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Effect of River Engineering, Excessive Nitrogen, and Climate Change, on Hydroecology of Upper Mississippi River

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EFFECT OF RIVER ENGINEERING, EXCESSIVE NITROGEN, AND CLIMATE CHANGE, ON HYDROECOLOGY OF UPPER MISSISSIPPI RIVER

by

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B.S., Kathmandu University, 2002

A Research Paper
Submitted in Partial Fulfillment of the Requirements for the
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RESEARCH PAPER APPROVAL

EFFECT OF RIVER ENGINEERING, EXCESSIVE NITROGEN, AND CLIMATE CHANGE, ON HYDROECOLOGY OF UPPER MISSISSIPPI RIVER

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Approved by:

Dr. Jonathan William Frank Remo, Chair

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Graduate School
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AN ABSTRACT OF THE RESEARCH PAPER OF

Deepak Raj Parajuli, for the Master of Science degree in Geography and Environmental Resources, presented on October 8, 2019, at Southern Illinois University Carbondale.

TITLE: EFFECT OF RIVER ENGINEERING, EXCESSIVE NITROGEN, AND CLIMATE CHANGE, ON HYDROECOLOGY OF UPPER MISSISSIPPI RIVER

MAJOR PROFESSOR: Dr. Jonathan William Frank Remo

The Upper Mississippi River (UMR) is a significant ecological and navigational system of the United States. Human-induced modifications such as river engineering, landuse change, and the extensive use of chemical fertilizers in agriculture have altered the hydrology and geochemistry of the UMR which has adversely impacted its globally important ecosystem. These adverse impacts have also likely been exacerbated by anthropogenic climate change. This review paper provides a synthesis of the effects of river engineering, excess nitrogen, and climate change on the hydroecology of the UMR. Peer-reviewed journal articles, government-funded reports, published books, unpublished theses/dissertations, and various review papers were used in this synthesis.

Floodplain disconnection from the UMR's main channel appeared to have the most significant impact on the UMR's hydroecology. Levees along the UMR have reduced the extent of floodplains subject to inundation, thereby reducing floodplain ecosystem's access to nutrients, such as nitrogen from floodwaters, resulting, in part, to increased nitrogen loads in the river. The navigation and hydroelectric dams have increased the water levels causing impoundments affecting vegetation and trees. The dams have primarily disrupted longitudinal connectivity, and the levees have obstructed lateral connectivity.

Research regarding the impacts of climate change to the hydroecology of the UMR is very limited. However, climate change will likely increase habitat fragmentation and will create a favorable environment to the nonnative species in the UMR. Similarly, an increase in temperature due to climate change will compel mussel and fish species to move farther upstream to reach a different and more habitable temperature regime. Large floods induced by climate change will likely disrupt both hydrology and ecology of the UMR.

Floodplain reconnection with the river main channel appears to be a more propitious strategy for the restoration and rehabilitation of the degraded hydroecology of the UMR. Similarly, enhancing the connectivity of the river with its floodplain, increasing the diversity of plants and animals, and minimizing the controlling variables such as sediment load, nutrients, total suspended solids, and limiting invasive species will contribute in achieving the adaptive capacity and resiliency of the UMR. To minimize the nitrogen loss from the UMR watershed, a combination of nitrogen management techniques and nitrogen removal strategies would be advantageous.

In due course, understanding the cumulative impacts of river engineering, land-use change, alterations in water quality, and change in climate over the long term backed up by research-based facts is necessary to sustainably manage the UMR’s hydroecology.

Keywords: River Engineering, Climate Change, Hydroecology, Resiliency

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CHAPTER I

INTRODUCTION

The Upper Mississippi River (UMR) is "a large and complex floodplain river ecosystem” (Bouska et al. 2018a p.1). The UMR extends from Lake Itasca, Minnesota to the confluence of the Ohio River south of St. Louis, Missouri (Figure 1). The UMR and its floodplain provide important ecosystem services to approximately 30 million people living near the river (Weitzell et al. 2003). These services include, but are not limited to, "regulating and reducing floods, maintaining water quality, carbon storage in wetlands and floodplain forests, providing habitat for the plants and animals we value, and supporting recreational areas and cultural identity" (Seavy et al. 2009, 334).

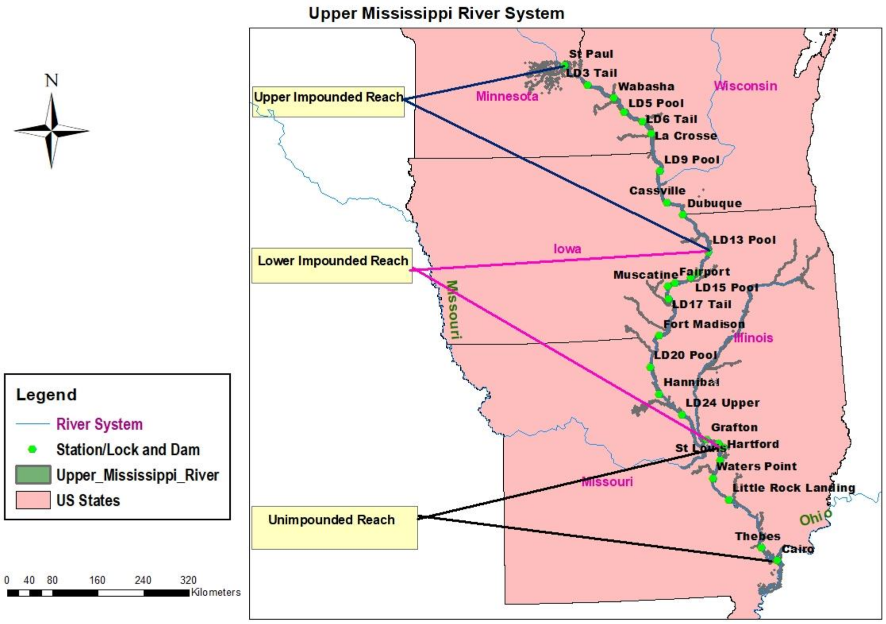

Figure 1: Location and Reaches of UMR

Major habitats within the UMR valley include the river itself, adjacent wetlands, and the floodplain forest (Weitzell et al. 2003). The UMR is home to unique biological resources and communities with more than 154 species of fish and 50 species of mussels. The UMR is also an important migratory flyway corridor for 40% of North America's waterfowl (Upper Mississippi River Conservation Committee [UMRCC] 2000). The river is managed for multipurpose use such as navigation, hydroelectricity, drinking water, and recreation (US Army Corps of Engineers [USACE] 1994)).

The natural characteristics and management of the UMR contribute substantially to the national economy and its multipurpose use makes it a unique resource that is an integral part of American heritage. The US Congress declared UMR as a nationally significant ecosystem and navigation system in the Water Resources Development Act of 1986 (Public Law 99-662). This Act authorized the Upper Mississippi River Restoration (UMRR) Program which was the first comprehensive program for ecosystem restoration, monitoring, and research on a large river system in the US (US Geological Survey [USGS] 1998).

PROBLEM STATEMENT

River engineering over the past 150 years has substantially altered the hydrology, hydraulics, and the morphology of the UMR (Schramm et al. 2015). Extensive levee construction along the UMR has reduced flood risk and subsequently altered flood stages, which is a crucial factor in the exchange of nutrients and sediments between the river, the floodplain, and its associated wetlands (Knox 2006; Remo 2016). Along some portions of the UMR, inundation of the natural floodplain has been significantly reduced (from 30 to 75%; Remo, 2016). Population growth within the UMR basin during the mid-19th into the late-20th century resulted in the conversion of most of the forest and prairie land cover into agricultural land (Knox, 2006). Alterations in agricultural practices, including the extensive use of chemical fertilizers, have resulted in increased nitrogen loads along the UMR (Sprague et al. 2011). In an unaltered riverine system, inundation delivers nutrient-rich sediments to the floodplain and the river delta, acting as a natural soil fertilizer. Dams along the UMR and its tributaries trap sediment, reducing sediment loads, and levees prohibit the nutrient-rich sediments from reaching the protected floodplains (Alexander et.al. 2012).

River training in the form of rock-dike structures and levees decrease the residence time of floodwater on the floodplain, affecting riverine organisms and increasing the speed of delivery of nutrients like nitrogen to the Gulf of Mexico, exacerbating Gulf hypoxia (Sprague et al. 2011; Alexander et.al. 2012). Besides, levees along the UMR have reduced the extent of floodplain subject to inundation, thereby reducing floodplain ecosystem’s access to nutrients, such as nitrogen from floodwaters, likely resulting in increased nitrogen loads in the Gulf (Alexander et.al. 2012).

Anthropogenic climate change is likely to increase temperature and change precipitation patterns, which alters the magnitude and frequency of flooding, and the variability of hydroperiods (Erwin, 2009). Relating to the impacts of climate change in the Mississippi River Basin (MRB), research by Jha et al. (2004) suggest storms during the summer are likely to increase the precipitation in MRB by 21% by 2050, which may increase the stream and river flows, subsequently increasing flooding events along the UMR. Increases in temperature brought by climate change will likely impair biogeochemical processing in the riverine system, thus leading to longer growing seasons for algal blooms, and as a result, eutrophication in the UMR and its associated wetlands (Visser et.al. 2013).

Natural disturbances, even the extreme floods, are beneficial for the sustenance of the river ecosystem, which helps to maintain the ecological integrity of the river (Poff et al. 1997). However, disturbances created by river engineering, landuse, and climate changes in the UMR appear to be surmounting the river's natural resilience (Bouska et al. 2018). Where resiliency is the capacity of the system to recover to the original state after fighting with the disturbances. Resilience in terms of river ecosystem is related to self-organized behavior of river ecosystems over time (Gunderson 2003). Ecosystem services provided by the UMR are at risk due to the negative impacts of these changes. Wetlands, marshes, and riparian environments throughout the UMR are in continuous threat due to landuse change and changes in nutrient delivery. Moreover, the unique biodiversity of the floodplain is decreasing, and many species are in potential danger of extinction (Sparks 1995).

Therefore, this review paper investigates the impacts of river engineering, excess nitrogen loads, and climate change on the hydroecology of the UMR. These topics are discussed collectively because it is likely their impacts on the hydroecology of the UMR are interrelated. Peer-reviewed journal articles, government-funded reports, published books, unpublished theses/dissertations, and various evaluation papers were used in this review paper. The following discussions are useful for those working in large river hydroecology. Additionally, the content at hand provides evidence to help make better-informed river management and policy decisions towards rehabilitating, restoring, and sustaining the UMR ecosystem.

RESEARCH QUESTIONS

This review intends to answer the following questions:

1. How is river engineering affecting the hydroecology of the UMR?
2. What are the effects of excessive nitrogen on the ecology of the UMR?
3. What are the documented/projected climate change impacts on the hydroecology of the UMR?

These research questions are important because they are the key to understanding the individual and aggregate impacts of anthropogenic stressors on the hydrology and ecology of the

UMR. More fully describing and understanding these stressors and their interactions will likely provide insights into specific mitigation measures, which might help ameliorate the impact of these stressors on the services the UMR provides to society and its supporting ecosystem.

CHAPTER 2

BACKGROUND

PHYSICAL GEOGRAPHY AND SETTING

The UMR starts at Lake Itasca, Minnesota, and continues to the confluence of the Ohio River (Ryherd 2017). The UMR basin encompasses 214,344 km^2 of Missouri, Illinois, Iowa, and Wisconsin. The UMR basin is currently comprised of 32.2% agricultural land, 41.1% forest, 26.2% grassland, and 2% built area (Foley et al. 2004). UMR is a riverine floodplain ecosystem that flows within five states and is managed by several federal and state agencies. For this review paper, the UMR is discussed in three segments between Lake Itasca and the Ohio River (Figure 1).

Between Minneapolis, MN and St. Louis, MO, the UMR is impounded by a series of navigation locks and dams. These structures create a series of 25 pools along the UMR. The first segment is the upper impounded reach, consisting of pools 1-13 between Minneapolis, MN and, Rock Island, IL. The morphology of this section of the river is characterized by and island-braided channel form and has a relatively narrow floodplain in comparison with the other two reaches. The upper impounded reach has fewer levees than the lower and impounded reaches to the south. This lends a larger area of the floodplain connected with the main channel, resulting in widespread non-channel aquatic habitats (Johnson and Hagerty 2008). The second UMR segment is the lower impounded reach consisting of pools 14-26 which extend from Rock Island to the Missouri River confluence north of St. Louis. This segment of the UMR has two narrow gorges named the Rock Island and the Keokuk.

Between these gorges, the river valley spreads out into a wide floodplain (>10 km; Johnson and Hagerty 2008). However, most of the natural floodplain is protected by flood mitigation levees (Remo 2016). The levees separate the river channel from many of its historic floodplain wetlands, resulting in non-channel aquatic habitats and marshes. The third river segment is often referred to as the unimpounded reach due to there being no locks and dams, however, a large area of the floodplain is isolated behind the levees. The floodplain along this segment is broader in comparison to unimpounded and lower impounded reaches of UMR. The unimpounded reach flows between the confluence of the Missouri and Ohio Rivers (Figure 1).

Lake Pepin

Lake Pepin is a riverine lake that is located along the UMR, forming a natural boundary between Minnesota and Wisconsin formed by the damming of the Chippewa River (Blumentritt, 2009; Figure 2). Two major rivers, Minnesota and St. Coix are the sources of water for Lake Pepin. This lake is located about 95 km below the confluence of the Minnesota River. The Mississippi River flows through Lake Pepin (DePinto 2009), and its water quality is directly linked with the UMR. It is important to discuss Lake Pepin because the water quality of the lake impacts the water quality of Mississippi River downstream. The Minnesota watershed which is the major drainage basin which contributes water to Lake Pepin is comprised of ~80% agricultural land (Engstrom and Almendinger 2000). Thus, the water and sediments from this watershed are a major source of the elevated nutrient pollution along this segment of the UMR. During an average flow year, the Minnesota watershed contributes 75% of the suspended solids and 32% of the phosphorus loads to the UMR up stream of the lake [Minnesota Waste Control Commission (MWCC) 1993]. In 2004, Lake Pepin was listed as “impaired” by the State of Minnesota due to excessive phosphorus and sediments continues to threaten the lake (Weller and Russell 2013) affecting the water quality of UMR and ultimately contributing eutrophication in the Gulf of Mexico.

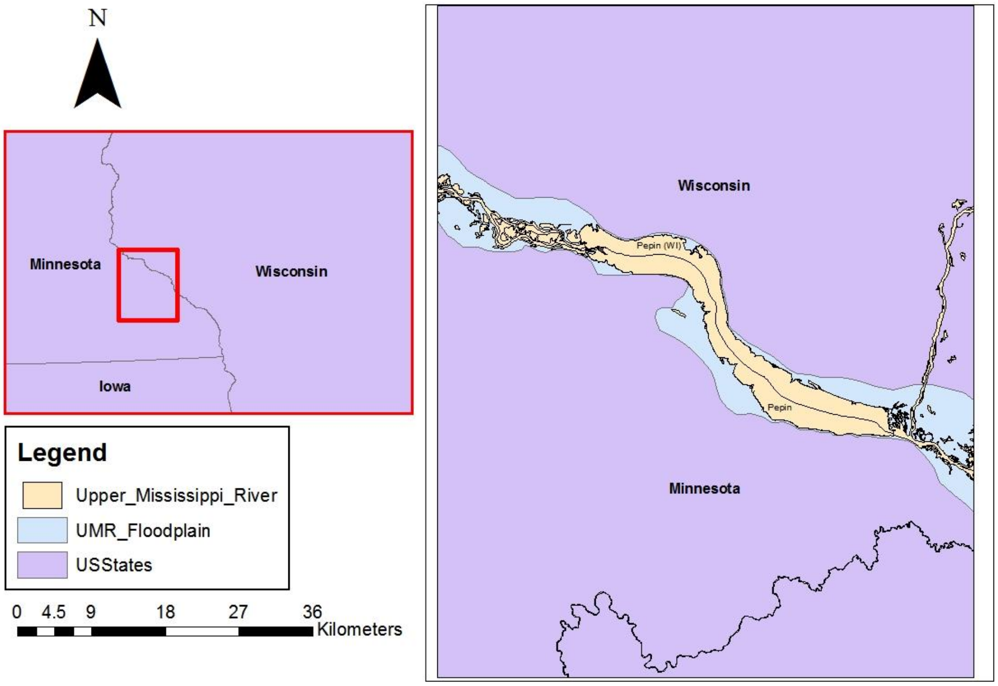

Figure 2: Location of Lake Pepin along the UMR

CLIMATE

The climate of UMR basin is the result of the interaction of the polar, subtropical, and low-level jet stream from the Gulf of Mexico. Moreover, UMR basin is considered to fall into a sub-humid continental climatic system with the mean annual temperature of this region ranging from approximately 9°C in the northern portion and 14°C for the southern portion of the basin (UMR Basin Information, 2000). The wind generally trends from the west to east in this region, comprised of warm moist air from the Gulf of Mexico during the summer, and cold dry continental air from Canada during the winter. There is an increase in precipitation trending from the relatively dry northwest to the substantially more humid southeastern portion of the basin. On average, annual precipitation ranges from 600 mm in the northwest to 1200 mm in the southeast with February being the driest month, and June the wettest (UMR Basin Information, 2000).

The flooding characteristics vary between the northern and southern portions of the UMR Basin. In the uppermost portion of the basin, upstream of the Iowa River (i.e., north-eastern Iowa, Minnesota, and Wisconsin), large floods are usually derived from late winter / early spring rain on snowmelt events. In the southern portion of the basin (Illinois, Missouri, and the rest of Iowa), floods are generally driven by persistent storm tracks in the winter, spring, and into the summer associated with meridional jet stream flow patterns (Knapp 1994; Jha et al. 2004).

FLOODPLAINS

A floodplain is simply the land adjacent to a river or stream that experiences temporary flooding during large discharge events. Floodplains are the source of important ecosystem services such as flood risk reduction and fisheries (Costanza et al.1997). But these floodplains are disconnected from the main river channel by levees and are often converted into agricultural land (Opperman et al. 2010). This disconnection has major implications for the biodiversity of the riverine floodplains. Natural inundation of the surrounding landscape helps riverine biota develop diverse ecosystems (Opperman et al. 2010); including wetlands, marshes, and riparian habitats. A major influence on biotic survival in these floodplain environments is the deposition of nutrient-rich sediments brought by river flood events. During the inundation, the flow of river water onto the floodplain takes place with lower velocity, allowing sediment to drop out of suspension. Consequently, floodplain water is more transparent to the sunlight and enhances higher productivity due to photosynthesis (Opperman et al. 2010).

UMR has approximately 4900 km^2 of floodplain areas, out of which almost 3300 Km^2 (67%) is agricultural and pastureland [Upper Midwest Environmental Sciences Center (UMESC n.d.)]. However, reach-wise, the floodplain of the upper impounded reach of UMR is hydrologically connected with the main river channels and are narrow ranging from 1.6 km to 5 km (Johnson and Hagerty 2008). Similarly, lower impounded reach which has more than 50% levees and floodplains have broader ranging from 8 to 11 km wide while unimpounded reach has floodplains broader up to 80 km wide near the confluence of Ohio river (Johnson and Hagerty 2008). Larger areas of floodplains behind the levees have been converted into the agricultural land except for upper impounded reach.

Rates of denitrification depend upon the natural inundation of the floodplains with the water from regular floods. UMR and its associated floodplains abide the "ideal conditions for removal of nitrates through microbial denitrification because of highly organic, anoxic sediments, and abundant rooted macrophytes"(Richardson 2004, 1103). Rates of denitrification in the UMR ranged from 0.14 μg N*cm–^{2}•h^{-1} measured in the main channel during the spring, to 1.97 μg N*cm^{-2}•h^{-1} measured in the backwaters during the summer (Richardson et al. 2004). Runoff from the agricultural land containing chemical fertilizers and pesticides increasing the load in the UMR. Levees prevent riverine inundation reducing the interaction of floodwaters with floodplain wetlands which could store and potentially denitrify these waters (Remo et al. 2016). In addition, the levees focus floodwater into a narrower area of conveyance increasing the speed in which floodwaters and their constituents travel (Jacobson et al. 2015) and consequently reduced the potential for excess nutrients to be denitrified likely resulting in more of the nutrients being transported to estuaries and coastal areas. This scenario is exemplified by the UMR, where nitrogen that could be removed through biological functions in the riverine environments, especially the floodplain, are instead being discharged into the Gulf of Mexico.

Ramsar Site

In 1986, the US Congress declared UMR as a nationally significant ecosystem and navigation system (Schram et al. 2015), and in 1987 the Ramsar Convention of wetlands declared over 1210 Km^2 of UMR's channel, floodplains, and its wetland was of international importance due to their ecological, social, and economic value (USACE 2016). It has been declared as the Ramsar site because floodplains and wetlands of UMR consist of various endangered and threatened flora and fauna, such as various native fishes, nationally endangered Higgins' Eye Pearly Mussel (*Lampsilis higginsii*) and a core region that supports the migration of 40% of North Americas' waterfowl, including threatened Canvasback Ducks (*Aythyavalisineria*) and Tundra Swans (*Cygnus columbianus*). The designated area includes lands and waters of the UMR floodplain from Wabasha, MN to just north of Rock Island, IL including UMR National Wildlife and Fish Refuge and the Trempealeau National Wildlife Refuge in Wisconsin (Figure 3).

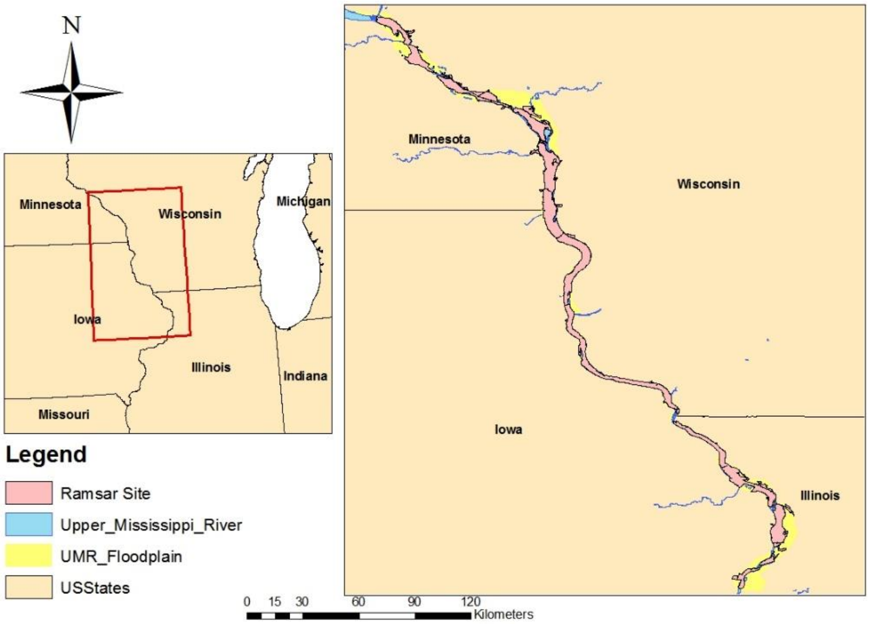

Figure 3: Location of Ramsar Site along UMR

HISTORY OF LANDUSE CHANGE IN UMR

Land use change in the UMR valley started in the 1820s with the introduction of mining and agricultural settlement (Knox 1987). At the confluence of the Mississippi and Minnesota rivers, Fort Snelling was developed to encourage settlement in the region by the US Army (Theiling 1998). From Fort Snelling, settlement expanded to the vast white pine forests of Minnesota and Wisconsin, west to the prairies which were transformed in agricultural fields, and southeast to mine lead deposits in southern Wisconsin and northern Illinois (Theiling 1998). “In 1850, corn and wheat production were clustered around the various mining settlements, but by a decade later these crops had spread over nearly the entire region” (Blanchard 1924 as cited in Knox 1987, 226). This led to a more rapid increase in the basin’s population, which subsequently increase the speed of landuse change towards predominantly agricultural use (Theiling 1998).

RIVER ENGINEERING - WHAT IS RIVER ENGINEERING?

River engineering is an alteration of a river system to enhance flows for services such as navigation, flood mitigation, power generation, and/or water supply (Alexander et al. 2012). Levees and floodwalls are forms of river engineering which acts as the barriers for mitigating the impacts of floods (Cuny 1991). Lock and Dams are the major river engineering structures constructed along the first two segments (Lock and dams 1-13 and 14-26) of UMR to maintain channel depths, while in the third segment (open water reach), channel training structures (e.g., stone dikes, closing structure, etc.) and dredging are employed to maintain the navigation depth (Johnson and Hagerty 2008). The UMR includes a series of 26 navigation "pools" (the area between two successive locks and dams). In general, these pools are characterized by having an upper, riverine reach that is typical of the pre-dam Mississippi River, and a lower, lacustrine reach that is atypical of conditions along the pre-dam river (Koel 2000).

Similarly, levees and floodways have been built extensively in the UMR. Levees are constructed to protect human settlements and farming from the floods, while floodways are a supplement to the levees and designed to carry and redirect excess flood discharges around cities to less densely populated areas (Alexander et al. 2012).

RIVER ENGINEERING HISTORY

UMR has been modified for navigation and flood mitigation for more than the last 150 years. However, the most substantial changes have occurred over the last 90 years. The establishment of river engineering structures started in the early-to-mid 1800s for the UMR. The United States Congress authorized US Army Corps of Engineers to build a 1.22 m channel in 1878 and a 1.83 m channel in 1907, respectively (Harvey 2004). However, significant changes in the river channel took place in between 1920-1930s, whereas a 2.74 m channel was built between the UMR and Illinois River to facilitate larger vessels for year-round navigation (USACE 1998).

Along the open river segment of the UMR starting in the late 19th century, river training was employed by the US Army Corps of Engineers to build a deeper and more uniform navigation channel to meet the Congressionally mandated channel width and depth requirements (300 m wide and 2.74 m deep). These river training structures included dikes and revetments that changed the shape of open river segment of the UMR into a narrower and deeper channel better suited for commercial navigation (Remo 2016). Along the other two segments of the UMR, river training structures were not able to meet the required 2.74 m minimum navigation channel depth, requiring the construction of locks and dams were used to achieve this minimum navigation depth. Currently there are 25 locks and associated dams along the 1080 km of the UMR (Theiling 1998).

The UMR levee system has also expanded significantly over the last 150 years for flood risk reduction. At present, along the borders of the states of Minnesota and Wisconsin, only 3%

of the original floodplain is leveed, while along the state borders of Iowa, Missouri, and Illinois, 53% of the original floodplain is leveed, and lastly between the mouths of Missouri and the Ohio tributaries, 82% of the original floodplain is leveed equating to approximately 8760 Km^2 of levee protected floodplain along the UMR (Sparks 2010; Figure 4).

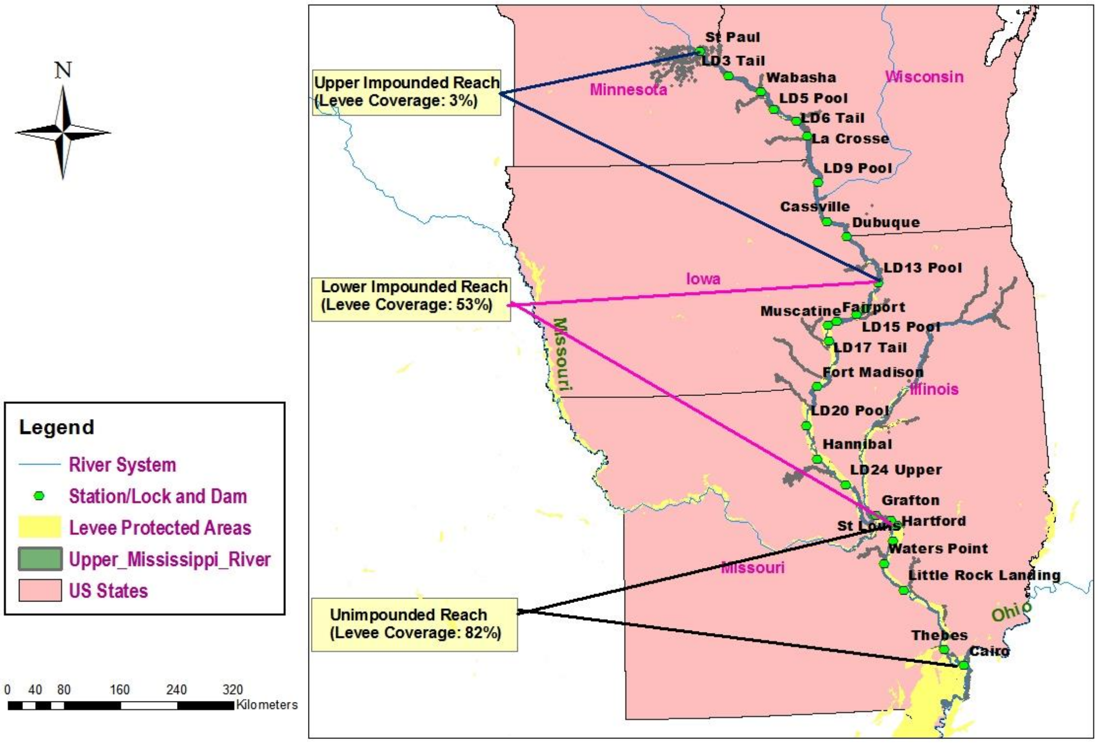

Figure 4: UMR with Levees, Floodplain and Navigation Dams

The extensive construction of levees and river training structures has contributed to the increment of the flood stage (Alexander et al. 2012). In the case of the UMR, the open river segment showed the largest increases river stage due to these structures (Remo and Pinter 2007; Pinter et al. 2008; Remo et al. 2009). Likewise, statistical modeling conducted by Pinter et al. (2010) showed that the UMR lock-and-dam construction projects have had a considerable impact on the river levels; with the greatest magnitude increases in stage for the lowest flows and progressively smaller increases for larger discharges.

Lateral hydrologic connectivity is an important component for fully functional floodplains and their associated water bodies (Opperman et al. 2010). In highly modified river systems like the UMR, human-induced changes (e.g. reservoir operation, levee construction/channelization) have altered lateral connectivity between the main channel and floodplain water bodies, reducing ecosystem restoration potential (Yarnell et al. 2015). Due to levees, water is delivered rapidly to the mainstem rivers, in turn, the capacity of the floodplain to store and convey flood water has been reduced (Sparks et al. 1998). Therefore, the exchange of nutrients, organisms, and organic matter between river and floodplain are reduced thereby diminishing the biological productivity of the organisms depending on floodplain environment (Sparks 1995).

Levees were constructed to protect the land behind from flood inundation and in most cases, levees have successfully protected the lands in which they were constructed to protect. According to the US Army Corps of Engineers [USACE] Levee Database (2018), there are ~2200 km of levees within the UMR basin, including 1400 km along the main stem of the UMR. However, levees have contributed to higher flood frequency.

A study was done by Wasklewicz et al. (2004) using river-stage data along the UMR revealed higher flood frequency and increased flood duration from the beginning of the 20th century (when river engineering structures were under construction and not meeting there design objective) to the end of the 20th century (when river engineering structures were effective). Similarly, a study done by Pinter et al. (2008) suggested that discharge records from 66 stations on the Mississippi River system confirm a pattern of increasing flows, although significant trends were detected only for 21 hydrologic monitoring stations located upstream of most of the flood retention reservoir capacity along the UMR system .

Levees have suppressed smaller flood events. But levees are unable to withhold large flood events, during which levee breaches can have devastating consequences. The Mississippi River flood of 1927 caused several levee breaches, resulting in property damage worth 1 billion 1927 USD, and the deaths of more than 600 people (USACE 1998). The Great Flood of 1993 was also responsible for levee breaching along multiple sections of Mississippi, Missouri, Illinois, and Iowa rivers, along with several other tributaries. During the 1993 flood, 1082 of the 1576 federal and non-federal levees within the Missouri and UMR basins over topped or failed, flooding some 93,000 km^2 of land (Gomez et al. 1997). On August 1st, 1993, the Mississippi River gaging station at St. Louis recorded its highest stage ever of 15.11m. Likewise, there were multiple incidents of levee over topping and breaching during 2008 UMR flood (Holmes et al. 2010).

HYDROECOLOGY OF UMR

Hydroecology is the term used to define the role of water in maintaining the interconnectedness among the biotic and abiotic factors of an aquatic ecosystem (Palmer and Bernhardt 2006). In this review paper, hydroecology represents the river channel, floodplains or wetlands where there is the systematic interaction of soil, water, nutrients, and living organisms. Being the transition zones between upland terrestrial zones and river ecosystem, floodplains of UMR has been the sheltering for both terrestrial and aquatic species and making them biological hotspots (Naiman et al. 2005). Therefore, it is significant to examine the effects of river engineering, excessive nitrogen and climate change in these systems.

INVASIVE SPECIES

An invasive species is one that arrives or introduced in a new habitat it had not previously occupied, then thrive as a population and spreads freely. Invasive species are contributing to biodiversity loss, ecosystem degradation, and impairment of ecosystem services (Pyšek and Richardson 2010). Characteristics such as freshwater fish tolerance to a broad range of environmental conditions, rapid dispersal and colonization, aggressive behavior and competitiveness (Moyle 1986) are the causes behind the growth and distribution of invasive species in freshwater ecosystem.

Invasive species could impact the habitats of native species and completely displace them from the ecosystem. In this review paper, Silver carp (*Hypophthalmichthys molitrix*) and Zebra mussels (*Dreissena polymorpha*) are discussed many times. Therefore, it is important to introduce these species here. Invasive Silver carp are exotic species for UMR which can grow quickly, spread rapidly, and dominate an area to the point where native species are displaced. It is believed that Silver carp was first introduced in Arkansas river for aquaculture in 1973. Due to natural reproduction or escape from that river, they expanded to the lower Mississippi river and subsequently reached the UMR, however the species was noticed for the first time in the commercial market of Jackson county IL in 1983 (Chick and Mark 2001).

Similarly, Zebra mussels are invasive to the UMR. The zebra mussel was first discovered in southern Lake Saint Clair in June 1988 (Hebert et al. 1989 as cited in Tucker et al. 1993), while in June 1991 Sparks and Marsden reported Zebra mussel in Bath Chute of the lower Illinois River (Tucker et al. 1993). Zebra mussels attach to hard substrates on the bottom of the river, covering water intakes and restricting native mussels (United States Army Corp of Engineers [USACE]. 2008. They attach to hard substrates because they secrete byssal threads that tightly hold the organisms to their substrate (Theiling et al. 2000). Therefore, they can travel far attaching to the substrate such as other fish or down surface of boat. Their feeding upon plankton leads to food unavailability to the native fish and mussels.

Invasive species are controlling variables, increase and decrease of these species affects the resiliency (Bouska et al. 2019). Achieving Resiliency needs enhancing the adapting capacity of the UMR to cope with the anthropogenic disturbances such as river engineering, excessive nitrogen, landuse change, and climate change. Serval indicators were developed to assess the resilience of the UMR, which is explained in chapter 6 of this paper.

REVIEW OF CLIMATE CHANGE (CC)

There are different time scales for climate change, but this review's focus is related to anthropogenic climate change, which has occurred over the past 120 years. This definition of climate change is relevant to this research due to the onset of effects, both with river engineering and atmospheric phenomena. Following the industrial revolution, carbon dioxide levels started to rise at a rapid rate. In the last 120 years, the earth's average temperature has increased by 1°C (Ruddiman 2014). In the US, the average temperature has increased from 1.3 to 1.9°C since 1895, (Melilo et al. 2014). Changes in temperature and precipitation have led to impacts such as sea-level rise, rapidly retreating glaciers, increased wildfire intensity, thawing permafrost, lengthening growing seasons, lengthening ice-free seasons in the ocean, earlier snowmelt, and changes in river flows (Karl et al. 2009). Future climate impacts in the US include increasing winter and spring precipitation for the northern US, and less for the Southwest. Also anticipated are a general intensification and an increase in the frequency of extremely hot temperatures and extreme precipitation events, while extreme cold temperatures are projected to decrease in intensity and frequency (Monier and Gao 2015). According to the latest Climate Change Assessment report published by the US Global Change Research Program (USGCRP), flooding due to an increase of heavy rainfall is expected, and would likely have the most impact on the Midwest and southeast regions of the US (Ray et al. 2018).

EFFECTS OF CLIMATE CHANGE IN UMR

The hydrology and ecology of the UMR are impacted by climate-driven changes in both temperature and precipitation. Higher temperature enhances evapotranspiration, which can result in increased precipitation intensity. Increased precipitation intensity is attributed to increases in flood frequency and magnitude. According to Kunkel et al. (2008), "During the 20th century, there has been a 50% increase in the frequency of days with heavy precipitation (>101.6 mm) in the UMR basin" as cited in Remo 2016 (25). Similarly, both the summer and winter precipitation across the UMR basin has been above average during the past 30 years (Kunkel et al. 2008). These empirical observations seem to suggest climate change is likely having an impact on the magnitude and frequency of the floods in the UMR basin. However, an observational study by Mallakpour and Villarini (2015) analyzed 774 stream gauge stations from the Central United States. The results of this study suggest the magnitude of the largest flood discharges have not been significantly increasing, rather, frequency of flood events is increasing, and the number of flood events are increasing in the spring and summer season.

FUTURE CLIMATE CHANGE SCENARIO FOR THE UMR BASIN

A modeling study undertaken by Jha et al. (2004) suggests a warming climate will substantially increase water yields (up to 100%) for portions of the UMR basin. Similarly, UMR has increased water yields in spring and summer while soil moisture would rise in spring and decline in summer leading to risks of both increases in floods and droughts in comparisons to past climatic periods (1961-1990; Wu et al. 2012). However, the temperature does not have a direct positive relationship with the discharge of the UMR (Gray et al. 2018).

Similarly, a climate change sensitivity assessment done on the UMR basin showed that, by increasing the CO_2 amount to 660 parts per million (ppm) and holding other climate variables constant, a 36% increase in average annual streamflow might occurred, suggesting that UMR hydrology is substantially sensitive to possible future climatic change (Jha et al. 2007). Similarly, Day et al. (2005) suggested that the mean discharge of the Mississippi River might increase as much as 40% by 2100. However, Knox (2009) expected discharges in the UMR basins will likely contain periods with unusually high frequency of large floods separated by periods of smaller floods and occasional very low discharges associated with short-term droughts (Knox 2009).

Increased temperatures through global warming will lead to increased evapotranspiration rates, reduced runoff, and more frequent drought events (Rind et al. 1990). Fourth Climate Assessment report of 2018 does not provide clear guidance on future frequency and magnitude of drought in the mid-west region of the United States. However, future projections show a higher level of soil moisture to be lost through evaporation in the summer (Wuebbles et al. 2017; Wu et al. 2011). Thus, increasing temperature and decline in precipitation decreases the soil water content. Wu et al. (2011) assessed the soil water content with three temperature rising scenarios for the UMRB and found that increase in temperature by 1℃, 2℃, and 4℃ decrease the soil water content by 1%, 3%, and 8% respectively. Similarly, projected “temperature rise caused substantial changes of evapotranspiration in May and June, with average increases in these 2 months of about 5 mm, 10 mm, and 23 mm under the temperature rises of 1℃, 2℃, and 4℃, respectively” (Wu et al. 2011, 993).

CHAPTER 3

IMPACTS OF RIVER ENGINEERING ON HYDROECOLOGY OF UMR

This chapter discusses the impacts of river engineering on the hydrology and ecology of the UMR. The goal of this chapter is to attempt to answer my first research question.
How has river engineering impacted the hydroecology of the UMR?

Periodic flooding in large rivers, such as the UMR, plays an important role in the floodplain’s biological productivity. River channel and its adjacent floodplains are a naturally dynamic ecosystem, largely due to periodic flooding (Poff 2002). Biological productivity in riverine ecosystems depends upon the temporary inundation of the floodplain (Junk et al 1989; Sparks 1995; Opperman 2009) which causes ecological rejuvenation (Poff 2002). Temporary inundation, especially the spring floods, "is critically important to the many fishes that use the expanded littoral zones of the floodplain lakes and the inundated floodplain itself as spawning and nursery sites” (Sparks et al. 1998, 707). Instead, over connection of the river to its floodplain results in permanent inundation of some historical floodplain areas. This led to a land cover transition from floodplain forest to wetlands or in some areas open water with aquatic vegetation (Sparks, 1995; Nelson et al. 1998). In the case of UMR, some portions of floodplains were impounded due to the water-level changes created by the locks and dams.

Floodplain Forest Communities

Navigation dams in the UMR have led to the formation of impoundments. After construction of 26 locks and dams along the UMR, water levels rose higher during low discharges, resulting in more of the floodplain becoming wet for longer periods (De Jager et al. 2012). The abundance of flood-tolerant species such as Silver Maple (*Acer saccharinum*) have also increased broadly in relative abundance across the floodplains of the UMR (Knutson and

Klass 1998) resulting in the loss of native American Elm (*Ulmus americana*) species due to the regulated water level since the 1950s (Johnson and Waller 2012). As the water level was regulated with the use of navigation dams, flooding frequency has increased and therefore the saplings of native species are not able to adapt as well to higher wet conditions compared to saplings of Silver Maple which have thrived (Knutson and Klass 1998). This will lead to the displacement of the native species. Similarly, due to constantly moist conditions, trees do not develop strong root systems, and strong winds push them over more easily (Anfinson 2003) and they are displaced by flood-tolerant species.

Fish Communities

Exchange of nutrients between river channel and floodplains due to temporary flooding, helps the aquatic species to grow. Floodwaters carry the nutrient-rich sediments and deposit them in such floodplains, helping the flora and fauna to inhabit and complete their life cycle. "With the natural inundation of the floodplains, Crappies (*Pomoxis annularis* and *Pomoxis nigromaculatus*) and Sunfish (*Centrarchidae*) build nests in shallow water, and Catfish (*Lctaluridae*) build nests or use natural cavities (undercut banks, root masses of trees, burrows of muskrats and beavers) for their eggs and newly hatched young ones" (Sparks et al.1998, 707). This shows the important relationship between river channels, temporary floods, and the floodplains.

Connectivity between river channels and floodplains is an important aspect of freshwater ecosystems. However, little or no connection or over connection can impact fish communities. Impoundments formed in the UMR due to navigational dams can enable the spread of disturbances; such as disease, invasive species, and pollutants (Anfinson 2003). While, floodplains disconnected due to levees in the unimpounded and lower impounded reach can limit recolonization following a local disturbance and reduce the potential for invasion (Bouska et al. 2019). However, river engineering structures such as navigational pools in UMR have direct and indirect effects on fish communities (Alexander et al 2012). During periods of low flow, fish find it difficult to migrate, because the head or difference between the pool and above and the one below, is too big and the speed through the gates is too strong (Anfinson 2003). “This influence on migration of fish cause to lose access to seasonal habitat needed for foraging, wintering over, or cool-water retreats in summer” (Anfinson 2003, 283). The high-head hydroelectric dam which comprises the dam portion of lock and dam 19 has been attributed with hindering migratory fish species such as Skipjack herring (*Alosachrysochloris*), a host fish for the Ebony shell (*Fusconaiaebena*), from accessing the river upstream of that dam (Anfinson 2003).

Altered hydrological regime enables the suitable habitats for invasive and newly introduced species in the river system (Bunn and Arthington 2002). For instance, floodplain disconnection due to the construction of levees and channelization changes the flow, depth and physio-chemical components required for the native species to complete its life cycle (especially juvenile condition) i.e. low recruitment high mortality. Similarly, a study done by Koel (2004) shows that native fish species richness is higher in pools 4, 8, 13 in comparison to highly altered (due to levees) pool 26 of UMR. This condition makes the resources easily available for the non-native species to grow (Kristen L Bouska, Ecologist-UMESC, Personal Communication, July 15, 2019). However, extensive research is required to assess the relation between river training structures and non-native species such as Silver carp in the UMR (Kristen L Bouska, Ecologist-UMESC, Personal Communication, July 15, 2019). Similarly, the increase in non-native species of fishes such as Silver carp in Illinois' river has been found to overuse riverine resources and remove the food sources of other native species (Solomon et al. 2016). Likewise, bluegills populations, which tend to make their habitat in backwater environments, are in decline in the UMR system due to lack of connected backwaters limited by river engineering (Johnson and Hagerty 2008). River engineering is not the single cause for the dominance of non-native species such as Silver carps but is the combination of habitat loss (floodplain disconnection and river channelization), water quality and sedimentation rate (Kristen L Bouska, Ecologist-UMESC, Personal Communication, July 15, 2019).

Invasive species in the UMR indicates, it is ecologically impaired. Silver carp, a nonnative species of fish is tremendously displacing the native fish species. Silver carp are large planktivorous filter feeders and have the capacity to impact all fish species in the UMR because their feeding habit exactly resembles other larval and juvenile fish species (Koel et al. 2000). Similarly, "by feeding at the base of the food chain, the Silver carps may compete with virtually all of the young native fishes, which start their lives as zooplankton feeders before graduating to other, larger food items, moreover, they may also compete with native species that consume plankton as adults" (Sparks 2016, 15). Consequently, native species starved to death. Likewise, characteristics such as fast dispersal capabilities, high reproductive potential, absence of natural predators, and broad environmental tolerance are other traits contributing in the growth of these species (Fuller et al. 1999).

Species composition and the productivity of floodplains are influenced by the quality of the inflowing water (Tocknor and Stanford 2002). Increasing urbanization, agricultural runoff with excessive nitrogen and phosphorus, and inadequate wastewater treatment are major causes behind impaired water quality in the UMR (Johnson and Hagerty 2008). "Suffocation can take place if waters carry higher pollutants which will oxidize and remove oxygen gas faster than it can be replaced leading to greater demand on the available oxygen, and fish, as well as other forms of aquatic life, will die" (Mills et al. 1966, 8). Higher native species richness in pool 4, 8, and 13 of the upper impoundments' segments in comparison to La Grange reach of Illinois river is also linked with the water pollution. The pools 4, 8, and 13 are moderately polluted, in comparison to La Grange section of Illinois River (Koel 2004).

Natural sediments brought by the flooding are important sources of nutrients to the aquatic species. However, excessive sedimentation in certain parts of the river system might be harmful to the aquatic species. Excessive sedimentation is another important aspect causing harm to the native species of fishes and creating a favorable environment for nonnative species. Excessive sedimentation in the river system due to continued landuse changes (e.g., soil erosion) along the watershed causes turbidity, subsequent disappearance of aquatic vegetation, and the deposition of silt over substrates reduces the feeding and spawning sites for native species thereby making it more favorable habitat for nonnative species to thrive (Smith 1971). As a group, fishes are tolerant and adaptable organisms that can survive considerable habitat change, but the ecological tolerances of the many different species vary tremendously, those who can adapt or tolerate the stressors, such as siltation, survive and those that cannot perish (Smith 1971). The existence and prevalence of non-native species in UMR indicate the ecological impairment of the river (Johnson and Hagerty 2008), resources competition challenges for native fishes (Howell et al. 2014), and uprooted aquatic vegetation increasing turbidity (Lubinski et al. 1986).

Mussel Communities

Mussel species are a good indicator of the health of a freshwater ecosystem (Hassel et al. 2007). If the number of mollusks in any freshwater ecosystem is decreasing, the ecology of the area is said to be impaired. This is because Mussels play an important role in water filtration, nutrient, and energy cycling in rivers (Newton et al. 2011). Overall, 65% of the mussel fauna in the UMR are imperiled (Master et al. 2000). Earliest records indicate that there were approximately 44-mussel species found along the UMR and their number is decreasing (Havlik and Sauer 2000). High levees may block currents needed by mussels or interfere with the migrations of the host fish mussels use in their spawning, feeding, and wintering areas (Sparks 1995). Morales et al. (2006) found that mussels number decreased with increasing flow because high flows during the spawning seasons affected the recruitment of young individuals to the mussel bed. Therefore, changes in the flow of water during a time of juvenile settlement is one of the factors in the decrease of native mussels along the UMR (Morales et al. 2006). Because native mussel's larvae depends upon host fishes and must survive there from weeks up to 10 months, while larvae of non-native zebra mussels can remain suspended in the flow for almost a month, during the high flow they can be transported to new places and increase their densities at a rapid rate (Morales et al. 2007).

Aquatic Vegetation

Spatial heterogeneity of vegetation diversity is higher with the increased duration of flooding in the UMR (DeJager et al. 2016). However, the abundance and richness of aquatic vegetation are linked with the availability of the nutrients in the river ecosystem. Floodplains of large river systems, such as the UMR, do not depend on the nutrients from downstream transport; instead, they rely on the pulsing of the river discharge to exchange the nutrients between river channel and floodplain (Junk et al. 1989). Thus, impounded reaches of UMR have higher frequency of submerged aquatic vegetations within the pools 4 to 13 of the upper impounded reach (Yin et al. 2000), while submerged aquatic vegetation is virtually absent from the lower reaches (Sparks 1995; Johnson and Hagerty 2008); moreover, 16 species of submerged aquatic species were found in pool 4 while 0 in pool 26 of the UMR (Yin et al. 2000). This is because, distribution and abundance of submerged vegetation depend mainly on water depth (which changes with water levels) and transparency (which depends mainly on levels of suspended solids), but in unimpounded reach of UMR, these conditions are uncommon and thus lacked submerged aquatic vegetation is extremely limited along this river segment (Johnson and Hagerty 2008). While in the upper impounded reach, with large shallow impounded areas with slow current velocities result in improved light penetration leading to more favorable conditions for the recruitment and growth of submerged aquatic vegetation (DeJager and Rohweder 2017). Areas containing submerged aquatic vegetation are important habitats for fish, macroinvertebrates, and waterfowl (Moore et al. 2010).

CHAPTER 4

EFFECT OF EXCESSIVE NITROGEN IN THE UMR

This chapter discusses the effects of excessive nitrogen in the river and floodplain and attempts to answer the second research question posed in this review paper: “What are the effects of excessive nitrogen on the ecology of the UMR?” This chapter also discusses the various consequences of excessive nitrogen on the biological resources of the floodplains and wetlands along the UMR.

Nitrogen and phosphorus are limiting factors for the plant productivity and considered critical for plant growth. Though these nutrients have a positive relationship on phytoplankton's primary production, excessive nutrients have a detrimental effect on the aquatic ecosystem. Most of the literature is focused on the transport of nitrogen and phosphorus into the Gulf of Mexico and its related impact on hypoxia. A very limited study has been done on the effects of nitrogen and phosphorus into the UMR (Hilton et al. 2006). However, nitrogen concentrations increased from about 2 mg/L in the upper impounded pools to 3 mg/L in the lower reaches while phosphorus increased downstream from about 0.1 mg/L in the upper impounded pools to 0.25 mg/L in the open river reach from 1994 to 2002, respectively (Johnson and Hagerty 2008). These excessive nitrogen and phosphorus concentrations within UMR "affect community composition of aquatic vegetation (e.g., the abundance of filamentous algae and duckweeds), dissolved oxygen concentrations in off-channel areas, and the abundance of cyanobacteria” (Houser and Richardson 2010, 71). When the amount of duckweed is abundant, they restrict the light to the submerged vegetation, which is the important habitat for fish and food for other aquatic species.

Although phosphorus is an important nutrient for the primary production in the aquatic ecosystem, an excessive amount of it in the aquatic ecosystem is detrimental. Phosphorus accumulation in Lake Pepin sediments has increased 15- fold since 1830, rising from 60 to 900 metric tons annually while lake-water total-phosphorus concentrations (total-P), estimated by weighted averaging regression and calibration, increased from 50 to 200 μg l^{-1} within last 200 years (Engstrom and Almendinger 2000). Higher phosphorous in Lake Pepin means higher phosphorous transport along the UMR because Lake Pepin is a natural flow through lake along the UMR (Figure 2). Increasing phosphorus in Lake Pepin has enhanced eutrophication and led to ecological impairment of the lake. For instance, over the past 200 years, the composition of benthic communities has shifted to planktonic species causing Lake Pepin to become eutrophic (Egstrom et al. 2009). This eutrophic condition limits the oxygen and entrance of sunlight into the deeper portions of the lake, which limits food production for the plant community, and eventually dying of the species. Similarly, elevated phosphorus concentrations lead to an increase in the abundance of cyanobacteria, the leading cause of hypoxia (Paerl 1996). According to Lung & Larson (1995), enhanced cyanobacteria in Lake Pepin are largely responsible for the killing of fish, as they form the thick layer of green film on the surface that deprives fish of dissolved oxygen concentrations enough for their respiration.

Excessive nitrogen in the aquatic ecosystem has adverse effects to aquatic species. Elevated nitrogen concentrations in the UMR enhanced the ammonia in the benthic sediments (Houser and Richardson 2010). Higher concentrations of ammonia suggest the water is becoming more acidic, and these acidic waters can become toxic to benthic organisms. Ammonia toxicity has been shown to a significant contribution to large-scale declines in freshwater invertebrates (Wilson et al. 1995). Moreover, Fingernail clams (*Sphaeriidae*) are sensitive to the ammonia toxicity (Bradely et al. 1996) and these Fingernail Clams are sources of food to the fish in UMR (Randy et al. 1998).

CHAPTER 5

CLIMATE CHANGE EFFECTS ON HYDROECOLOGY OF UMR

Temperatures are likely to increase in the future throughout the UMR basin. Changes in temperature have both positive and negative impacts on the biomass in the wetlands and floodplains. An increase in temperature will likely "…affect the biodiversity of the region through changes in growing seasons, species distributions & phenology, and other associated components of ecosystem function" (Backlund et al. 2008, 9). In the case of the Mississippi river basin, southern species are expected to shift northward as the climate warms, while northern species are expected to contract against the headwaters in Minnesota (Remo 2016); this is because anthropogenic warming changes the thermal regime of the aquatic ecosystem (Newton et al. 2013). The species, which can adapt to tolerate higher temperature, will thrive while others who cannot perish (Sparks 2010). Similarly, increasing temperature caused by climate change increases the water temperature (Poff et al. 2002). Warmer water is a suitable place for warm invasive species and can displace some of the cold-water native species (Sharma et al. 2007).

Elevated temperatures can adversely affect aquatic organisms (Newton et al. 2013). For example, elevated water temperatures have been associated with increased energy requirements of recently born fish (McDonald et al. 1996, as cited in Newton et al. 2013). Likewise, Kentaro and Berg (2017) conducted a study on Pearly mussels (*Cumberlandia monodonta*), investigating their population connectivity and genetic diversity in the UMR using Ecological Niche Models (ENM) with populations' genetic simulations under a scenario of changing the climate. ENM showed that populations in the UMR do not impede gene flow under the current conditions, however, a further rise in temperature will influence declines in their current habitat. Likewise, the simulations also suggest that an increase in temperature will reduce their genetic diversity by fragmentation of larger into smaller isolated populations. Kentaro and Berg (2017) suggest that eventually, this endangered species will likely be extinct from the UMR. Another similar study done on effects of water temperature and sediments on mussel beds by Newton et al. (2013) concludes that increase in temperature due to climate change will compel mussel species to move farther to reach to a different and more habitable temperature regime within the UMR. The juvenile stage of mussels will likely be negatively affected by the increasing temperature because heart rate was declined with the increment of the temperature (Ganser et al. 2013) therefore, the likely increment of temperature due to climate change might reduce the juvenile mussel species in the UMR.

With increasing temperatures within the UMR basin, there will likely be a dominance of non-native species. These exotic species are likely to disrupt the native species with competition for prey, and transfer of disease (Rahel and Olden 2008). For example, invasive Zebra mussels have the quality to survive and thrive in three climatic settings [Cold (10℃), Cool (20℃) and Warm (30℃)], so their prevalence across a latitudinal gradient will most likely occur at increased temperatures due to climate change (Jilek et al. 2009). However, McMahon and Ussery (1995) claimed that Zebra mussel's population will decline rapidly after 25℃ and exposure to hot water at 36°C for 1 hour or 40°C for 15 minutes results in 100-percent mortality. It seems there is not any direct relationship between increasing temperature and increasing dominance of Zebra mussels. But a more in-depth study is required to confirm it in the case of UMR.

Hydrological components such as the flow, occurrence, and distribution of water are highly influenced by the changes in the frequency and the intensity of precipitation (Palmer et al. 2009). Increases in the intensity of precipitation can lead to more flooding and floods affect the living organism of water along with sediments and nutrients (Knox 2001). However, natural flooding, or flood pulses, is the most important event for the sustenance of the plants and animals in the floodplains (Junk et al. 1989). Nevertheless, large floods induced by anthropogenic climate changes have negative impacts on living organisms. For instance, unusually large 1993 flood 1993 (it is not clear that this flood is caused by climate change, but, unusual extreme floods can be caused by the climate change) uprooted large trees, shrubs, and plants in the UMR (Poff et al. 2002; Johnson and Hagerty 2008). Similarly, "the entire understory was eliminated in substantial portions of the floodplains within approximately 150 km of St. Louis, consequently, no saplings were available to grow following the death of the overstory trees (cottonwoods)" (Sparks et. al. 1995, 712)". Similarly, Knopf and Sedgwick (1987) suggested that understory dependent and ground foraging bird species are more vulnerable to extreme flood events. Small fish are transported by the swift water current to downstream and juvenile aquatic invertebrates are crushed (Fisher et al. 1982 as cited in Poff et al. 2002).

Too little water or drought conditions also have negative impacts for the aquatic species. In the case of the UMR, increased water levels reduce the Aquatic-Terrestrial Transition Zone (ATTZ), while lower water levels would expand the ATTZ into areas that would otherwise be permanently inundated, and they would reduce flood durations across the ATTZ (De Jager et al. 2016). Therefore, "very small changes in water levels may impact flood durations across very large areas, setting up the potential for large-scale shifts in plant community distributions (De Jager et al. 2016 p.170)". Likewise, increased frequency of exceptionally large floods in UMR (such as 1993 flood), "disrupt the riparian plant succession or availability of low energy, backwater habitats for aquatic species" (Poff 2002, 1500).

Land cover varies with the changes in frequency and duration of precipitation and increasing temperature. Therefore, under a warming climate changes in land cover are likely changes its ranges. For instance, winter crops expand northwards, distribution of forest to expand southward (Lant et al. 2016). Similar effects happen with the distribution of fish with the increase in temperature and changes in flow regimes caused by climate change (Wang et al. 2007). In similar conditions, a study done by Bouska et al. (2018a) found that among 14 native UMR fish species, the geographic range shift of these fish is impacted based upon their sensitivity to changes in precipitation, discharge, land cover, and water temperature. The study showed that 5 of 14 species are projected to expand northward, maintaining the current distribution scenario; while 3 species are projected to expand northward with the range contraction in the southern extent of their current distributions and all these 8 species shifts are driven by the temperature. Likewise, three species are projected to contract northward with a slight expansion in their southern extent and remaining 3 species are projected to lose their current distributions sites without substantial gains elsewhere (Bouska et al. 2018a).

CHAPTER 6

POTENTIAL MITIGATING MEASURES

The engineering of the UMR has been an enormous project that has provided the services of commercial navigation and flood mitigation to society. Consequently, this engineering has provided large economic benefits to communities along the UMR as well as the nation. However, changing the current system of river engineering will likely be extremely difficult because communities and their economies are now dependent upon the modified river system (McGuiness 2000). Nevertheless, the unique biodiversity residing in the floodplains and wetlands of the UMR are under continuous threat due to unintended consequences of river engineering. The UMR's ecosystem and the regulating and provisioning services it provides is under a serious threat. To help address these threats, there are a few mitigation measures which can be adopted to conserve the hydroecology of UMR and are discussed herewith.

Floodplain reconnection is the process of connecting nonfunctional floodplains with rivers to make them ecologically functional so that they provide a wider array of benefits including additional provisioning and regulating services. Hydrological connectivity of floodplain with the river, variable flow regime that produces high and low flows, and enough spatial scale for floods to occur and benefits to accrue to an ecologically meaningful level are the basic elements that need to be considered for floodplain reconnection (Opperman et al. 2010). Moreover, floodplain reconnection will accomplish three primary objectives: flood-risk reduction, an increase in ecosystem services, and maintaining resiliency to potential climate change impacts (Tockner and Stanford 2002: Opperman et al. 2009).

Strategic floodplain reconnection through levee setback, as discussed by Guida et al. (2016), give priority to reduce flood heights by allowing portions of lower-valued land to flood and rehabilitating or creating new habitat. Levee setback strategies were examined in The La Grange Segment (LGS) of the Illinois River, a substantial tributary to the UMR, by Guida et al. (2016) for the strategic reconnection of the Illinois River to its floodplain, including the costs of building losses, losses of agricultural profits, levee removal, and construction cost. This study showed that the aggressive levee setback scenario contributed to maximum flood height reduction and environmental benefits with higher costs, while lower-cost scenarios contributed in less flood height reduction and less environmental benefits due to this scenario's smaller impacts. However, in the case of UMR having reaches with different hydroecological conditions altered by the river engineering requires extensive reach to segment scale research to evaluate ecological benefits (Matella and Merenlender 2015; Schramm et al. 2015), before carrying out any floodplain reconnection strategies. Without extensive research we cannot determine the ecosystem returns after the reconnection (Matella and Merenlender 2015), because natural flow regime must fall in the range required by species life history patterns (Poff et al. 1997). Furthermore, the impacts of climate change likely increase further uncertainties (Matella and Merenlender 2015). Therefore, likely changes in the floodplain ecosystem that would occur after the reconnection need to be confirmed through extensive research.

Resilience simply means the capacity of the system to resist the disturbance and bouncing back to the original state or recovering quickly to the disturbances. Ecological resilience is defined as “the amount of disturbance that an ecosystem could withstand without changing self-organized processes and structures” (Gunderson 2000, 425). In the case of UMR, maintaining resiliency means revival to the original state and function as a natural ecological system. Managing the resilience of the river system such as UMR requires: 1) the ability to anticipate potentially unwanted flow regime shifts within the system and taking actions that prevent them from occurring; 2) maintaining a diversity of the system elements and feedback interactions that keep it within a particular desired state; and 3) working to reduce the likelihood of system crashes or flips into a different state (Allen et al. 2011). US Army Corps of Engineers Upper Mississippi River Restoration Program (UMRR) in partnership with various other concerned stakeholders are undertaking resilience assessment in UMR with the vision of "a healthier and more resilient ecosystem that sustains the river's multiple uses". To meet this vision, UMRR devised 12 major indicators for the quantification of ecosystem resilience of UMR under three major resilience principles; connectivity, redundancy and diversity, and controlling variables (McCain et al. 2018). Connectivity indicators quantify how organisms moving through the UMRS can access a wide range of conditions and quantify the transport of materials and energy moving down river and across the river floodplain transition zone. It consists of longitudinal and lateral connectivity. Whereas, diversity and redundancy in a system provide options and insurance for responding and adapting to change and disturbances such as biological diversity and ecosystem services (DeJager et al. 2018). Controlling variables includes flow, sediment and total suspended particle's concentration and changes in the controlling variables might affect the system if the variables increased dramatically. For instance, water level and sediments interact with vegetation to influence habitat characteristics (DeJager et al. 2018). Moreover, Bouska et al. (2018b) divided four reaches of UMR into three interconnected subsystems: lotic channels (longitudinal flowing water), lentic off-channel areas (backwater, impounded areas, floodplain lakes or wetlands), and floodplains and evaluated resilience assessment under three resilience principles explained above. Furthermore, these developed indicators quantify both essential ecosystem features and characteristics of a resilient river system (DeJager et al. 2018). These indicators are mentioned below (Table 1).

Table 1: Ten indicators for UMR with the application of three resilience principles and relationships of the resilience with the indicators (Bouska et al. 2019 p. 1095).

S. No	Resilience Principles	Indicators	Relationship with the indicators (Positive or negative)
	Connectivity	Longitudinal Connectivity (exchange of nutrients, sediments from upstream to downstream)	+
		Lateral Connectivity (Exchange of nutrients, sediments from the river channel to floodplain areas)	Intermediate
	Diversity and Redundancy	Aquatic habitat diversity & redundancy	+
		Floodplain inundation diversity	+
		Fish functional diversity and redundancy	+
	Controlling Variables	Water surface elevation ranges	+/-
		Total suspended solids	-
		Nutrients Concentrations	-
		Sedimentation rates	-
		Aquatic invasive species	-

Table 1 shows the relationship of resiliency principles with the indicators that provide an assessment of the overall resiliency of the UMR. The first principle is the connectivity because dams have primarily disrupted longitudinal connectivity, and the levees below Rock Island have obstructed lateral connectivity (Anfinson 2003). Enhancing longitudinal and lateral connectivity would likely improve resiliency in UMR. Similarly, increasing aquatic habitat diversity (range of habitats available in the UMR such as lotic, lentic, floodplain, backwater areas) and redundancy (habitats in the same ecosystem that fill similar roles and perform similar functions). Even if such types of habitats are eliminated from the system, resiliency would not be affected like shallow lotic-channel areas are more important than deeper channels in the case of UMR (DeJager et al. 2018). Hence, shallow lotic channel should be given more importance to maintain the resiliency. In addition, redundancy buffers an ecosystem against change, but it provides an opportunity for further and future functions such as adaptation (Walker 1995). Likewise, increasing floodplain inundation and fish functional diversity (range of functional traits of fish in UMR) and redundancy (prioritizing species protection which can substitute the function of fish even eliminated from the UMR) contributes to the resiliency of the UMR. Lastly, reducing total suspended solids concentration, minimizing nutrients concentration, and restricting the growth of invasive species, or controlling these variables in the UMR helps to achieve resiliency.

Total Suspended Solids (TSS) concentration has increased due to the extensive landuse practices such as agriculture in the UMR. Minimum tillage of the land could minimize the loss of soil/sediments in the UMR. Crop rotation would be another important technique that can be implemented in farming. Planting different crops in a planned rotation to manage nutrient and pesticide inputs, enhance soil quality, or reduce soil erosion for instance including a legume, hay, or a close grown crop in the rotation (United States Department of Agriculture [USDA]. 2012).

Drawdowns during summer helps to reduce TSS concentration (Landwehr et al. 2005) in UMR because it exposes bottom sediments to dry and promote the growth of submerged aquatic vegetation (SAV) (Johnson and Hagerty 2008) and SAV are the important species in UMR which helps in settlement of sediments and TSS (Giblin 2017). Regarding reducing the nutrients concentrations, techniques of nitrogen management and nitrogen removal are significant and are discussed in the next section of this chapter.

As discussed in chapter 3, changes in water level and flow regime, water pollution, excessive sedimentation and nutrients are the major causes enhancing the growth of invasive species such as Silver carp. Floodplain reconnection strategy is the most beneficial strategy to prevent the growth of invasive species (Phelp et al. 2014). Floodplains that are connected to rivers with variable flow supports functional ecosystems and provides space to accommodate their form and processes (Loos and Shader 2016). Floodplain reconnection enhance the functional and structural diversity of aquatic species thereby helping in reducing excessive nutrients from the rivers through floodplain. On the other hand, higher biological productivity in the reconnected floodplains help suppress invasive species through biotic resistance, though active control will likely be necessary periodically (Lemke et al. 2017). Where, biotic resistance is the ability of species in a community to limit the invasion of other species by limiting space, nutrients, and light (Moel and Light 1996; Byun and Lee 2017).

Eradication of invasive species is enormously difficult and expensive, moreover, it has occasionally been successful if the efforts were focused on small-scale and closed systems like reservoirs, ponds, small locks, and marinas (Buck et al. 2010). Hence, restricting the introduction of new invasive species in the aquatic habitat, regulating imports of certain invasive species, preventing or slowing the spread of already introduced species, and monitoring to detect new invaders when their populations may be localized and at low densities are some of the techniques that can be used to control invasive species along the UMR (Buck et al. 2010).

Adaptive capacity is the ability of the system to respond to the stressors or disturbances, adjust to potential damage and to take benefits of the opportunities created. In the case of UMR, the ability of an ecosystem to adapt and respond to disturbances is resilience (DeJager et al. 2018). In other words, strengthening adaptive capacity means to maintain the resiliency of the UMR (Bouska et al. 2019). Therefore, resiliency indicators developed and used for the resiliency assessment can be linked with the adaptive capacity of the UMR. Based on these indicators, resiliency assessments of four reaches were conducted. Descriptions of the resilience assessments of three reaches of UMR are covered here. These descriptions were assessed by Bouska et al. (2019) with the help of 10 resilience indicators to determine the adaptive capacity on three reaches of UMR. Their findings are described as follows

> “High aquatic habitat diversity and redundancy, fish functional diversity and redundancy, and water clarity, and the scarcity of invasive fish species are all factors that likely contribute to the high general resilience of the Upper Impounded Reach. However, the limited longitudinal connectivity and establishment of a minimum water level for navigation are factors that may inhibit the general resilience of this reach. In the Lower Impounded Reach, there is high within reach variability for individual indicators such as aquatic habitat diversity, fish functional diversity and redundancy, and longitudinal and lateral connectivity. In the Unimpounded Reach, a high degree of longitudinal connectivity likely enhances its general resilience, but low aquatic habitat diversity, low lateral connectivity, and relatively high number of invasive fish species inhibit general resilience” (Bouska et al. 2019, 1094).

Upper impounded reach of the UMR shows the higher general resilience as illustrated by the assessment of all ten indicators mentioned above. However, longitudinal connectivity of this reach is limited due to the navigational dams (Bouska et al. 2019). The upper impounded reach currently offers a high diversity of aquatic and floodplain hydrogeomorphic areas but may also undergo a large degree of change during the next 50 to 100 years due to over connection of water to the floodplain areas leading to single species floodplain forest (DeJager 2018). Additionally, sedimentation rate has increased in the backwaters due to over connection of rivers with the floodplains (Knox 2006). On account of over connection of river channel with the floodplains, Schramm et al. (2015), suggested two important management options for the benefits of fish in upper impounded reach which says " (1) the construction of large island complexes to replace those lost to erosion and (2) drawdowns: lowering the water level about 0.3–0.6 m at the dam in summer to partially emulate pre-dam low-water conditions" (190). On the contrary, extensive research is required to devise the measures that enhance the longitudinal connectivity of this reach.

The lower impounded reach is more similar in the features to the upper impounded reach than any other segments of the UMRS. Furthermore, longitudinal connectivity is much more improved than the upper impounded reach (Bouska et al. 2019). Nevertheless, this reach showed future loss of deep and gain of shallow lentic classes during the next 50 years like the upper impounded pools which indicates that sedimentation is likely to cause a shift toward shallower lentic areas (DeJager et al. 2018) and might create a new area. Soil erosion control techniques as discussed in the preceding section could be beneficial to reduce the sedimentation in this reach.

Unimpounded reach of the UMR has least capacity to cope with the disturbances due to low aquatic habitat diversity, low lateral connectivity, and relatively high number of invasive fish species hindering the maintenance of general resilience (Bouska et al. 2019). However, this reach has higher longitudinal connectivity downstream, but the degree of longitudinal floodplain connectivity and lateral river-floodplain connectivity found in this segment of the UMRS is significantly less (DeJager et al. 2018). Floodplain reconnection technique will help in increasing the aquatic habitat diversity due to seasonal flooding of the floodplains (Oppermann et al. 2010). Moreover, connecting floodplains by removing levees or repositioned, flooding risk will be reduced (Sparks and Braden 2007), and enhance the adaptive capacity of this reach (Bouska et al. 2019).

The nitrogen load of has increased during the past 150 years with the expansion of agricultural practices and land-use change. However, the largest increases have occurred since the 1950s and the advent of chemical fertilizers (Mitsch et al. 2001). Most of the nitrogen that reaches the Gulf of Mexico is from the UMR watershed. Even though land use change has been relatively consistent over the past 75 to 100 years with a small increase in forest landcover, the mitigation of nitrogen running off removal agriculture lands has been problematic.

Excessive nitrogen is the major nutrient affecting the hydroecology of the UMR. A single technique or approach will not help to minimize the nitrogen load into the UMR. Integrating nitrogen management strategies (improvements in fertilizer management [application rate, placement, and timing]), use of nitrogen inhibitors, conservation tillage, and cover crops] and nitrogen removal techniques (stream-channel restoration, rehabilitation of wetlands, and floodplain reconnection) as suggested by Dinnes et al. (2002) may be useful strategies to reduce the nitrogen load for the UMR basin. Descriptions of these techniques are listed below respectively.

1. Limiting the amount of nitrogen use at the end of a crop's growing season and before the next crop has been an important factor to reduce nitrogen (N) losses (Dinnes et al. 2002). However, using the correct amount of nitrogen is more important than any other strategies (Power and Schepers 1989). Similarly, changing the timing of a single preplant fertilizer from fall to spring could substantially decrease N loss and increase fertilizer use efficiency (Dinnes et al. 2002)

2. Nitrification inhibitors are chemicals that slow down the nitrification process, thereby decreasing losses of nitrate will occur before the fertilizer nitrogen is taken up by plants (Nelson and Huber 1992). These inhibitors function by limiting the activity and populations of - *Nitrosomonas* bacteria that convert NH_4 to NO_2. "The primary use for nitrification inhibitors in the Upper Midwest is to slow the conversion of fall (Season) applied anhydrous NH_3 fertilizer to the more leachable NO_3 form, thus potentially reducing N fertilizer losses before peak nitrogen demand by subsequent corn crops" (Dinnes et al.2002, 159).

3. Conservation tillage is the approach used to reduce the intensity and frequency of tillage in the agricultural farm, which helps in controlling soil erosion. Crop rotation is the practice of growing a series of dissimilar types of crops in the same area in sequenced seasons. Rotation helps in reduction of leaching of nitrogen and other nutrients from the soil. One example is the rotation of corn with soybeans; growing corn requires a large amount of nitrogen, while soybeans can deposit nitrogen in the soil (Randall et al. 1997).

4. Cover crops are planted to maintain the soil health and protect the soil during the winter from erosion, as they are planted in the fall and grow until the soil freezes (Christianson et al. 2016). "Fall-planted winter cover crops reduce annual leaching losses of NO_3 because they extend active NO_3 and water uptake into this fallow period of the year" (Kladivko et al. 2014,

279). According to Christianson et al. (2016, 15), likely cover crops in the Midwest include small grains (oat, winter wheat, barley, triticale, and winter rye), legumes (alfalfa, hairy vetch, and clover), grasses (annual ryegrass), and brassicas (oilseed radish, oriental mustard, and winter canola). Planting winter rye species in 10 counties of Iowa and Minnesota reduced 48% and 13% of NO_3 leaching from the soil, respectively (Kladivko et al. 2014).

Stream restoration is the process of re-establishment the natural function of a stream that have often be degraded by human disturbances. These disturbances include removal of watershed disturbances impacting a stream's water quality, protecting streambanks by planting of vegetation or constructing structures to reduce bank erosion, and converting the unstable stream reaches into functional streams including floodplains (Doll et al. 2003). Riparian Buffers are vegetated strips of land adjacent to a stream which partially protects the water body from the impacts from overland erosion and agricultural runoff. Riparian ecosystems along streams and rivers are effective sinks or buffers for nitrates in agricultural watersheds thereby reducing the amount of nitrogen flow in the streams (Jacobs and Gilliam 1985). Equally important, forested riparian zones can moderate temperatures, reduce sediment inputs, and stabilize stream banks (Osborne and Kovacic 1993). Buffers strips within and between agricultural fields and the watercourses to which they drain are intended to intercept shallow groundwater moving through the root zone below the buffer (Helmer et al. 2008). These root systems are responsible for uptaking the nitrates from the shallow ground or soil water that passes through these zones (Dinnes et al. 2003). Typically, denitrification rates in riparian buffers range between 2 and 6 g N m^{-2} yr^{-1}, which shows that riparian buffers have the potential for nitrate-nitrogen reduction via denitrification (Mitsch et al. 2001). Some of the plant species that can be used in riparian buffers to reduce nitrogen loads within and discharge from the UMR basin are monocultures of switchgrass (*Panicum virgatum L.*), alfalfa (*Medicago sativa* L.), willow (*Salix matsudana Koidzumi*), and corn (*Zea mays L;* Gill et al. 2014). However, "for nitrate to be removed from groundwater before it reaches surface water, the groundwater must enter a zone where plant roots are or have been active, where plant roots may either absorb the nitrate for growing purposes or, more importantly, provide a carbon source for the denitrification of bacteria" (Mitsch et al. 2001, 379).

A wetland is a unique ecosystem where water is flooded permanently or seasonally. Natural or constructed wetlands are important ecosystems for the removal of nitrogen (Kadlec and Wallace 2009). Therefore, "restored wetlands can play important roles as filters for nutrients discharged from agricultural areas into coastal aquatic ecosystems" (Romero et al. 1999, 323). Wetlands have submerged vegetation which contains epiphytic biofilms and could remove NO_3 by denitrification (Dinnes et al. 2000). Likewise, a study conducted Xue et al. (1999) in three constructed wetlands of Illinois concluded that "the ratios between denitrification capacity and mean load for the three wetlands ranged from 19 to 59% with an average of 33%" (268). Another study done in Mississippi-Ohio-Missouri (MOM) basin by Mitsch and Day (2006) suggested two approaches for the strategic creation and restoration of 22000 square kilometers of MOM basin which are: 1. creation and restoration of wetlands and riparian buffers between farms and adjacent streams and rivers, and 2. diversion of river water into adjacent constructed and restored wetlands along main river channels and in the Mississippi River delta during flood periods" (59). Therefore, restoration and rehabilitation of wetlands in the UMR basin would likely help in the removal of nitrogen. Lastly, these combined strategies (nitrogen management and nitrogen removal) could meet the 45% nutrient reduction goal while converting less than 1% of cropland in the Upper Mississippi-Ohio River Basin to nitrogen-removal practices (McLellan et al. 2015).

Climate Change has already affected the hydroecology of the UMR, and will likely exacerbate the impacts of river engineering, landuse change, and excessive load of nitrogen in the UMR system. However, floodplain reconnection would be the resiliency option towards reducing climate change impacts such as increased flood risk (Opperman et al. 2009). Similarly, restoring and conserving riparian ecosystems could be the ecological adaptation to climate change. Riparian ecosystems are naturally resilient, provide linear habitat connectivity, link aquatic and terrestrial ecosystems, and create thermal refugia for wildlife: all characteristics that can contribute to ecological adaptation to climate change (Seavy et al. 2009), because many riparian plants are adapted to hydrologic and geomorphic disturbances and withstand both seasonal and annual variation in environmental conditions (Naiman and Decamps 1997). Rivers and riparian vegetation connect high elevation areas to sea-level estuaries and oceans while river flow across elevational gradients, linking ecological zones with different climates and thereby enhancing connectivity among different habitats, which provides paths for species’ movements in response to climate change (Seavy et al. 2009). In the case of UMR, it is predicted that with the changing climate southern species will likely shift from south to the north while northern species ranges are expected to contract against the headwaters in Minnesota (Remo 2016). With this likely scenario of changing climate and species movement, restoration efforts of the riparian ecosystem should be considered along with this range (south to north and head waters of Minnesota) in achieving resilience. Moreover, enhancing connectivity through floodplain reconnection would improve the habitats of riparian ecosystem and hence, enhances connectivity among different habitats of riparian zones in the UMR. Similarly, riparian ecosystem act as thermal refugia to the wildlife because riparian areas have higher water content than surrounding upland areas, which absorb heat and protect wildlife against extreme temperatures caused by the climate change (Naiman et al. 2000).

CHAPTER 7

SUMMARY AND CONCLUSIONS

Review of the literature shows that anthropogenic stressors such as river engineering, excessive nitrogen loads, and climate change are adversely affecting the hydroecology of the UMR. Construction of levees along the UMR are responsible and have reduced the extent of the floodplain subject to inundation, thereby reducing the floodplain ecosystem's access to nutrients, such as nitrogen from floodwaters. The reduction of lateral connectivity has likely, in part, contributed to the elevated nitrogen loads delivered to the Gulf of Mexico (Alexander et.al. 2012). Disruption of lateral connectivity due to floodplain disconnection also affects the biological productivity of the floodplain ecosystem (Anfinson 2003). Likewise, the navigation and other dams along the UMR reduced the current velocity needed by mussels to thrive or interfere with the migrations of host fish of juvenile mussels to their spawning, feeding, and wintering areas resulting in a reduction of mussel propagation adversely impacting their survival (Sparks 1995).

Locks and dams constructed to improve navigability of the UMR have permanently inundated some portions of the UMR floodplain (Sparks 1995; Anfinson 2003), killing vegetation and enhancing the dominance of nonnative flood-tolerant species such as Silver Maple; consequently, displacing native species of such as Elm trees (Johnson and Waller 2012; Knutson and Klass 1998; Yin et al.1997). Whereas, impoundments formed in the UMR due to navigational dams can enable the spread of disturbances such as disease, invasive species, and pollutants (Anfinson 2003). River engineering is not the sole cause for the dominance of non-native species of fish such as Silver carp, but it is a combination of habitat loss (floodplain disconnection and river channelization), excessive sedimentation, and water pollution. Silver carps have the capacity to impact all fish species in the UMR (Koel et al. 2000) because they feed on the resources of native species and can grow quickly, spread rapidly, and dominate an area to the point where native species are displaced. The existence and prevalence of non-native species in UMR indicate the ecological impairment of the river (Johnson and Hagerty 2008).

Runoff from agricultural lands containing chemical fertilizers and pesticides increases a load of nitrogen and phosphorus in the UMR. Likewise, construction of levees along the rivers cuts off the floodplain from the river and contributes to an increase of transported nitrogen loads in the main river. It is because of reduction of the denitrification process by aquatic species that they are restricted due to the floodplain disconnection. Excessive nitrogen loads in the river system have affected community composition of aquatic vegetation (e.g., the abundance of filamentous algae and duckweed), dissolved oxygen concentrations in off-channel areas, and the abundance of cyanobacteria (Houser and Richardson 2010). Elevated nitrogen concentrations in the UMR have enhanced the ammonia in the benthic sediments (Houser and Richardson 2010). Higher concentrations of ammonia suggest the water has become more acidic, and these acidic waters can become toxic to benthic organisms (Wilson et al. 1995).

Various climate models have predicted that the temperatures within the UMR basin will continue to increase while changes in the amount and intensity of precipitation will become more variable (Jha et al. 2004) which will likely impact the frequency and magnitude of the floods (Remo 2016). Increment in the intensity of precipitation can cause flooding which can affect the living organisms in the water (Knox 2001). Similarly, anthropogenic warming has been linked to the loss of diversity in species and biomass along the UMR (Strayer et al. 2004. Increasing temperatures are expected to collapse the range and fragment the habitat of temperature-sensitive species like the Pearly Mussel (Kentaro and Berg 2017). Similarly, increase in temperature, due to climate change, will compel mussel species to move from their current locations to reach a different and more habitable temperature regime within the UMR (Newton et al. 2013).

Floodplain reconnection makes the floodplain ecosystem ecologically functional. Aquatic diversity and fish functional diversity increases, while excessive nutrients are used by the aquatic species. These increments enhance the adaptive capacity of the UMR and maintain its resiliency. Strategic floodplain reconnection can be achieved through the levee setback process. It prioritizes reducing flood heights by allowing portions of lower-valued land to flood and rehabilitating or creating new habitat. Levee setback strategies examined by Guida et al. (2016), for the strategic reconnection of the river to its floodplain, suggested that aggressive levee setback scenarios contributed to maximum flood height reduction and environmental benefits with higher monetary costs, while lower-cost scenarios contributed to less flood height reduction and fewer environmental benefits due to less floodplain area being reconnected.

Connectivity, diversity of species in river and floodplains, and controlling variables (total suspended particles, sediment load, nutrient concentration, and invasive species numbers) are important components for achieving resiliency in the UMR. Bouska et al. (2018b) divided four reaches of UMR into three interconnected subsystems: lotic channels, lentic off-channel areas, and floodplains, subsequently, they evaluated resilience assessment under three resilience principles. These authors found longitudinal and lateral connectivity indicators need to be enhanced to maintain resiliency and adaptive capacity along the UMR. Similarly, by increasing aquatic habitat diversity and redundancy, as well as increasing floodplain inundation and fish functional diversity and redundancy contributes to the resiliency of the UMR. Lastly, controlling variables such as reducing total sediment loads, reducing total suspended solid’s concentration, minimizing nutrients concentration and restricting the growth of invasive species, would help in achieving resiliency in the UMR. Enhancing the hydrological connectivity of the river with the floodplain through floodplain reconnection can help to achieve these goals. The ecologically functional floodplains are more adaptive to the disturbances than ecologically impaired. Floodplain reconnection helps to make the floodplain ecologically functional (Opperman et al. 2009). Ecologically functional floodplains rejuvenate a river-floodplain system to deliver multiple benefits to people and ecosystems, while enhancing the resilience of river-resources (Loos and Shader 2016).

Excessive nitrogen loads in the UMR has been a major concern, due to higher eutrophication in the Gulf of Mexico. To minimize the concentration of nitrogen into the UMR, nitrogen management and nitrogen removal techniques seem to be advantageous. Nitrogen management strategies include; maintaining the timing of application and nitrogen rates, nitrification inhibitors, crop rotation, conservation tillage, and cover crops. In addition, nitrogen reduction techniques such as riparian buffers and restoration of wetlands can help in reducing the excess nutrients from the agricultural land flowing into the UMR. If the controlling variables of river ecosystems such as total suspended solids, excessive nutrients, and invasive species are reduced, adaptive capacity of the UMR will increase. Soil conservation techniques such as conservation tillage, cover crops help in reducing soil erosion and other agricultural runoff which can lead to the reduction in riverine sedimentation, nutrient loads and total dissolved solid concentrations. Reconnecting the floodplain to the river's main channel can also help in reduce the growth of invasive species through biotic resistance (Lemke et al. 2017), while functional floodplains reduce excessive nitrogen by denitrification through the aquatic species (Dinnes et al. 2002). Climate Change has already affected the hydro-ecology of the UMR and will likely exacerbate the impacts of river engineering and landuse change in the UMR system.

Therefore, to enhance the adaptive capacity of UMR, the findings of resilience assessment as presented by (Bouska et al. 2019) should be implemented. Similarly, nitrogen management techniques and nitrogen removal strategies also contribute to achieve climate change adaptation, while reducing the excess nitrogen in the UMR. Nevertheless, floodplain reconnection would be an important resiliency option towards climate change and flood risk reduction (Opperman et al. 2009). Reconnecting floodplains in geographically strategic locations can increase a river's capacity to contain floodwaters (Loos and Shader 2009), minimizing the flood risks and enhancing the biological productivity of the floodplain ecosystem. Similarly, floodplain reconnection provides multiple benefits and delivers self-sustaining climate adaptation assistance to floodplain inhabitances (Opperman et al. 2011).

It is apparent that anthropogenic stressors such as river engineering, landuse change, excessive nitrogen, and climate change have impacted the hydroecology of the UMR. To preserve the nationally significant UMR system, it will require an integrated effort of the governmental stakeholders, river scientists, engineers, ecologists, river communities, and other concerned stakeholders. This review of the literature confirms that there is still a need for comprehensive research with regards to the effects of river engineering, excessive nutrients, and climate change on the hydroecology of the UMR.

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