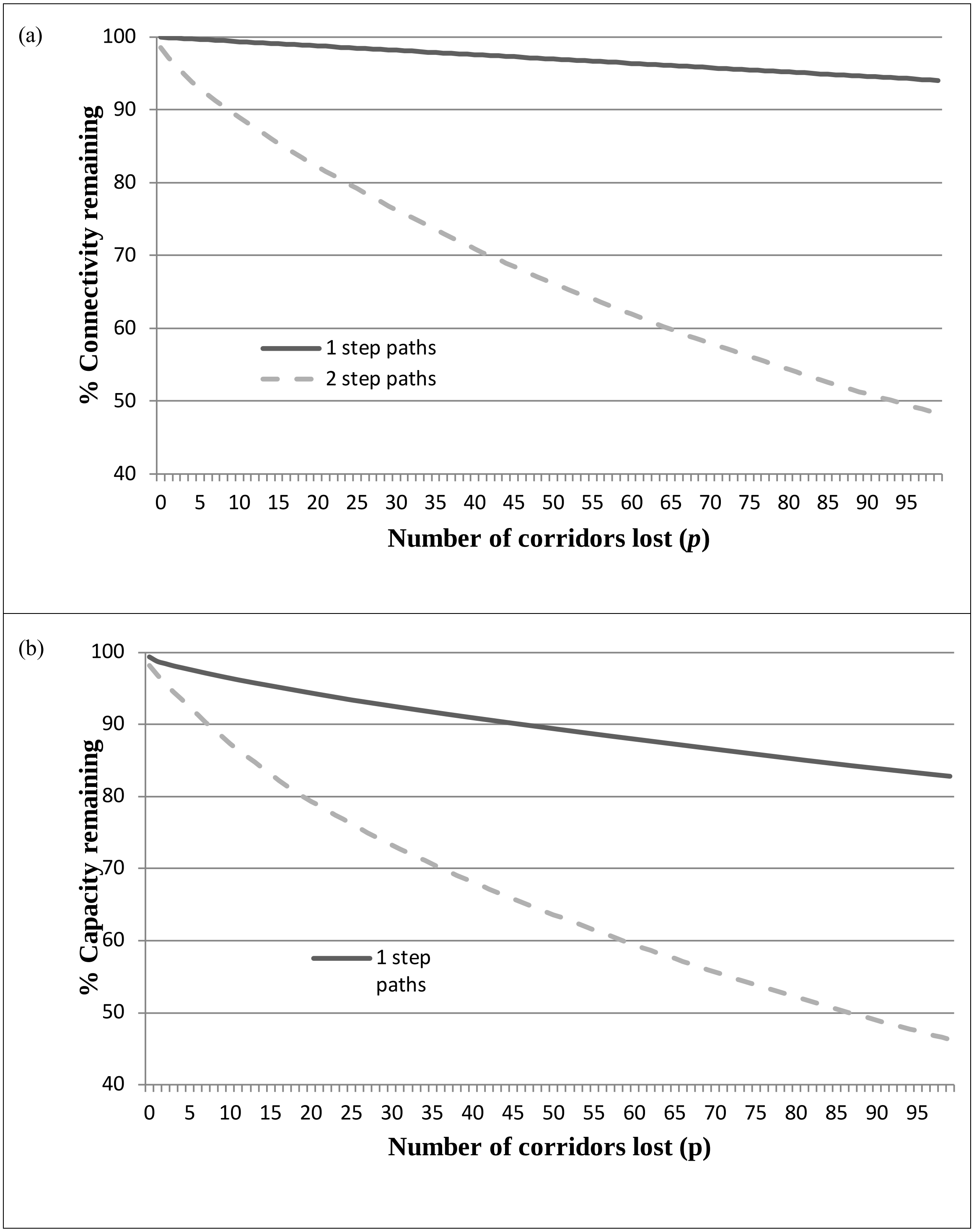

Figure 34: Impact on network for the wetlands excluding riverine, ponds and PFOs and modified by stream due to: a) change of connectivity, and b) change of capacity

For any scenario identified by the vulnerability assessment model, the arcs comprising the worst-case scenario can be visualized in a GIS. The result of simultaneous arc loss on connectivity, for a network excluding rivers and ponds (Figure 20b in Chapter 4), is shown in Figure 33. Considering only one-step paths, the impact of all of the arc loss scenarios are similar because the loss of each arc equates to the loss of only one path and connectivity between one pair of wetlands. Thus, given the simultaneous loss of 100 arcs (p=100), any set of 100 arcs is equivalent regardless of the location of the arcs in the network. Figure 35a shows that the lower edge arcs of the watershed are selected because the ID of arcs started lower to higher from the bottom to top respectively. When this connectivity-based arc loss model is repeated considering both one and two-step paths, the arcs in the worst-case scenarios are selected from the middle of the network rather than any edge of the watershed as is shown in Figure 35b. Again, this change occurs given that incorporation of two-step paths allows arcs to become important to movement between multiple wetland pairs instead of just one. An arc that is situated at the edge of a network can be used by a single path, but an arc that is situated in the middle of a network has a better chance of being used by multiple paths. Thus in two-step or multiple step paths, the mostly impacting arcs depend on the location of the arc in a network.

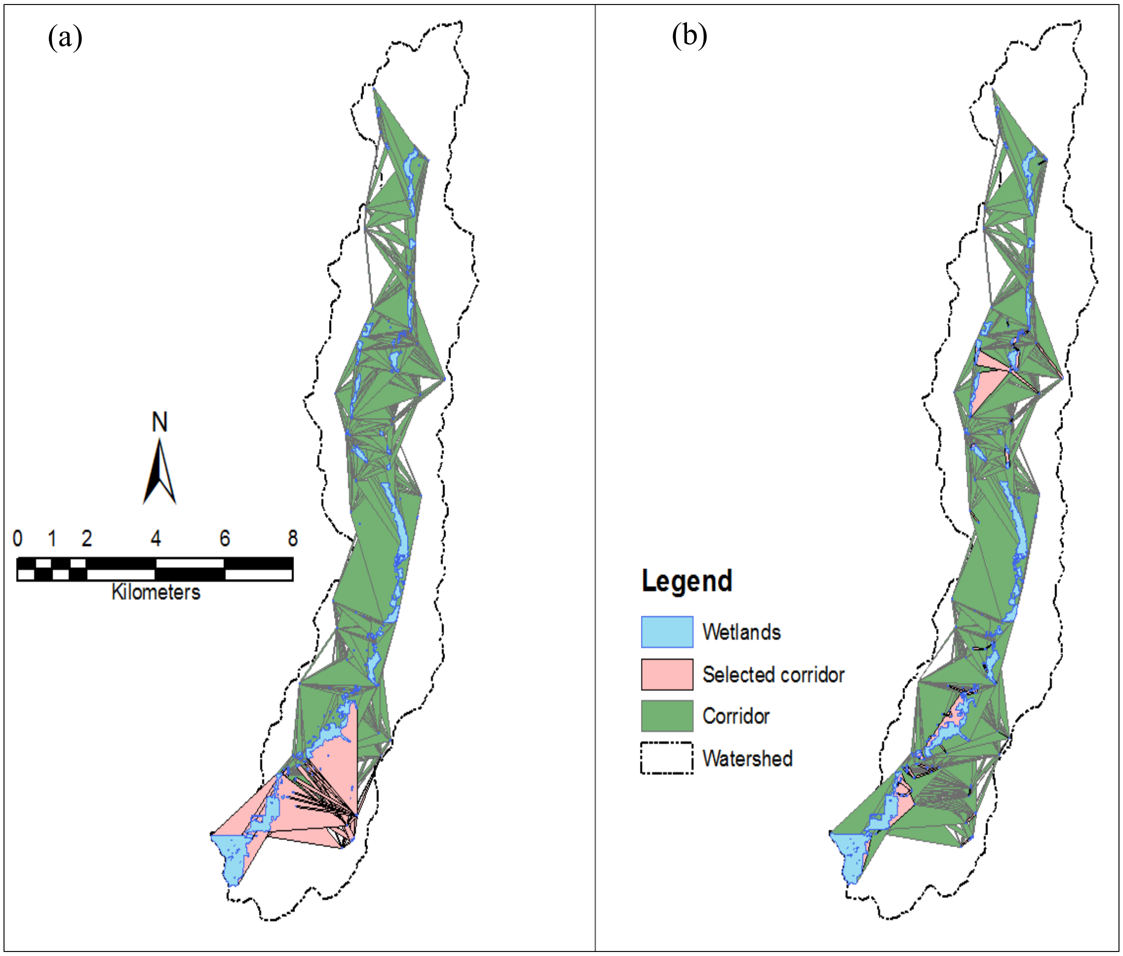

Figure 35: Corridors from "no riverine wetlands and pond network" involved in p=100 scenario of simultaneous arc loss model where impact to connectivity is maximized for: a) one-step paths; and b) both one and two-step paths

When simultaneous arc loss scenarios maximizing impact to capacity are considered for the same network excluding riverine wetlands and ponds, the results become very different. In cases where only one-step paths are allowed, worst-case scenarios involved arcs that contained more capacity regardless of their location in the network. Figure 36a shows that the higher capacity corridors are selected because the bigger width corridor contains more capacity. When both one and two step paths between pairs of wetlands are considered, the corridors identified reflect importance to system capacity between multiple pairs of wetlands as depicted in Figure 36b.

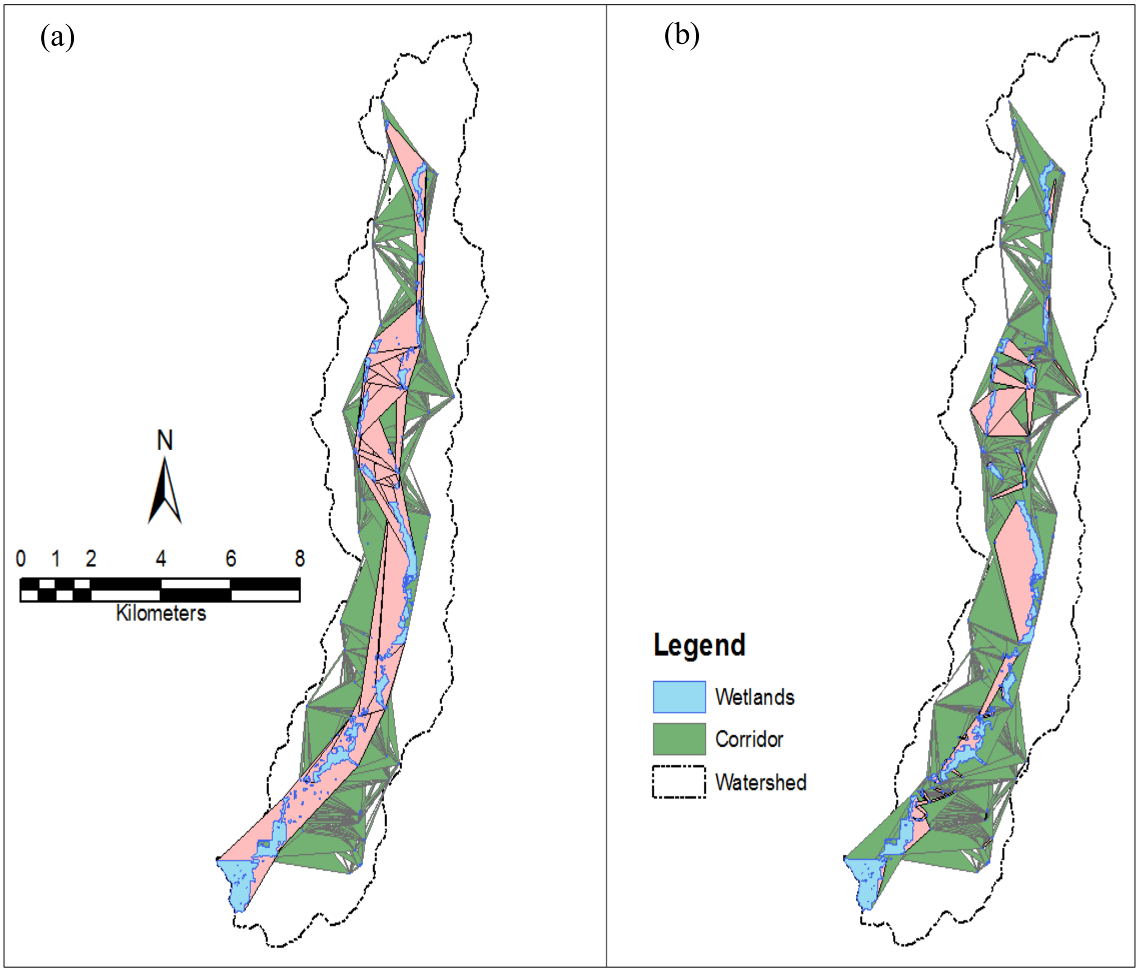

Figure 36: Corridors from “no riverine and pond network” involved in p=100 scenario of simultaneous arc loss where impact to capacity is maximized for: a) one-step paths; and b) both one and two-step paths

The result of simultaneous arc loss model focusing connectivity and capacity is showing the same pattern for modified no riverine wetlands and pond wetland networks (configuration 2) as shown before for excluding riverine wetlands and pond wetland networks (configuration 5) (comparing Figure 35 with Figure 37, and Figure 36 with Figure 38). For configuration 5, the bottom edge corridors of the watershed are selected for simultaneous 100 arc loss (p = 100) of one-step paths for the same reason as for configuration 2. Again, for the two-step paths within the corridors located in the inner part of the watershed are selected because of their multi-use by different paths.

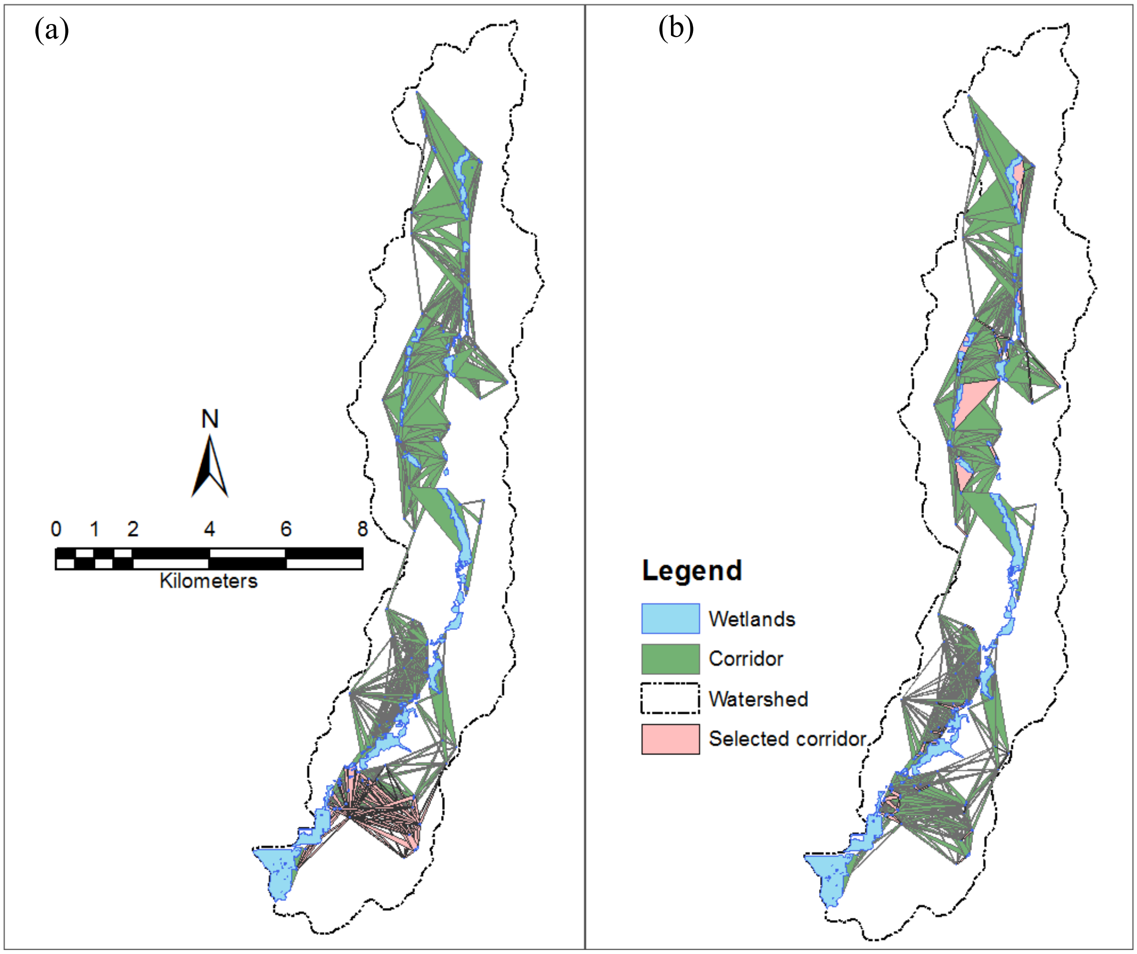

Figure 37: Corridors from “no riverine and pond network modified by perennial stream” involved in p=100 scenario of simultaneous arc loss model where impact to connectivity is maximized for: a) one-step paths; and b) both one and two-step paths

Eventually for the same reason as for configuration 2 in Figure 36a, the higher capacity corridors are selected for one-step paths shown in Figure 38a. Selected corridors for two-step paths are not only dependent on corridors capacity but they are also dependent on corridors location for use by multiple-paths. From Figure 38b, it can be shown that the corridors carrying higher capacity and located in the middle of the watershed are selected as most vulnerable in terms of capacity in the network.

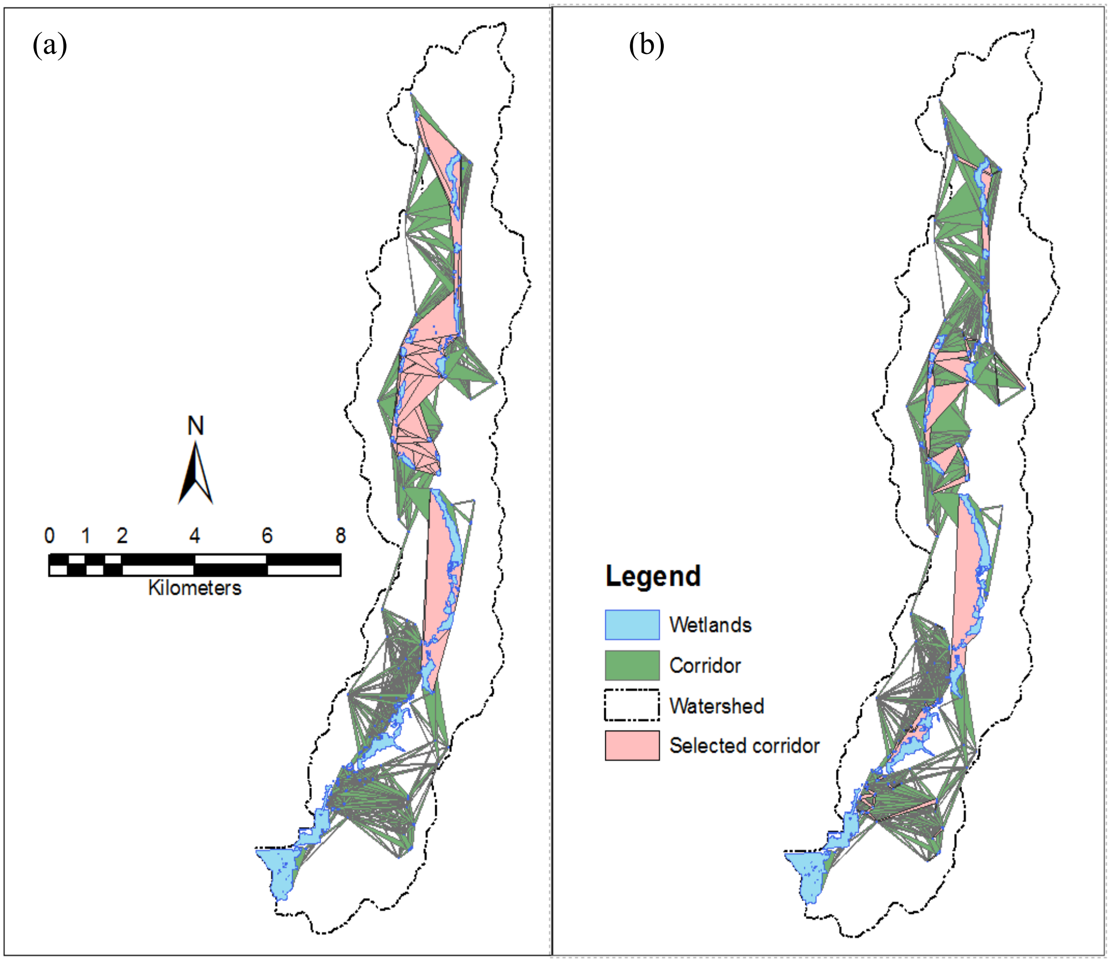

Figure 38: Corridors from “no riverine and pond network” involved in p=100 scenario of simultaneous arc loss model where impact to connectivity is maximized for: a) one-step paths; and b) both one and two-step paths

5.2 Site Selection for Wetland Mitigation

GIS can be used to track and visualize the convergence of the new wetland site selected using Weiszfeld’s solution technique for the Weber Problem before reaching the final optimized point location that is shown in Table 11.

Table 11: Convergence of wetland site using Weiszfeld's algorithm

Iteration number	Objective value	X Coordinate	Y Coordinate
0	1000,000,000	480000	4410000
1	5,046,252	486926.7091	4412246.019
2	502,338.8	486935.2586	4412294.926
3	499,872.5	486929.7126	4412322.123
4	499,002	486922.9639	4412338.565
5	498,625.9	486917.7646	4412348.832
6	498,463.9	486914.2373	4412355.252
7	498,397.3	486911.977	4412359.233
8	498,371.1	486910.5728	4412361.68
9	498,361	486909.7157	4412363.172
10	498,357.3	486909.1978	4412364.077
11	498,355.9	486908.8864	4412364.625
12	498,355.4	486908.6998	4412364.955
13	498,355.2	486908.588	4412365.153
14	498,355.1	486908.5211	4412365.273
15	498,355.1	486908.481	4412365.344
16	498,355.1	486908.457	4412365.387
17	498,355.1	486908.4426	4412365.413
18	498,355.1	486908.434	4412365.429
19	498,355.1	486908.4288	4412365.438
20	498,355.1	486908.4257	4412365.444
21	498,355.1	486908.4239	4412365.447
22	498,355.1	486908.4228	4412365.449
23	498,355.1	486908.4221	4412365.45
24	498,355.1	486908.4217	4412365.451

Here only distance and capacity of wetlands are considered to select a site for a new wetland that minimizes weighted cost to other existing wetlands in the system. It is assumed in this site selection model that the new wetland can be placed anywhere in the landscape. In reality, the location identified as optimal by this approach may not be available for constructing a new wetland, but the value in these continuous site location approaches is to highlight where the best potential exist for augmenting a system. However, practically, the location also depends on land use/land cover and also on an array of economic factors. Finding different location points from Weiszfeld's method and some different approaches can make the model flexible in location choice. The availability of the land can be further evaluated by overlaying the optimized location with other landscape layers (i.e. parcel databases) using GIS (Figure 39).

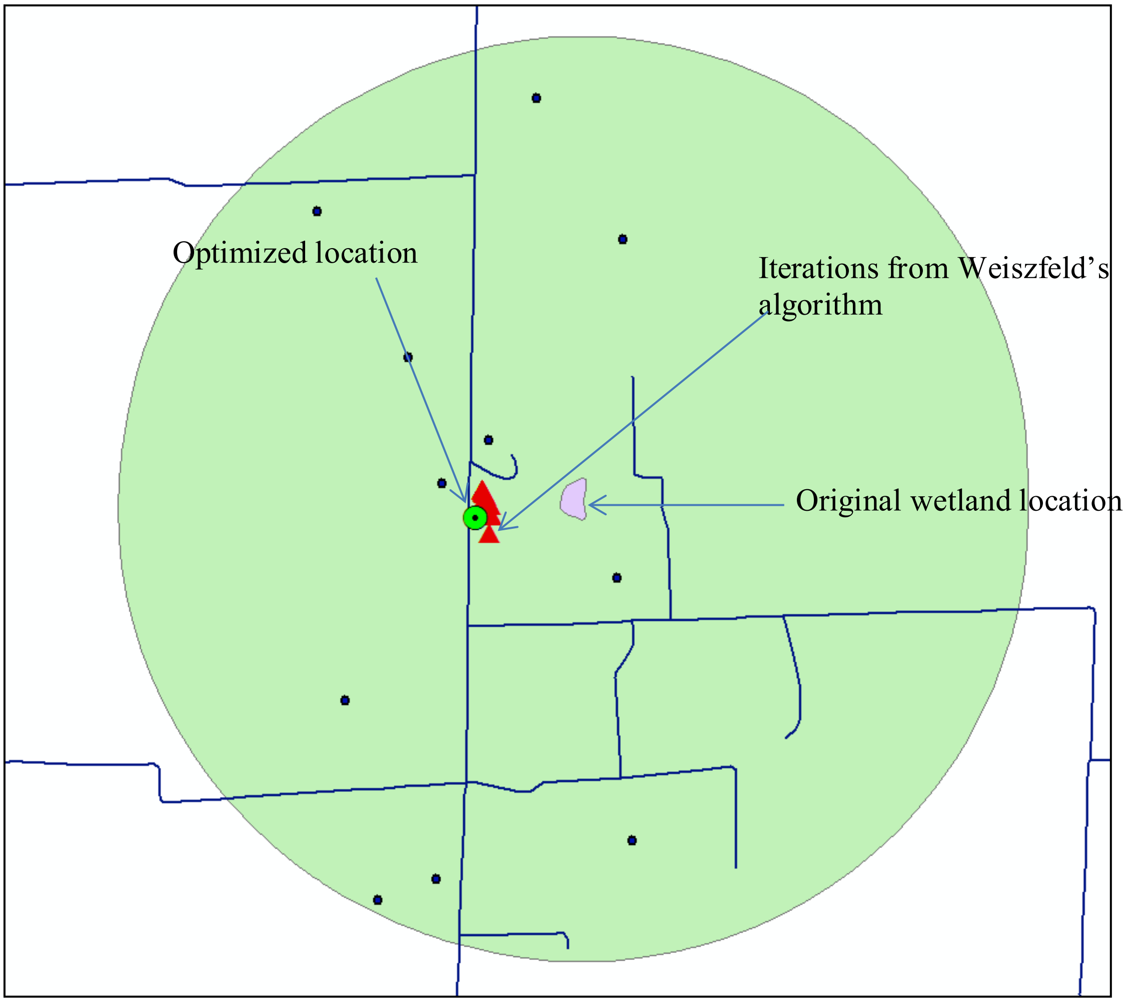

Figure 39: Optimized locations for wetland construction

Chapter 6

CONCLUSION

The connectivity of wetlands can be identified or characterized in different ways based on a multitude of different biological, chemical, and hydrologic factors and/or wetland planning objectives. However, an initial baseline representation based on general and universal constructs such as distance/proximity, is useful for understanding and visualizing wetlands interactions for managers and planners. Given a base representation, planners should be able to further modify system circumstances to accurately reflect situation specific factors and objectives. This thesis demonstrates a new methodology to represent and generate corridors between wetlands in a watershed. These vector corridors are initially generated based on a general assumption of geographic proximity. Although distance is the only parameter that is considered when generating the corridors, the resulting corridors can then be modified to adjust for landscape barriers and to more adequately reflect different types of connectivity such as hydrologic relationships. The capacity of each corridor is calculated from the geometric properties of the corridor. The set of corridors is represented by a network containing wetland as nodes and corridors as arcs. This network can be used in different types of analysis. This generated network has been used in this thesis to model habitat vulnerability for incremental and simultaneous wetland loss. Attentively, for mitigation purpose a methodology for siting a new wetland location is presented based on this same network analysis.

An incremental node/arc loss and a simultaneous arc loss model are presented in this thesis focusing on amphibian behavior. In the incremental node/arc model, it is assumed that any node/arc loss impacts only its own network (wetland region). Thus, such a loss cannot represent the impact that a network suffers when impacted by the loss of nodes/arcs of other networks. This model is appropriate for a wetland system where the impact of each wetland/corridor loss needs to be known for planning and management purposes.

This simultaneous arc loss model is an extension of the PCUP model of Matisziw et al. (2007) aimed at explicitly accounting for linkages/arcs based network vulnerability model. Unlike the PCUP model, it incorporates arc capacity with connectivity to quantify maximum impact to network capacity. For design and management purposes, it is important for wetland planners to know where potential vulnerabilities to corridor capacity may exist. In the simultaneous arc loss model the distance constraints incorporated for direct and indirect connectivity are alike. There is also a step constraint for enumerating paths of the pairs of wetlands in the network. The increase of the number of each step for enumerating path can exponentially increase the number of paths which also increases the model's solution time. Although adequate connectivity and less network impact might be good for wetland network studies from the biological point of view, there is no guarantee that amphibians follow the connectivity rule. The quantitative impacts on the network due to arc and capacity loss may not be exact, but showed a method to implement this vulnerability model. The selected arcs for disruption from the model to maximize connectivity and capacity can be visualized in GIS. This kind of flexible model, distance constraint and step constraints can be easily adapted to reflect the behavior and movement potential of other species. The site selection methodology proposed in this thesis has not been extensively applied at the watershed level. However, this does represent a promising avenue for future research. Furthermore, this siting approach is not limited to single site selection and could be adapted to siting multiple wetland locations.

So far, all the analysis is performed by using a vector data model and focusing on biological connectivity. The raster data model can easily incorporate a number of potential parameters with the distance parameter to characterize corridors. This thesis represents the dynamic behavior of raster corridor based on different seasons of a year. The cost values that are used in the raster corridor were selected based upon values reported in the literature to demonstrate the methodology of generating dynamic raster corridor based on seasons. This raster method can be implemented for any animal, as long as parameter surface cost values for selected parameters are known. New parameters can be added or parameters can be removed from the analysis for different animals in different places. The raster corridor model will be more robust when the resistance values of the different factors/parameters are quantified from biological experiments (from animal's behavior) (Cosentino et al., 2011).

To incorporate hydrological connectivity, a GIS based approach is presented to define the surface water hydrological connection. This approach uses a DEM to derive water flow directions and water flow accumulation. Hydrological connectivity is related to chemical connectivity because it provides a pathway for chemical components to travel from one wetland to another. The main challenge in determining hydrologic connectivity is to select a distance range that derives accurate contributing areas for most of the wetlands. Generally all water bodies in a watershed are connected to each other, but here, this model did not consider all the water bodies as wetland. Thus, most of the contributing areas in a cluster are not connected to each other. This approach to evaluating hydrologic connectivity currently deals with surface water connectivity only, leaving assessment of groundwater connectivity as a future task.

All the models and methodologies in this thesis deal with a range of available spatial datasets; there has been no field data collection or validation. The models and methodologies can be further extended and tested through the field verification process. Although the models have not been subject to ground truth, they are believed to be useful by incorporating parameters of interest from biology: distance and slope (derived from DEM). Distance and slope are two universal and easy to collect parameters. The algorithms of the models presented in this thesis can be implemented in any programming language.

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APPENDIX

APPENDIX A. CONNECTIVITY AND CAPACITY MAXIMIZATION OUTPUT

Table A.1. Network properties of the six different configurations

Types of network configurations	# 1 step paths			# 2 step paths			# of OD	# OD Pairs
	# of paths	# of constraints	# of variables	# of paths	# of constraints	# of variables		
All wetlands	21588	86345	64762	924072	537525	290352	388	21588
Riverine and ponds	3500	14001	10500	83902	67545	37272	129	3500
PFOs	3174	12697	9522	73572	62461	34404	125	3174
All modified	15801	63205	47403	525561	343207	187404	388	15801
Riverine modified	1974	7897	5922	29760	27917	15932	129	
PFOs modified	1676	6705	5028	22610	22141	12746	125	1676

Table A.2. All wetlands and all wetlands modified by stream's connectivity and capacity maximization output

P	All wetlands				All wetlands modified by stream			
	1 step path		2 step path		1 step path		2 step path	
	Obj (Con)	Obj (Cap)	Obj (Con)	Obj (Cap)	Obj (Con)	Obj (Cap)	Obj (Con)	Obj (Cap)
1	3	14969	277	35419	1	2999	77	9800
2	4	18692	353	45063	2	5997	149	17329
3	5	21691	427	54174	3	7530	210	24857
4	6	24690	496	62621	4	9063	269	32111
5	7	27688	559	70793	5	10450	325	38952
6	8	30687	621	78698	6	11837	381	45580
7	9	32220	682	86277	7	13176	436	51918
8	10	33752	743	93509	8	14515	488	57833
9	11	35285	803	100253	9	15854	537	63702
10	12	36818	863	106911	10	17194	584	69470
11	13	38205	923	113411	11	18533	630	75195
12	14	39592	983	119857	12	19872	672	80873
13	15	40980	1043	126278	13	21196	712	86493
14	16	42367	1101	132667	14	22520	752	91945
15	17	43706	1154	138874	15	23844	792	97242
16	18	45045	1205	145046	16	25168	831	102477

17	19	46384	1256	150890	17	26160	867	107669
18	20	47723	1305	156735	18	27152	903	112449
19	21	49062	1354	162493	19	27938	939	117144
20	22	50401	1402	168232	20	28724	975	121779
21	23	51726	1448	173940	21	29511	1010	126322
22	24	53050	1494	179623	22	30297	1045	130814
23	25	54374	1540	185253	23	31083	1080	135306
24	26	55698	1586	190790	24	31869	1114	139726
25	27	57022	1632	196303	25	32655	1148	144122
26	28	58347	1677	201755	26	33441	1181	148299
27	29	59338	1722	207188	27	34202	1214	152284
28	30	60330	1767	212609	28	34964	1247	156170
29	31	61116	1811	217983	29	35725	1280	159969
30	32	61903	1855	223264	30	36486	1313	163741
31	33	62689	1898	228246	31	37248	1346	167480
32	34	63475	1941	233035	32	38009	1378	171151
33	35	64261	1984	237730	33	38762	1410	174782
34	36	65047	2026	242425	34	39515	1442	178412
35	37	65833	2067	247037	35	40188	1473	182025
36	38	66619	2108	251620	36	40861	1504	185617
37	39	67382	2149	256138	37	41533	1535	189201
38	40	68145	2189	260648	38	42206	1566	192780
39	41	68909	2229	265127	39	42879	1597	196357
40	42	69672	2268	269569	40	43551	1627	199844
41	43	70435	2306	273997	41	44224	1657	203229
42	44	71198	2344	278423	42	44897	1687	206577
43	45	71961	2381	282832	43	45570	1717	209888
44	46	72724	2418	287228	44	46242	1747	213164
45	47	73486	2455	291543	45	46843	1777	216429
46	48	74247	2491	295836	46	47444	1806	219669
47	49	75008	2527	300100	47	48045	1835	222884
48	50	75770	2563	304277	48	48646	1864	226086
49	51	76531	2599	308453	49	49247	1893	229283
50	52	77292	2635	312612	50	49848	1921	232452
51	53	78045	2670	316768	51	50449	1949	235602
52	54	78799	2705	320896	52	51050	1977	238715
53	55	79471	2739	324975	53	51619	2005	241823
54	56	80144	2773	329035	54	52188	2033	244911
55	57	80817	2807	333093	55	52756	2060	247992
56	58	81489	2841	337149	56	53325	2087	251068
57	59	82162	2875	341200	57	53894	2114	254121
58	60	82835	2909	345219	58	54462	2141	257172
59	61	83507	2943	349220	59	55026	2168	260208
60	62	84180	2977	353219	60	55591	2195	263214
61	63	84853	3010	357208	61	56108	2221	266168
62	64	85525	3043	361194	62	56626	2247	269103
63	65	86146	3076	365166	63	57117	2273	272035
64	66	86767	3108	369124	64	57608	2299	274950
65	67	87368	3140	373063	65	58060	2325	277862
66	68	87969	3171	376969	66	58513	2351	280757

67	69	88570	3202	380824	67	58965	2377	283652
68	70	89172	3233	384665	68	59417	2403	286518
69	71	89773	3264	388506	69	59869	2429	289368
70	72	90374	3295	392280	70	60322	2454	292202
71	73	90975	3325	396052	71	60774	2479	295035
72	74	91576	3355	399801	72	61226	2504	297850
73	75	92177	3385	403520	73	61679	2529	300618
74	76	92778	3415	407238	74	62131	2554	303373
75	77	93376	3445	410954	75	62578	2579	306108
76	78	93975	3475	414658	76	63025	2604	308829
77	79	94573	3505	418360	77	63472	2629	311544
78	80	95172	3535	422056	78	63919	2653	314257
79	81	95740	3565	425750	79	64366	2677	316965
80	82	96309	3594	429345	80	64813	2701	319672
81	83	96878	3623	432940	81	65260	2725	322375
82	84	97446	3651	436528	82	65707	2749	325075
83	85	98015	3679	440107	83	66154	2773	327774
84	86	98584	3707	443672	84	66601	2797	330462
85	87	99152	3735	447214	85	67042	2821	333141
86	88	99721	3763	450750	86	67483	2845	335806
87	89	100285	3791	454249	87	67894	2869	338464
88	90	100849	3819	457734	88	68305	2893	341114
89	91	101367	3847	461216	89	68716	2917	343746
90	92	101885	3875	464689	90	69127	2941	346368
91	93	102376	3903	468157	91	69537	2965	348972
92	94	102867	3931	471610	92	69948	2989	351575
93	95	103328	3959	475060	93	70341	3013	354154
94	96	103789	3987	478471	94	70735	3036	356720
95	97	104251	4014	481875	95	71128	3059	359277
96	98	104712	4041	485271	96	71521	3082	361833
97	99	105173	4068	488656	97	71915	3105	364371
98	100	105634	4095	492035	98	72308	3128	366907
99	101	105173	4068	488656	99	72701	3151	369422
100	102	105634	4095	492035	100	73094	3174	371930

Table A.3. No riverine wetlands/ponds and no riverine wetlands/ponds modified by stream's connectivity and capacity maximization output

P	No riverine wetlands/ponds				no riverine wetlands/ponds modified by stream			
	1 step path		2 step path		1 step path		2 step path	
	Obj (Con)	Obj (Cap)	Obj (Con)	Obj (Cap)	Obj (Con)	Obj (Cap)	Obj (Con)	Obj (Cap)
1	1	5935	41	7273	1	2999	31	6099
2	2	11870	77	14545	2	5997	58	12131
3	3	15900	111	21700	3	7530	83	17311
4	4	19929	139	28769	4	9063	105	21817

5	5	22928	166	34707	5	10450	125	26282
6	6	25927	192	39479	6	11837	143	30746
7	7	28925	217	44127	7	13176	161	34359
8	8	31924	240	48681	8	14515	178	37474
9	9	33457	262	52550	9	15854	195	40447
10	10	34989	284	55867	10	17194	211	43294
11	11	36522	305	59159	11	18533	226	46018
12	12	38055	326	62386	12	19872	241	48597
13	13	39442	347	65604	13	21196	256	51088
14	14	40829	368	68719	14	22520	270	53326
15	15	42217	389	71812	15	23844	284	55540
16	16	43604	410	74890	16	25168	298	57715
17	17	44943	430	77960	17	26160	312	59795
18	18	46282	449	81029	18	27152	326	61872
19	19	47621	467	84099	19	27938	339	63929
20	20	48960	485	87168	20	28724	352	65968
21	21	50299	503	90186	21	29511	364	68004
22	22	51638	521	93127	22	30297	376	69949
23	23	52963	539	95999	23	31083	388	71848
24	24	54287	557	98865	24	31869	400	73604
25	25	55611	574	101629	25	32655	412	75261
26	26	56935	591	104393	26	33441	424	76702
27	27	58259	608	107035	27	34202	436	78131
28	28	59584	625	109659	28	34964	447	79526
29	29	60575	641	112242	29	35725	458	80913
30	30	61567	657	114750	30	36486	469	82277
31	31	62354	673	117165	31	37248	480	83624
32	32	63140	689	119563	32	38009	491	84969
33	33	63926	705	121929	33	38762	501	86305
34	34	64712	721	124283	34	39515	511	87629
35	35	65498	737	126571	35	40188	521	88924
36	36	66284	752	128809	36	40861	531	90185
37	37	67070	767	131043	37	41533	541	91438
38	38	67856	782	133271	38	42206	551	92667
39	39	68618	797	135493	39	42879	561	93861
40	40	69379	812	137666	40	43551	570	95046
41	41	70140	827	139827	41	44224	579	96225
42	42	70902	842	141983	42	44897	588	97401
43	43	71663	856	144139	43	45570	597	98536
44	44	72424	870	146288	44	46242	606	99656
45	45	73177	884	148433	45	46811	614	100772
46	46	73930	898	150534	46	47379	622	101881
47	47	74603	912	152620	47	47948	630	102989
48	48	75276	925	154700	48	48517	638	104075
49	49	75949	938	156761	49	49081	646	105159
50	50	76621	951	158742	50	49645	654	106232
51	51	77294	964	160676	51	50136	662	107263
52	52	77967	977	162574	52	50627	670	108289
53	53	78639	989	164435	53	51080	678	109302
54	54	79312	1001	166296	54	51532	686	110308

55	55	79985	1013	168119	55	51984	694	111311
56	56	80657	1025	169937	56	52437	702	112314
57	57	81278	1037	171697	57	52889	709	113307
58	58	81899	1049	173447	58	53341	716	114299
59	59	82498	1061	175191	59	53793	723	115261
60	60	83096	1072	176931	60	54246	730	116194
61	61	83695	1083	178601	61	54693	737	117149
62	62	84294	1094	180267	62	55140	744	118081
63	63	84862	1105	181923	63	55587	751	119008
64	64	85431	1116	183569	64	56034	758	119920
65	65	85999	1127	185189	65	56481	765	120832
66	66	86568	1138	186806	66	56928	772	121740
67	67	87137	1149	188410	67	57375	779	122640
68	68	87705	1159	190013	68	57822	786	123538
69	69	88270	1169	191616	69	58233	793	124415
70	70	88834	1179	193217	70	58644	800	125267
71	71	89325	1189	194816	71	59055	807	126105
72	72	89816	1199	196374	72	59465	814	126962
73	73	90277	1209	197921	73	59876	821	127796
74	74	90738	1219	199443	74	60287	828	128608
75	75	91190	1229	200931	75	60660	835	129415
76	76	91642	1239	202417	76	61033	842	130206
77	77	92095	1249	203895	77	61396	848	130996
78	78	92547	1259	205369	78	61759	854	131782
79	79	92999	1269	206842	79	62105	860	132566
80	80	93452	1279	208316	80	62451	866	133345
81	81	93904	1289	209783	81	62797	872	134124
82	82	94356	1299	211233	82	63142	878	134889
83	83	94808	1309	212677	83	63488	884	135654
84	84	95261	1319	214110	84	63834	890	136416
85	85	95708	1329	215541	85	64180	896	137177
86	86	96155	1339	216957	86	64526	902	137938
87	87	96602	1349	218354	87	64872	908	138700
88	88	97049	1359	219741	88	65218	914	139453
89	89	97496	1368	221104	89	65564	920	140207
90	90	97943	1377	222440	90	65910	926	140941
91	91	98390	1386	223775	91	66248	932	141669
92	92	98837	1395	225104	92	66587	938	142396
93	93	99284	1404	226431	93	66925	944	143116
94	94	99731	1413	227755	94	67264	950	143832
95	95	100172	1422	229074	95	67602	956	144547
96	96	100613	1431	230394	96	67941	962	145255
97	97	101054	1440	231705	97	68279	967	145960
98	98	101495	1449	233005	98	68618	973	146655
99	99	101936	1458	234281	99	68956	979	147348
100	100	102377	1467	235546	100	69295	984	148029

Table A.4. No riverine wetlands/ponds/PFOs and no riverine wetlands/ponds/PFOs modified by stream's

P	1 step path		2 step path		1 step path		2 step path	
	Obj (Con)	Obj (Cap)	Obj (Con)	Obj (Cap)	Obj (Con)	Obj (Cap)	Obj (Con)	Obj (Cap)
1	1	2999	77	9800	1	1088	25	3162
2	2	5997	149	17329	2	2176	48	5523
3	3	7530	210	24857	3	2710	67	7536
4	4	9063	269	32111	4	3243	86	9436
5	5	10450	325	38952	5	3677	104	11290
6	6	11837	381	45580	6	4111	119	13120
7	7	13176	436	51918	7	4545	134	14934
8	8	14515	488	57833	8	4979	147	16723
9	9	15854	537	63702	9	5389	160	18425
10	10	17194	584	69470	10	5800	173	20109
11	11	18533	630	75195	11	6194	185	21776
12	12	19872	672	80873	12	6587	197	23325
13	13	21196	712	86493	13	6950	209	24835
14	14	22520	752	91945	14	7313	221	26306
15	15	23844	792	97242	15	7659	233	27767
16	16	25168	831	102477	16	8005	245	29181
17	17	26160	867	107669	17	8351	256	30588
18	18	27152	903	112449	18	8697	267	31952
19	19	27938	939	117144	19	9043	278	33262
20	20	28724	975	121779	20	9389	289	34448
21	21	29511	1010	126322	21	9727	299	35632
22	22	30297	1045	130814	22	10066	309	36736
23	23	31083	1080	135306	23	10396	319	37824
24	24	31869	1114	139726	24	10727	329	38912
25	25	32655	1148	144122	25	11058	339	39999
26	26	33441	1181	148299	26	11389	349	41086
27	27	34202	1214	152284	27	11682	359	42115
28	28	34964	1247	156170	28	11975	369	43144
29	29	35725	1280	159969	29	12268	379	44143
30	30	36486	1313	163741	30	12561	389	45142
31	31	37248	1346	167480	31	12852	398	46102
32	32	38009	1378	171151	32	13144	407	47052
33	33	38762	1410	174782	33	13434	416	47972
34	34	39515	1442	178412	34	13724	425	48892
35	35	40188	1473	182025	35	14005	434	49807
36	36	40861	1504	185617	36	14286	443	50720
37	37	41533	1535	189201	37	14568	452	51616
38	38	42206	1566	192780	38	14849	461	52486
39	39	42879	1597	196357	39	15120	470	53338
40	40	43551	1627	199844	40	15390	479	54165
41	41	44224	1657	203229	41	15655	488	54971
42	42	44897	1687	206577	42	15919	496	55777
43	43	45570	1717	209888	43	16184	504	56573
44	44	46242	1747	213164	44	16448	512	57364

45	45	46843	1777	216429	45	16713	520	58146
46	46	47444	1806	219669	46	16977	528	58925
47	47	48045	1835	222884	47	17234	536	59693
48	48	48646	1864	226086	48	17491	544	60456
49	49	49247	1893	229283	49	17748	552	61219
50	50	49848	1921	232452	50	18005	560	61981
51	51	50449	1949	235602	51	18261	568	62735
52	52	51050	1977	238715	52	18516	575	63489
53	53	51619	2005	241823	53	18772	582	64240
54	54	52188	2033	244911	54	19027	589	64986
55	55	52756	2060	247992	55	19278	596	65732
56	56	53325	2087	251068	56	19528	603	66452
57	57	53894	2114	254121	57	19778	610	67169
58	58	54462	2141	257172	58	20028	617	67877
59	59	55026	2168	260208	59	20272	624	68585
60	60	55591	2195	263214	60	20515	631	69283
61	61	56108	2221	266168	61	20758	638	69977
62	62	56626	2247	269103	62	21000	645	70651
63	63	57117	2273	272035	63	21243	652	71322
64	64	57608	2299	274950	64	21485	659	71986
65	65	58060	2325	277862	65	21728	666	72644
66	66	58513	2351	280757	66	21971	673	73297
67	67	58965	2377	283652	67	22213	680	73949
68	68	59417	2403	286518	68	22456	687	74589
69	69	59869	2429	289368	69	22697	693	75226
70	70	60322	2454	292202	70	22937	699	75863
71	71	60774	2479	295035	71	23178	705	76494
72	72	61226	2504	297850	72	23419	711	77124
73	73	61679	2529	300618	73	23657	717	77744
74	74	62131	2554	303373	74	23895	723	78356
75	75	62578	2579	306108	75	24133	729	78966
76	76	63025	2604	308829	76	24371	735	79568
77	77	63472	2629	311544	77	24609	741	80166
78	78	63919	2653	314257	78	24847	747	80748
79	79	64366	2677	316965	79	25085	753	81326
80	80	64813	2701	319672	80	25323	759	81903
81	81	65260	2725	322375	81	25560	765	82474
82	82	65707	2749	325075	82	25798	771	83041
83	83	66154	2773	327774	83	26024	777	83607
84	84	66601	2797	330462	84	26251	783	84174
85	85	67042	2821	333141	85	26477	789	84739
86	86	67483	2845	335806	86	26703	795	85303
87	87	67894	2869	338464	87	26929	801	85860
88	88	68305	2893	341114	88	27155	806	86412
89	89	68716	2917	343746	89	27367	811	86952
90	90	69127	2941	346368	90	27578	816	87485
91	91	69537	2965	348972	91	27787	821	88016
92	92	69948	2989	351575	92	27996	826	88546
93	93	70341	3013	354154	93	28205	831	89067
94	94	70735	3036	356720	94	28414	836	89583

95	95	71128	3059	359277	95	28623	841	90097
96	96	71521	3082	361833	96	28832	846	90604
97	97	71915	3105	364371	97	29041	851	91106
98	98	72308	3128	366907	98	29250	856	91605
99	99	72701	3151	369422	99	29450	861	92101
100	100	73094	3174	371930	100	29649	866	92593

Symbols: Objective (obj), connectivity (con), capacity (cap), constraint (cnstr), variable (var), origin-destination (OD).