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Defining ecosystem restoration potential using a multiple reference condition approach: Upper Mississippi River System, USA

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DEFINING ECOSYSTEM RESTORATION POTENTIAL USING A MULTIPLE REFERENCE CONDITION APPROACH: UPPER MISSISSIPPI RIVER SYSTEM, USA

by

Charles H. Theiling

An Abstract
Of a thesis submitted in partial fulfillment
of the requirements for the Interdisciplinary
Studies-Ph.D. degree in Large River Ecology
in the Graduate College of
The University of Iowa

May 2010

Thesis Supervisors: Professor Larry J. Weber
Adjunct Associate Professor John Nestler

ABSTRACT

Large scale ecosystem restoration is an important societal issue because significant risks, costs, and benefits can accrue on large landscapes. It is important to understand baseline ecosystem conditions, existing condition, and to the extent possible estimate ecosystem response to alternative management scenarios. Incorporating sound ecological theory for ecosystem process and function into restoration planning and implementation is critical to make restoration sustainable. The Upper Mississippi River System is an excellent case study for such issues because it is an important, multiple-use ecosystem with significant ongoing investment in ecosystem, agri-system, and navigation system management.

I compared large-scale geomorphology, hydrology, and land cover information among presettlement, contemporary, and potential future reference conditions to examine ecosystem state and evaluate mechanisms responsible for ecosystem condition. Ecologically relevant geomorphic classes were devised from existing data and evaluated by river reach to characterize presettlement geomorphology. I superimposed dams and levees onto the geomorphic landscape to reflect the altered hydrogeomorphology of the contemporary ecosystem. I also analyzed pre- and post-impact river stages and aquatic habitat class distribution. My floodplain inundation simulation analysis provided new information on the potential spatial distribution of frequent floods. Land cover data available for presettlement and modern reference periods were compared at several spatial scales. I used multivariate analyses to evaluate land cover characteristics among geomorphic reaches, as well as to assess the influence of hydrogeomorphic drivers on land cover for presettlement and contemporary reference periods.

The hydrogeomorphic response to development was clear with impoundment altering the 2-yr flood distribution in the north and levees altering it in the south. The hydrogeomorphic response to development indicates several restoration objectives that are appropriate system-wide and others that are best suited to specific river reaches.

I was also able to test several hypotheses related to large river ecology. The Upper Mississippi River System does have distinct reaches that are formed by ancient glacial influences and tributary influences during the last 10,000 years. Tributaries delivering sediment as alluvial fans create diverse floodplain topography which supports diverse plant communities. Tributaries appear to diversify floodplain habitats in many ways.

Abstract Approved:____
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Iowa City, Iowa

CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph.D. thesis of

Charles H. Theiling

has been approved by the Examining Committee for the thesis requirement for the Interdisciplinary Studies-Ph.D. in Large River Ecology, at the May 2010 graduation.

Thesis Committee: ___________________________________
Larry J. Weber, Thesis Supervisor

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David Bennett

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Elmer A. Bettis

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George P. Malanson

To
The “River Rats” at the
Upper Mississippi River Conservation Committee

“Tell me what right looks like.”

Lieutenant General Carl A. Strock
2nd National Conference on Ecosystem Restoration,
23 April, 2007
Kansas City, Missouri

ACKNOWLEDGEMENTS

My Family has been of great support and inspiration on this learning expedition. My Mother inspired me by the example of her hard work to support us, her commitment to education, and her unequivocal love. Susan, my Wife of 20 years, is the closest friend I’ve ever had. She supports me in all my crazy ideas and has made me a much better person. My Boys, Jack and Thomas, inspire me to inspire them. I hope to demonstrate commitment to life-long learning and public service.

My mentors are many, but a few educational and professional influences are noteworthy. Dr. Mike Wiley (Univ. of Michigan) told me “nobody ever said it would be easy”; words I remember many days. Dr. Rip Sparks (Ill. Natural History Survey) gave me an opportunity to learn. My introduction to the River through an ecosystem model and a mountain of literature set my course for a Big Picture perspective that has stuck with me to this day. Drs. Ken Lubinski (USGS) John Barko (USACE), Carl Korschegen, and David Galat (Univ. of Missouri) have all supported me with advise and opportunities for success. Drs. John Nestler, Steve Bartell, Rob Jacobson, and Jean O’Neil taught me how to model. Nani Bhowmik and Mike DeMisse introduced me to hydraulic engineering and geomorphology. My thesis committee members are newer friends, I appreciate their welcome back to academia. It’s been a gas and I hope to continue the associations for many years.

The Upper Mississippi River Conservation Committee (UMRCC) is a dedicated group of professionals with a 70 year history of natural resource conservation, education, and learning. The membership has contributed to all aspects of river management in a professional manner dedicated to supporting a multiple use sustainable resource. The group is the target for this research because they are the ones who will apply it in the field. I thank them for the inspiration and outlet for my research and look forward to many, many more years working together.

I have been fortunate to work with great people for 20 years on the UMRS. Some of these guys go back to the early days: Dan Wilcox, Jeff Janvrin, John Nelson, John Tucker, Rob Maher, Eric Ratcliff, Scot Johnson, and Joe Wlosinski. My USGS friends: Hank DeHaan, Tim Fox, JC Nelson, Jason Rowheder, Jim Rogala, and Linda Leake have guided me and supported my GIScience investigations for many years. Their professionalism and dedication to organizing and serving information is an invaluable asset to the entire river research and management community. Ken Barr provided a vision in 2000 when I got to Rock Island; I still believe in the "Evil Master Plan" that aims to coordinate river management for sustainable multiple uses. Mark Cornish and Scott Whitney have been great colleagues to grow with over the years. My H&H colleagues have helped me understand the physical world and support so much terrific science and engineering with their modeling capabilities. Kevin Landwehr, Jon Hendrickson, John Burant, Dan McBride, Nicole McVay, Claude Strauser, Rob Davinroy, Dave Busse, and Clint Beckert have all helped me understand the river in their respective reaches to support my broader view. Newer colleagues, Matt Hiett, Mike Siadak, and Eddie Brauer helped create data layers and will add much to the utility of these data in the future. I am very grateful to Paul West and Michael Reuter, The Nature Conservancy, Great Rivers Partnership, Peoria, Illinois for developing and sharing the Public Land Survey data. I've missed many folks and apologize to all of the hundreds of other people and Guardian Angels who have helped me along the way.

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CHAPTER 1: WHAT ARE THE SCIENTIFIC AND MANAGEMENT INFORMATION NEEDS FOR LARGE RIVER ECOSYSTEM RESTORATION?

Introduction

Natural resource management issues are becoming increasingly larger, more complicated, and expensive as the relevance of ecological scale, interconnectedness, and function is integrated into law and policy. The most recent revisions of the U.S. Federal Principles and Standards for Water Resources Planning (Council on Environmental Quality, 2009) include explicit guidance to use science-based approaches for environmental benefit benefits analysis and impact assessment. There is also guidance to incorporate adaptive management principles into all Federal projects. Thus, as with the prior guidance, there is a need to understand and quantify existing ecosystem status, projected future without-project condition, and projected response to proposed alternative projects or management scenarios, but under the new guidance future planning must also consider the fast changing sciences of aquatic ecology, landscape ecology, environmental hydrology, and many other disciplines in an adaptive management framework. Large ecosystem restoration programs will need to incorporate sound ecological theory into their design and use adaptive management principles to test those theories. Fortunately for ecosystem restoration practitioners, there are an abundance of recent advances in large river ecological theory, there are ambitious restoration programs authorized, and there are abundant environmental data on the Upper Mississippi River System (UMRS).

River ecology theory has expanded over many years from an initial concept of longitudinal, downstream energy transport in cool-water, forested ecosystems (Vannote et al., 1980). The theory was refined by authors in other systems (Wiley et al., 1990;

Junk et al., 1989; Thorp et al., 2008) and by incorporating additional concepts (Ward and Stanford 1983; Benda et al ., 2004). Expanding the view of the stream in a landscape ecology approach helped organize large complex systems (Frissel et al., 1986 ; Wu and Loucks, 1995; Ward, 1998; Weins, 2002; Naiman et al., 2005; Thorp et al., 2008). The most recent comprehensive river ecology theory integrates fluvial geomorphology, hydrology and hydraulics, land cover and other parameters as important ecological drivers. The importance of physical processes in supporting ecosystem services is recognized as fundamental to large scale ecosystem function and, by extension, ecosystem management (Fischer et al., 2006; Rey Benayas et al., 2009; Thorp et al., 2010). Some authors are integrating hydrogeomorphic concepts into land cover predictive models (Klimas et al 2010), but most large ecosystem theory remains untested and is in need of system level documentation.

Interdisciplinary science, planning, and engineering conducted in an active adaptive management framework is the current model recommended for large scale ecosystem restoration (Society for Ecosystem Restoration, 2004). In the following dissertation I document the hydro-geomorphic template of the UMRS and relate it to presettlement vegetation community distribution. I also document changes to the hydro-geomorphic template and vegetation community in response to impoundment, levees, and development. Spatial modeling and analysis allows simulations for many alternative floodplain conditions, a Virtual Reference Condition. I use multivariate statistical analysis to compare the quantity and distribution of parameters along environmental, spatial, and temporal gradients. I conclude with answers to the hypotheses for large river ecology and examples of the utility of the Multiple Reference Condition Analysis applied to recent UMRS planning to establish ecosystem restoration objectives for almost 3 million acres of a multiple-use river-floodplain ecosystem. I have three primary objectives for my research: 1. Support Upper Mississippi River System ecosystem restoration benefits analysis by establishing physical landscape and plant community relationships for several ecosystem reference conditions, including the virtual reference (Thorp et al., 2010), 2. Testing hypotheses derived from the River Ecosystem Synthesis (Thorp et al., 2008) and the Network Dynamics Hypothesis (Benda et al., 2004), and 3. Establishing the baseline data for potential vegetation mapping using the Hydrogeomorpic Methodology (Klimas et al., 2010).

The River Ecosystem Synthesis (RES) is the most recent of several prominent conceptual models for the structure and function of aquatic ecosystems (Thorp et al., 2008). The RES presents several model tenets that they recommend for consideration in river management and restoration. The tenets are organized by ecological factors affecting the distribution of species, community regulation, and ecosystem and riverine landscape processes. My research addresses several tenets within the first and last categories:

Distribution of Species/Physical Characteristics:

H_0: Can hydrogeomorphic patches be defined on the scale of the UMRS?

H_0: Can hydrogeomorphic functional process zones be defined for the UMRS?

H_0: Does development change functional process zones?

H_0: Is ecological/hydrodynamic/geomorphic diversity greatest at Nodes?

H_0: Does community complexity increase with increased hydraulic retention?

Community Regulation:

None

Ecosystem and Riverine Landscape Processes:

H_0: Does primary production vary with hydraulic residence time?

H_0: Does dynamic hydrology support diverse habitat?

H_0: Do UMRS landscape classes demonstrate flood-linked evolution?

H_0: Does biocomplexity peak at intermediate levels of connectivity?

H_0: Do landscape patterns characterize UMRS functional process zones?

Benda et al. (2004) integrated principles of fluvial geomorphology and riverine ecology in an analysis of watershed stream networks and also suggested several testable predictions. Their work was more related to watershed characteristics, but their presentation of tributary effects and several conclusions related to tributaries as "biological hotspots" are relevant on the UMRS river-floodplain ecosystem. Several of their predictions related to watershed disturbances can be adapted to the UMRS:

H_0: Do glacial influences (i.e., higher punctuated sediment supply and transport) cause greater confluence effects?

H_0: Do channelized disturbances (i.e., gorges in the natural system, or river engineering in the modern system) lead to greater hydro-geomorphic heterogeneity?

H_0: Is the age distribution of landforms skewed toward older features in the upstream portions of the valley and younger features in downstream portions of the valley?

H_0: Is physical heterogeneity concentrated in certain parts of the river valley?

Study Site

The Upper Mississippi River System (UMRS; Figures 1 and 2) is an excellent example of a multiple-use river. The "System" refers to the U.S. Army Corps of Engineers Inland Waterway 9-Foot Channel Project which includes the Upper Mississippi River above the Ohio River to Minneapolis, Minnesota, the Illinois River including connecting waterways to Lake Michigan, and parts of several tributaries; the legal designation notably excludes the Missouri River which is a very significant hydrogeomorphic influence near and below St. Louis. The system has supported humans for more than 12,000 years, it was prominent in the evolution of agriculture and agrarian society, and its unique biological production capacity was noted early and often in anecdotes and published accounts of early explorers and settlers (Carlander,1954). The modern river supports large scale commercial navigation (>120 million tons annually) with a 1,200 mile network of navigable waterways, 37 lock and dam sites (Figures 1 and 2), and thousands of local channel stabilization structures (USACE, 2004). There are 180 flood protection structures (i.e., levees and floodwalls) extending 2,200 miles to protect 1.1 million acres of agricultural and urban development which is about one-half of total floodplain area, and almost all located in the southern half of the system (Figure 3; Thompson, 2002; USACE, 2006). Flood protection has prevented over $83 billion in economic damages over the last several decades (USACE, 2006), but catastrophic flooding sometimes occurs with large economic consequences (Belt, 1975; White & Meyers, 1993; Changnon, 1996; NOAA, 2008). A 1995 recreation economic analysis estimated annual spending of $1.2 billion in direct and secondary expenditures, and 11 million visitor-days of use by people who hunt, fish, boat, sightsee and otherwise visit the river and the natural communities it supports (Carlson et al., 1995). A more recent estimate valued recreation at 12 million visitors spending $6.6 billion each year (Black et al., 1999), and mostly in the north where there is abundant public land. Urban areas built on the industrial power and transportation advantages of the river now capitalize on the environmental benefits of the river by revitalizing unused industrial areas as green space and desirable housing (City of Minneapolis, 2004). Water quality has improved considerably river-wide since the 1970’s, but nutrient enrichment and sedimentation remain significant impairments in lower river reaches.

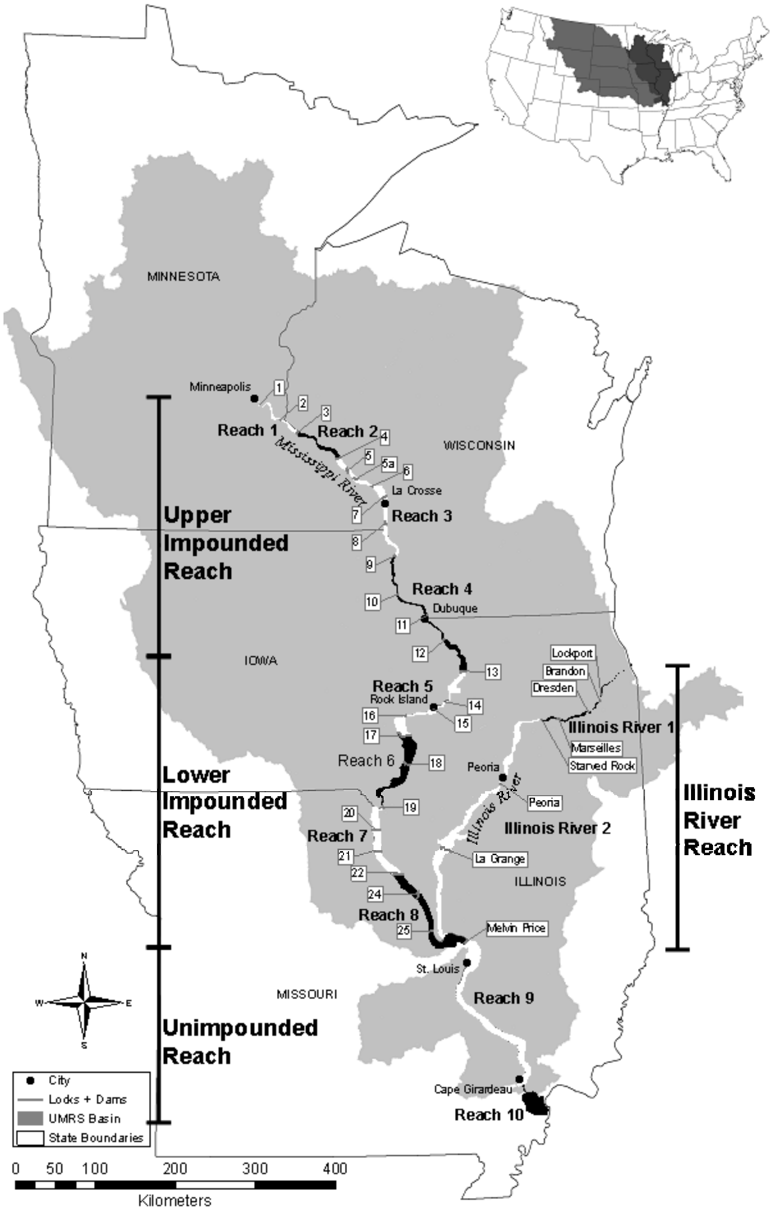


Figure 1. The Upper Mississippi River System with 4 floodplain reaches roughly designated by bars and pool reach designations that are represented by alternating black and white segments of the floodplain outline.

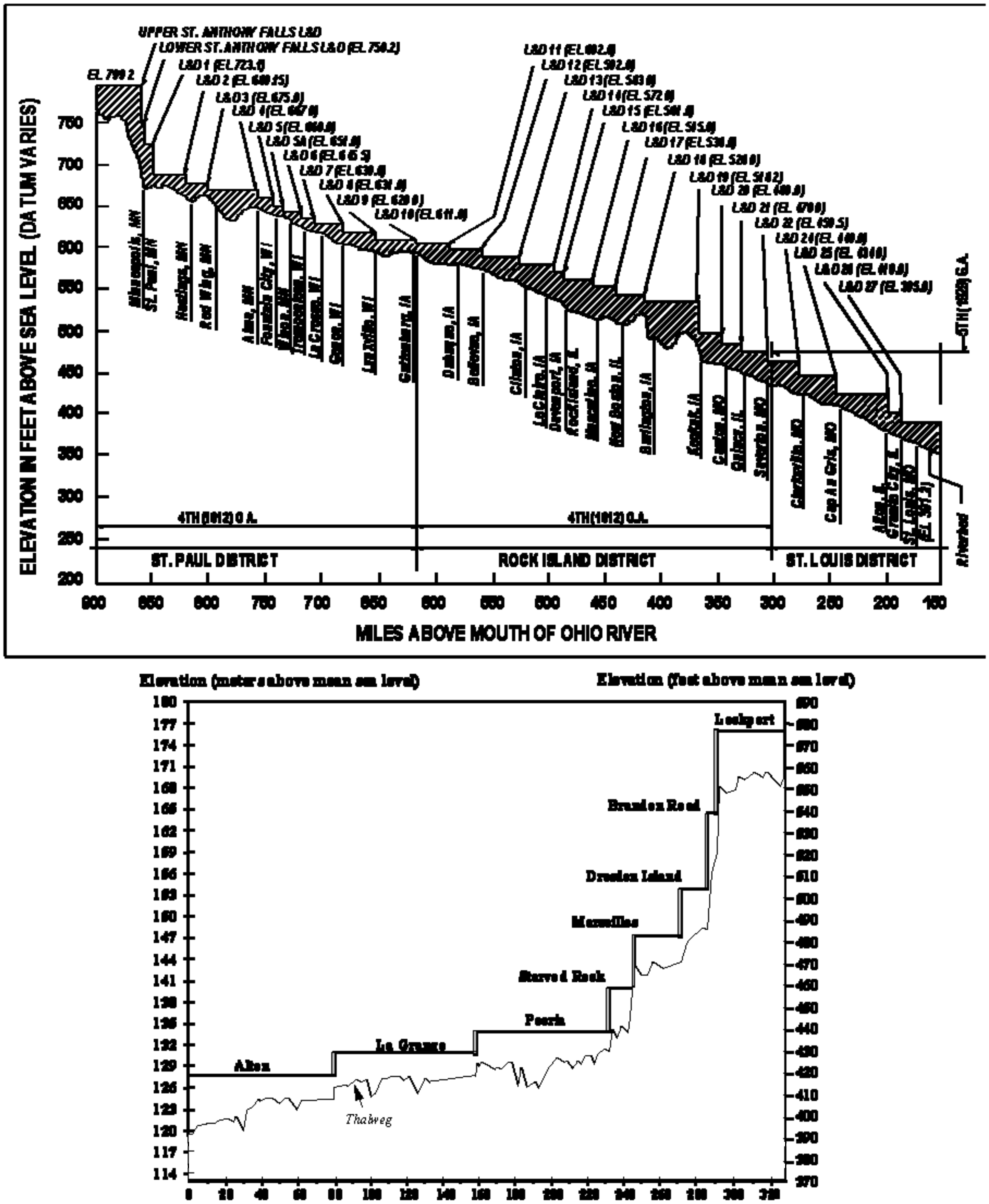


Figure 2. Upper Mississippi and Illinois River thalweg profiles, dam locations, and approximate regulated river stages.

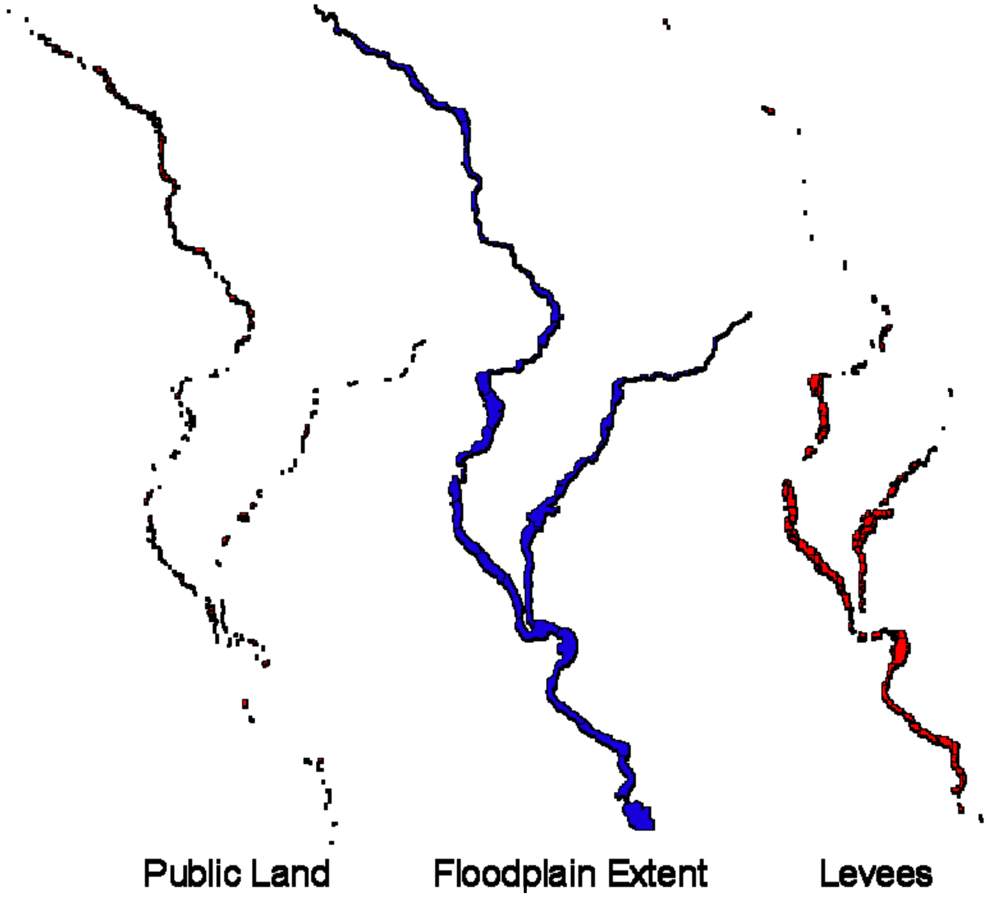


Figure 3. Upper Mississippi River System floodplain extent, public land (Conservation Biology Institute, 2008), and levees (Interagency Floodplain Management Review Committee – SAST database, 1994).

UMRS Ecosystem Conceptual Model

UMRS ecological monitoring and restoration programs have embraced a simple ecosystem conceptual model to illustrate relationships among ecosystem drivers and ecosystem structure and function (Figure 4; Lubinski and Barko, 2003). The model considers Boundary Conditions such as basin geology and climate (which had previously been considered quite stable but is now changing and strongly influencing river hydrology). Ecological stressors are natural or anthropogenic disturbances, like drought or system-wide agriculture development that can act at very large scales or may act more locally on the scale of channel avulsion or levee construction (Theiling et al., 2000). Management actions are anthropogenic stressors to affect a desired response (e.g., navigation dam, ecosystem restoration project, hunting seasons, crop management, etc.). Ecological conditions at any point in time can be considered responses to stressors that are expressed through Essential Ecosystem Characteristics (EECs: Geomorphology, Hydrology, Biogeochemistry, Habitat, Biota; Harwell et al., 1999) that can describe ecosystem structure, function, and processes (Pastorok et al., 1997; Society for Ecological Restoration, 2004; Galat et al., 2008). Physical processes are generally viewed as driving habitat and biological outcomes, but feedbacks occur throughout the system. Individual indicators can be described in the model to help establish ecosystem goals and objectives and to monitor condition.

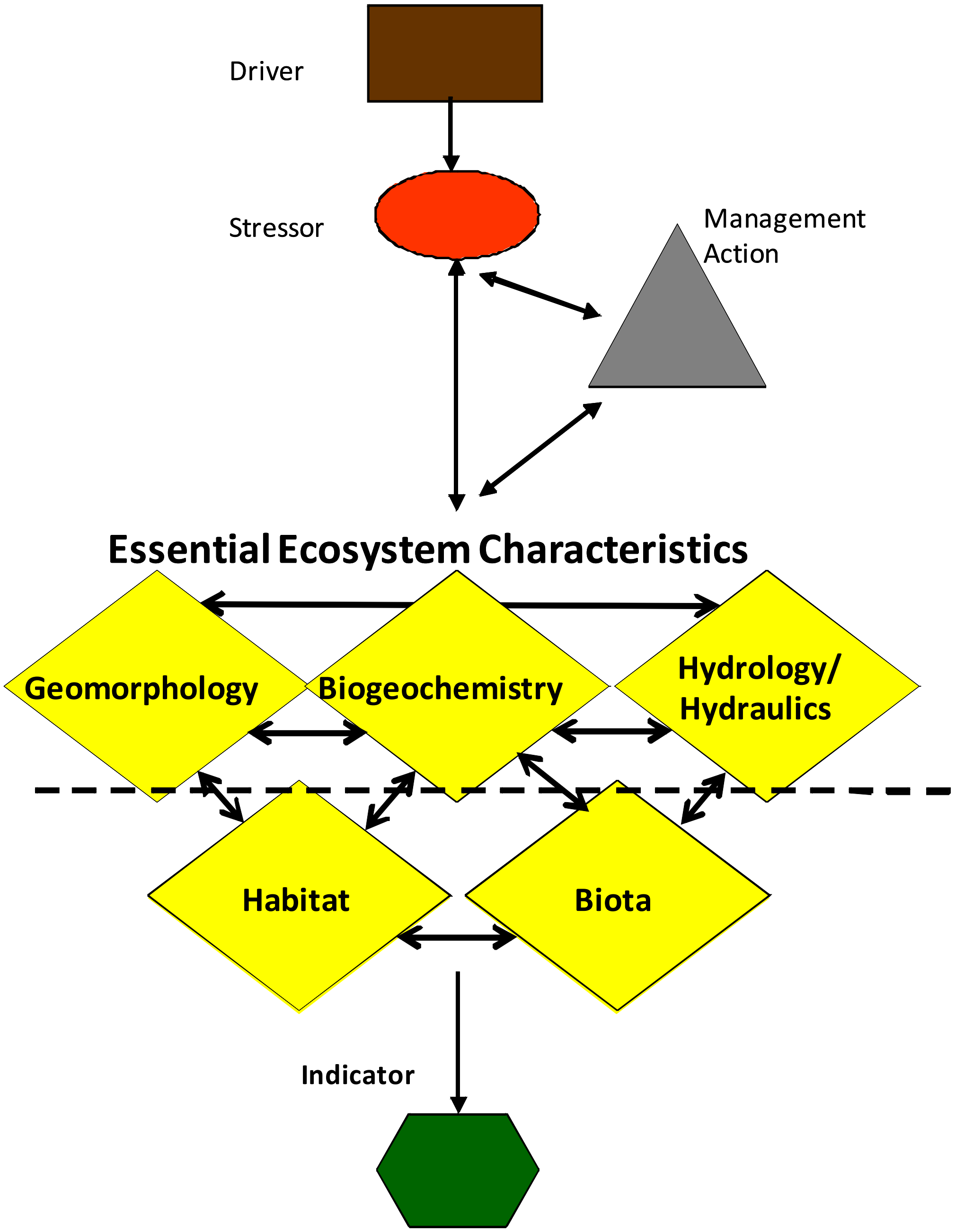


Figure 4. UMRS ecosystem conceptual model emphasizes Essential Ecosystem Characteristics: Geomorphology, Biogeochemistry, Hydrology and Hydraulics, Habitat, and Biota which are driven by large scale boundary conditions and disturbance.

Multiple Reference Condition Analysis

Multiple Reference Condition Analysis (MRCA) is a quantitative restoration framework based on a comprehensive, but simple mathematical framework that can be used to effectively apply restoration knowledge and evaluate alternatives (Nestler et al., 2010). Nestler et al. (2010) propose a geometric representation of restoration planning because: 1) conceptual representations of ecosystem degradation and recovery are often presented in a geometric form; 2) many dimensional reduction techniques, such as principal components analysis, cluster analysis, and factor analysis, commonly used in ecological assessment and categorization, are based on geometric relationships among variables; and 3) one of the seminal ideas in ecology, the niche, is defined as a geometric hyper-volume of limiting variables (Hutchinson, 1957). The niche hyper-volume concept is also consistent with the representation of the state of a homogeneous system in phase space used by physicists. In phase space, every variable or parameter describing a homogeneous system is represented as an axis in multidimensional space (Figure 5). Every possible state of the system can then be represented as a point within multidimensional space and a succession of plotted points represents the system's state trajectory over time (Figure 6). Ecosystems are not homogeneous; therefore, ecosystem state dynamics are better characterized as envelopes of points depicted at discrete time intervals that describe conditions within a heterogeneous spatial domain.

A quantitative restoration framework should, at a minimum, include these elements:

1. one or more relatively pristine historical conditions,
2. a period of degradation to an unacceptable condition,
3. an awareness that restoration to a less degraded state is needed,

4. a realization that there are a large number of future possible conditions,
5. a need for a precisely defined desired future condition to guide restoration action by providing a reference against which alternatives can be evaluated, and
6. one or more no-action future alternatives to serve as a baseline to justify restoration.

The concept was used as the basis for the development of ecosystem restoration alternatives for the Upper Mississippi River-Illinois Waterway System Navigation Feasibility Study (USACE, 2004). Ecosystem restoration alternatives examined in the study achieved a range of benefits, generically represented as ecological diversity, that approached a stakeholder desired future condition (Figure 7). A virtual reference condition was presented to illustrate what could only be achieved with participation of agencies and stakeholders from the river basin because of administrative constraints limiting activities to the river-floodplain area. This premise was the basis for the $5.3 billion ecosystem restoration plan authorized in the 2007 Water Resources Development Act (WRDA 2007) which included Ecosystem Restoration Alternative D' along with 7 new locks and other navigation efficiency measures (USACE, 2004).

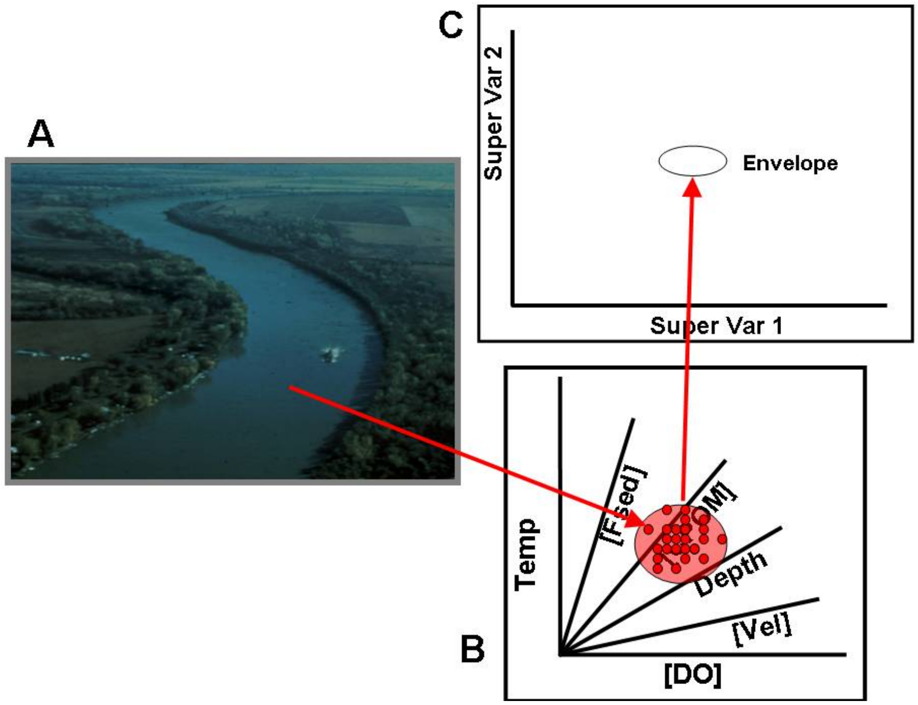


Figure 5. Conceptualizing a homogeneous system in multidimensional space. Legend: A = any river system; B = hypothetical conditions for several aquatic habitat parameters;C = a system’s characterization in multivariate space. (Source: John Nestler, University of Iowa, IIHR Hydroscience & Engineering, Iowa City, Iowa).

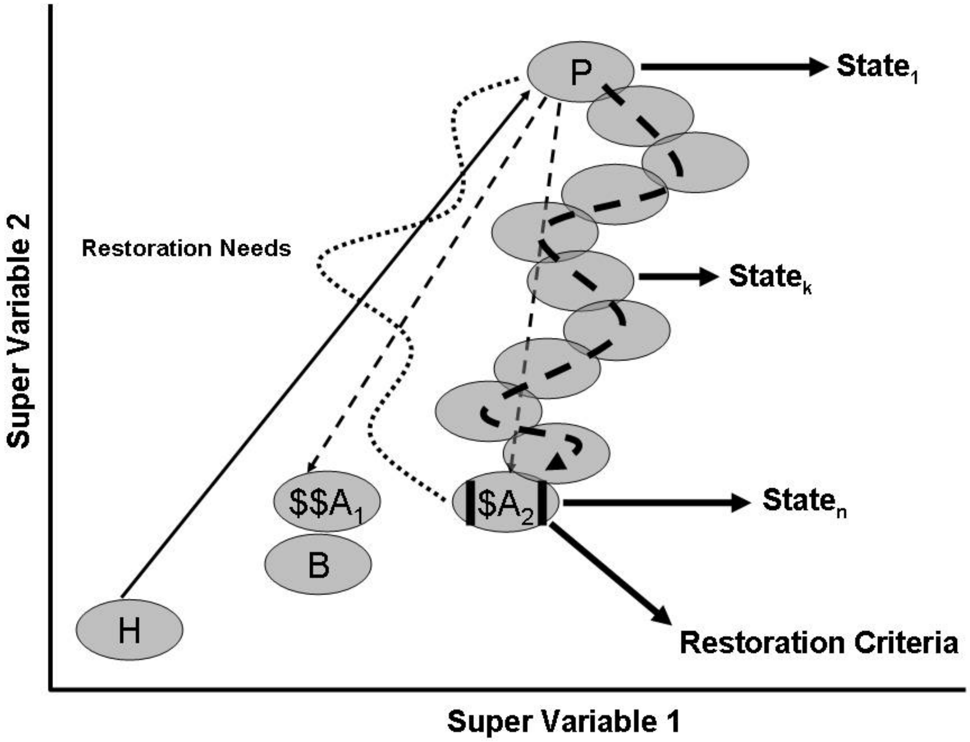


Figure 6. Tracking ecosystem condition trajectory among multiple reference conditions. Legend: H = Historical (“Natural”); B = “Best Achievable State”; Ai = Competing Alternatives; P = Present. (Source: John Nestler, University of Iowa, IIHR Hydroscience & Engineering, Iowa City, Iowa).

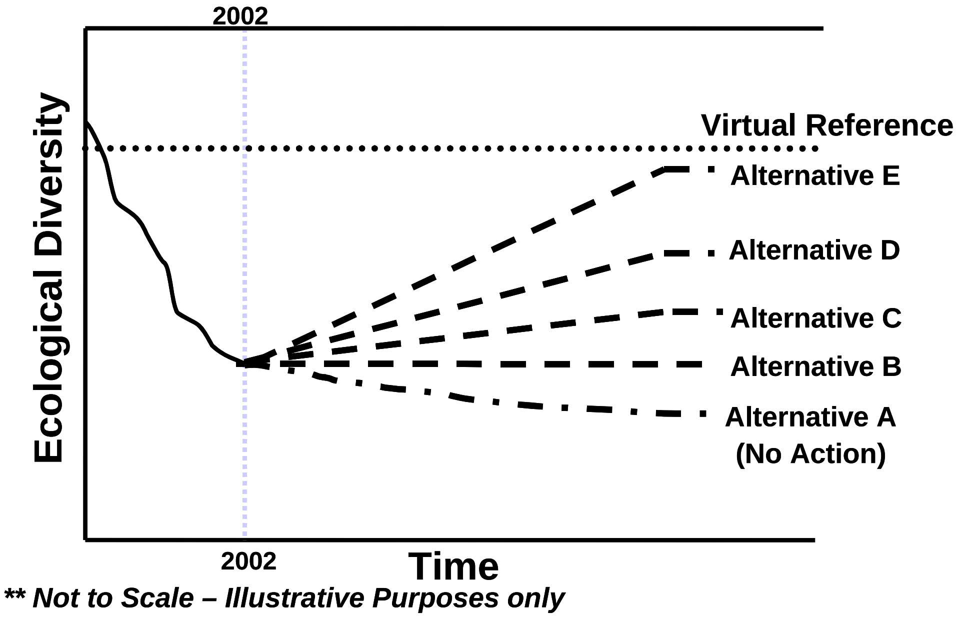


Figure 7. Schematic representation of how environmental alternatives help achieve desired ecosystem conditions (no scale implied; USACE, 2004).

Use of Multiple References in UMRS Ecosystem Restoration Science

With the framework above, it should be relatively straightforward using multivariate statistics to demonstrate that different river reaches will each have different swarms of points associated with them because of climatic gradients, local geomorphology, and human use. Similarly, historical periods of different lengths will also have different envelopes, and by association, different centroids and different measures of dispersion. Alternative future conditions can also be represented in a number of ways ranging from expert opinion to explicit simulation models. In reality of course, it is not possible to sample historical conditions, but fortunately, systematic data collection efforts began prior to significant development and at several time steps as development occurred on the UMRS to provide those historical samples.

The following terms, definitions, data sets, and models are used in developing reference conditions and habitat design criteria:

- **Reference Condition for Biological Integrity:** A presettlement (1806 – 1850) land cover dataset collected for the Public Land Survey (Source: Paul West and Michael Reuter, The Nature Conservancy, Great Rivers Partnership, Peoria, Illinois).
- **Least Disturbed Condition:** Mississippi River Commission (1891) maps for the Mississippi River and Woermann Maps for the Illinois River (1903) include topography, bathymetry, and land cover. Significant channel clearing, dredging, and channelization occurred since 1824 prior to surveys.
- **Historic Condition:** Any one of a number of land cover or topographic map sets, hydrologic and hydraulic models, or surveys completed after the LDC. Widespread stream gauging and comprehensive topographic mapping for lock and dam design occurred

on the Mississippi River between 1927 and 1930 (i.e., the Brown's Surveys).

- **Contemporary Condition:** Modern land cover assessments using aerial photography and other remote sensing, hydraulic mapping and modeling, coring and geomorphic analysis, water quality assessment and modeling, biological assessment, etc.
- **Virtual Reference Condition** : Any one of a number of stakeholder Desired Future System Condition alternatives or environmental objectives modeled using tools that simulate change in ecosystem indicators (i.e., benefits).

Land cover and physical change information will be compared among reference periods to examine and evaluate mechanisms responsible for the change. Some data will be applicable only to large scale analysis, while other data can be used in site-specific applications. Scales to be examined include: floodplain reaches which are several hundred river miles in length; geomorphic reaches range from about 40 to a couple hundred miles; pool reaches range from 10 to 80 miles; and lastly, a mile-by-mile segmentation of the river floodplain extent. Land cover data are available for several reference periods and can be compared at several scales. Multivariate statistical analyses will be conducted to assess land cover characteristics among geomorphic reaches, as well as to assess the influence of hydrogeomorphic drivers on land cover. The objective of the approach is to clearly delineate the divergence of environmental conditions among reference periods to evaluate which drivers need to be, and can be, altered to change ecosystem state.

Similar data sources are available for much of the rest of the United States through the Public Land Survey and engineering surveys of any significant civil works projects. Crop compliance and other survey photography from the early 20th century are widely available. The MRCA framework should be applicable across a wide range of public works project's environmental assessments specifically, and in scientific investigations also.

Statistical Methods

Geomorphic, aquatic area, floodplain inundation, and land cover data were summarized in contingency tables with class type as columns and scale (i.e., mile, pool, reach) as rows. The contingency table was used as input for Unweighted Pair Group Average method cluster analysis using the Multi-Variate Statistical Package (Kovach Computing Service, 2008). Cluster analysis was used to depict similarity among the gauges with the idea that analysis parameters would be sorted by the reference periods, reaches, or environmental characteristics. Physical and land cover parameters could organize in multivariate space by time and space depending on the similarity of characteristics at various scales. Cluster analysis became harder to interpret as resolution (i.e., number of reaches) got finer, so it was dropped for pool scale analyses. Finer resolution analysis may be achieved with parametric statistics, but the focus of this study was large scale and the multivariate procedures fit the relatively small number of reach or environmental parameter classes.

Correspondence analysis was used to visualize the landscape in two-dimensions and relate the land cover pattern to underlying reach scales (i.e., variable plots and joint plots). Correspondence analysis is a geometric technique for displaying rows and columns of a two-way contingency table as points in low-dimensional space to obtain a global view of pattern in data useful for interpretation. (see CA of rainfall data in Silveira (1997) as an example hydrologic analysis). Correspondence analysis is based on chi-squared tests (X^2) to measure discrepancy between observed frequencies in a contingency table and the expected frequencies calculated under the hypothesis of homogeneity of row or column profiles. Discrepancy is expressed in term of inertia (variation) and can be interpreted as the weighted average of squared X^2 distances (as opposed to Euclidian distance) between the row profiles and their average profile or equivalently between the column profiles and their average. Results are displayed in two-dimensional scaled maps because most of the variability is captured by the first two axes of the CA output. Variance explained in each CA is reported on each graph.

Correspondence analysis provides projections based on simplifications that depict pattern in the data for easy visualization, but the projection changes as variables or sites are added or removed so that associations among gauges are best represented by the cluster analysis. Correspondence analysis is criticized for the “arch effect” as more environmental variables are added and other reasons (Ter Braak, 1987) in which the second and subsequent axis appear as polynomial functions of the first axis and obscure underlying gradient structure (Peet et al., 1988). Kovach (2008) explains the arch effect as a result of the data reduction process that may be more pronounced on long environmental gradients where there is great dissimilarity at extremes. Another ordination method was employed to substantiate CA results.

Nonmetric multidimensional scaling (NMS) is an ordination method suited to data that are nonnormal or are on an arbitrary, discontinuous, or otherwise questionable scales (McCune and Grace, 2002). The advantages of NMS are it avoids the assumption of linearity, its use of ranked distances, and flexibility with units (Clarke, 1993; McCune and Grace, 2002,). “NMS is an iterative search for the best position of *n* entities on *k* dimensions (axes) that minimizes the stress of the *k*-dimensional configuration. Stress is a measure of departure from monotonicity in the relationship between the dissimilarity (distance) in the original p-dimensional space and distance in the reduced k-dimensional ordination space.” (McClune and Grace, 2002). PC-ORD NMS autopilot (MjM Software, 2002) was used to assess relationships of land cover classes at the various scales above to determine if whether relationships were more or less evident at finer special scales. The Sorensen distance measure and random start were used and up to 200 Monte Carlo iterations were run. The two-dimensional ordination, stress, and number of Monte Carlo iterations are reported.

Upper Mississippi River System Ecosystem Restoration Objectives

The UMRS has been the focus of significant planning and evaluation because of its importance to the United States as a commercial waterway linking international grain markets as well as its ecological role supporting international flyways and local wildlife populations (WRDA, 1986). Ecosystem restoration (ER) planning on the UMRS has advanced from a site-specific, species based approach to more comprehensive and transparent ecological community needs assessments (Theiling et al., 2000) for hydrologically distinct habitat complexes (i.e., subareas; DeHaan et al., 2003; RRCT, 2004). Greater emphasis on physical and ecological process and function to implement adaptive management was recommended for the most recent system scale ER planning (Galat et al., 2008). The UMRS Conceptual Model (see Figure 3; Lubinski and Barko, 2003) helps manage UMRS ecosystem adaptive management because it provides the Essential Ecosystem Characteristic (EEC) framework that integrates the theory, applied science, and ER objectives across scales and disciplines.

UMRS goals and objectives are organized in a hierarchy, its broadest vision being a multiple use waterway that supports “sustainability of the economic uses and ecological integrity.” Ecological goals range in number and emphasis depending on which stakeholder group or region is considered, but they are generally quite broad and qualitative. Most goals emphasize functions, processes, and structures that contribute to ecological sustainability (Pastorok et al., 1997; Society for Ecological Restoration, 2004; Galat et al., 2008). Goals are scalable and may differ among and within geomorphic reaches. Eighty-one specific objectives were developed from a large list of 2,600 site-specific stakeholder objectives during a first iteration of planning (Lubinski and Barko, 2003). A second review applied a rigorous screening that combined, deleted, or amended the list of 81 (Table 1; Barko et al., 2006) to 43 objectives and made them specific, measurable, action-oriented, realistic, and timely (SMART Objectives).

The objectives list is and detailed and designed for use as an organizing feature in a Decision Support System (Barko et al., 2006). The list is generalized to a bare minimum and presented in Table 1, objectives are categorized hierarchically within EECs. Ecosystem Restoration practitioners in established River Teams will use these objectives to establish their own set of objectives for each geomorphic reach along the UMRS. Reach objectives will be combined for system scale sequencing within appropriate authorities.

Table 1. Upper Mississippi River System ecosystem objectives (Lubinski and Barko 2003).

Manage for processes that input, transport, assimilate, and output materials within UMR Basin river-floodplains: sediments and nutrients, water quality (Biogeochemistry)
Reduce contaminant loadings to the river
Reduce contaminants in the rivers
Reduce mobilization of sediment contaminants
Achieve State Total Maximum Daily Loads (TMDLs)
Reduce, maintain, or increase sediment loadings to the rivers
Reduce nutrient loading from tributaries to rivers
Reduce nutrient export from the UMR to Gulf of Mexico
Maintain adequate DO concentrations for fishes
Maintain water clarity sufficient to support submersed aquatic vegetation, aquatic invertebrates and fish species appropriate to location
Manage for processes that shape a diverse and dynamic river channel (Geomorphology)
Enhance channel geomorphic diversity
Modify the channels and floodplains of tributary rivers
Increase the extent and number of sand bars
Increase the extent and number of mud flats
Increase the extent and number of gravel bars
Increase the extent and number of islands
Increase the extent and number of rock and gravel riffles and substrate areas
Increase topographic diversity and elevation of floodplain areas
Modify delta areas
Modify exchange between channels and floodplain areas
Modify exchange between channels and floodplain areas floodplain areas
Modify contiguous backwater areas
Increase the number and extent of isolated floodplain lakes
Manage for a more natural hydrologic regime (Hydrology and Hydraulics)
Naturalize hydrologic regime of main-channels
Reduce stage and discharge fluctuations caused by dam operation
Restore a more natural hydrologic regime in the navigation pools
Restore a more natural hydrologic regime in floodplain waterbodies
Naturalize hydrologic regime of tributaries
Increase storage and conveyance of flood water on the floodplain
Reduce wind fetch in open water areas
Manage for a diverse and dynamic pattern of habitats to support native biota (Habitat)
Provide desirable pattern of hydraulic conditions in tailwaters for fishes
Provide pathways for animal movements
Modify the extent, patch size and succesionnal variety of plant communities
Modify the extent, abundance and diversity of submersed aquatic plants
Modify the extent, abundance and diversity of emergent aquatic plants
Restore and maintain large contiguous patches of plant communities
Modify backwaters to provide suitable habitat for fishes
Modify channels to provide suitable habitat for fishes
Increase habitat corridor sizes and connectivity
Increase vegetated riparian buffers along tributaries and ditches in the floodplain
Increase woody debris in channels
Manage for viable populations of native species and diverse plant and animal communities (Biota)
Maintain viable populations of native species throughout their range in the UMRS at levels of abundance in keeping with their biotic potential
Maintain the diversity and extent of native communities throughout their range in the UMRS
Reduce the adverse effects of invasive species on native biota

CHAPTER 2: CAN GEOMORPHIC LANDSCAPE PATTERNS BE DEFINED FOR THE UPPER MISSISSIPPI RIVER SYSTEM?

Geomorphology has been a determinant of human use of the Upper Mississippi River (UMR) region for thousands of years. Archeologists use information regarding the relative age and location of geomorphic formations to predict the likelihood of occurrence of archeological remains. A large scale geomorphic survey of Landform Sediment Assemblages (LSA) of the entire UMRS was conducted to support archeological site classification and identification (Bettis et al, 1996; Madigan and Schirmer 1998; Hajic, 2000). The data may also be applicable for ecological investigations because of the strong relationships among geomorphology, soils, hydrology, and plant communities which are then strong determinants of animal use expected in an area.

I consider the glacial origin of the UMRS and the landscape transition through the Holocene to modern conditions to support this landscape analysis (Malanson, 2003; Clarke et al., 2003; Stallins, 2006). My work identifies river reaches of distinct geomorphic formation that influence hydrology, natural landscapes, and human development activity. Changes to the hydrogeomorphology (Clarke et al., 2003; Newson, 2006) of the UMRS since the end of the Civil War are comparable in scale to the area of influence of catastrophic glacial disturbances. Individually, each human action is relatively insignificant, but multiple, cumulative effects of human activity have resulted in significant geomorphic and ecological changes in the UMRS river-floodplain and in other rivers around the world (Tockner and Stanford , 2002). The 60 years (1880 to 1940) of large-scale UMRS development which centered around large Federal public policy and civil works projects is not nearly as instantaneous as a glacial torrent (Clayton and Knox, 2008), yet it is rapid in the scale of geologic time. The combined effects of upland development, flood protection, and the navigation system have altered geomorphic and hydrodynamic characteristics of the entire UMRS river-floodplain system.

Physical Setting

Boundary Conditions

The Upper Mississippi River drains about 189,000 mi^2 (490,000 km^2) excluding the Missouri River basin (529,000 mi^2, 1,370,000 km^2) that joins the Mississippi River at Mississippi River Mile (MRM) 178 (km 286) at St. Louis, Missouri (see Figure 1). It is a large regional watershed draining 20 percent of the United States (see Figure 1). Floodplain features are the result of the Pleistocene geology, glacial processes, and Holocene evolution creating great geomorphic, hydric, and soil diversity from upstream to downstream and across the channel-floodplain gradient. Glacial processes created distinct geomorphology that has become part of the social and environmental management structure on the UMRS. Lubinski (1993, 1999) defined a floodplain classification scheme with the System broken into four Floodplain Reaches.

UMRS Floodplain Reaches are defined by geologic structures and rock strata of variable erosional resistance that, in combination with repeated glaciation, creates great reach variability in river-floodplain geomorphic characteristics (Knox and Schuum in WEST Consultants, Inc. 2000). The upper river valley was cut through resistant Paleozoic marine carbonates and sandstones to create a deep, narrow valley. The reach has steep valley walls and is highly influenced by groundwater and cool, clear tributary inflow. The reach below Muscatine, Iowa has greater lithologic variation including Pennsylvanian sandstone intersecting carbonates in gorges. Repeated inundation formed terraces which are prominent upstream, but become buried under alluvium in a wide valley below Qunicy, Illinois (Bettis et al., 2008). Holocene geomorphology is most influenced by the Wisconsin Ice Age ending ~10,000 BP (before present).

The reaches roughly track the Driftless Area (Upper Impounded Reach), the ancient Iowa/Mississippi from Muscatine to the Missouri confluence (Lower Impounded Reach), the Middle Mississippi below the Missouri River (Unimpounded Reach), and the Lower Illinois River (Figure 8; Table 2). An expert review of large scale geomorphology further refined the classification to identify 10 geomorphic reaches on the Mississippi and 2 on the Illinois River (Table 2, Knox and Schumm in WEST Consultants, Inc., 2000). My analysis defines the reaches at their geomorphic breakpoints (Figures 9 and 10; Table 2) rather than navigation pools as was common in prior work.

The hierarchical scheme is convenient to examine landscapes in the Holocene more closely. Geomorphic characteristics and response to development are similar within Geomorphic Reaches, but as the river gets larger and the floodplain wider in the downstream direction human use changes and river response to development differs considerably. Contemporary land use exhibits a gradient from significant dam effects but little floodplain agriculture in the north to less apparent dam effects and substantial floodplain agricultural development in the south. There are many natural and constructed features that determine the contemporary UMRS hydrogeomorphology (WEST Consultants, Inc., 2000; Theiling et al., 2000).

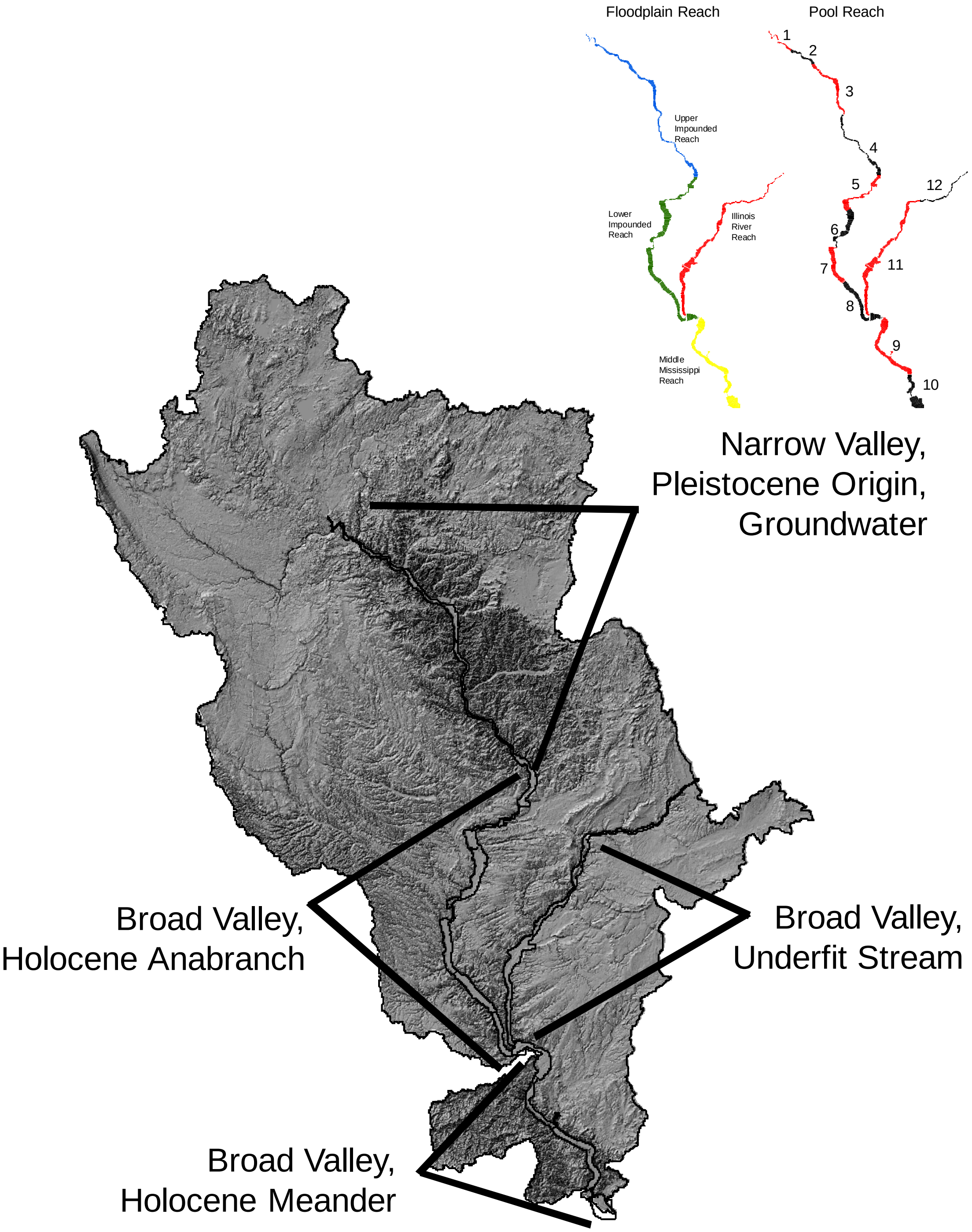


Figure 8. Upper Mississippi River and Illinois River reaches are defined by Pleistocene geology in the north and glacial and Holocene evolution in the south. Inset defines reaches.

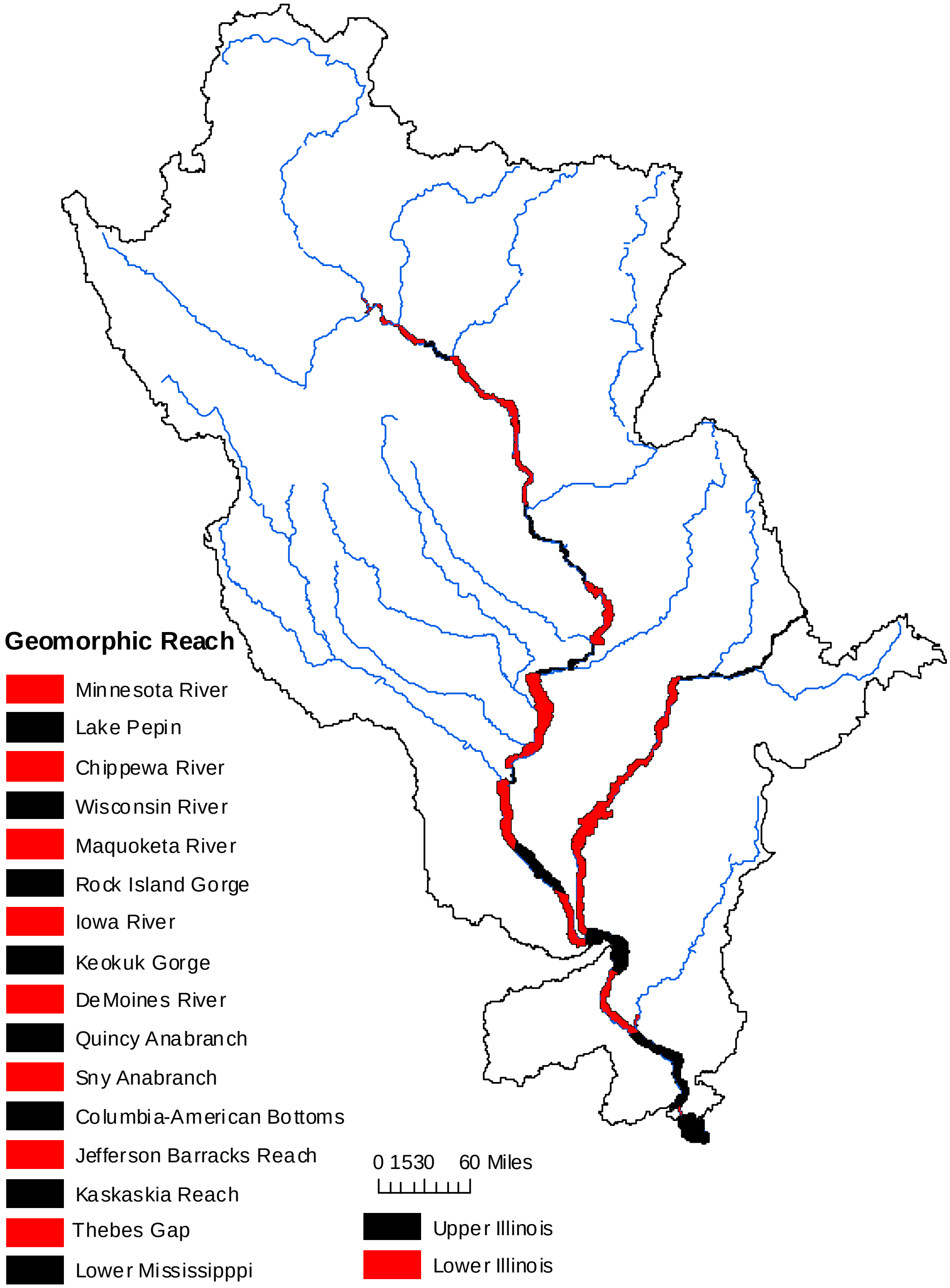


Figure 9. Upper Mississippi River System geomorphic reaches. Legend is listed in downstream order of reaches in alternating red and black bands.

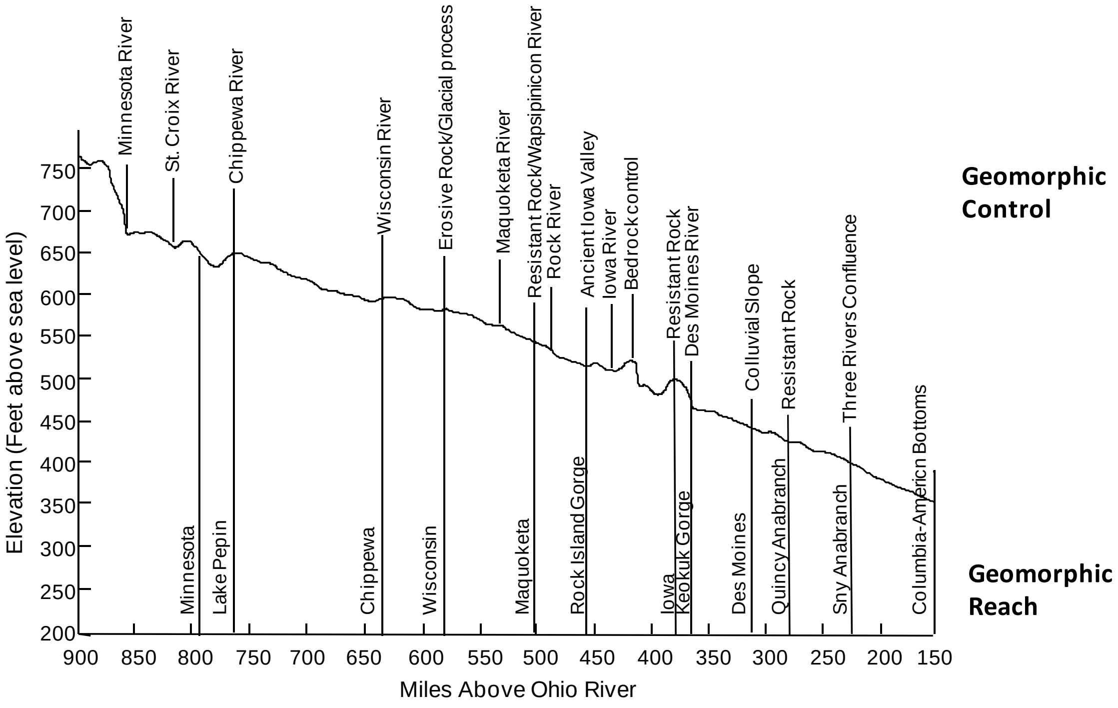


Figure 10. Upper Mississippi River thalweg profile with geologic controls listed along the top and geomorphic reaches listed along the bottom.

Table 2. River reach classifications commonly used on the Upper Mississippi River.

River	Floodplain Reach	District	Pool Reach	Geomorphic Reach (River Mile)	Lock & Dam	Dam Location (River Mile)
Upper Mississippi River	Upper Impounded Reach	St. Paul	N/A	N/A	USAF	854.7
					LSAF	853.4
			1	Minnesota River - MN (786 - 858)	1	847.6
					2	815.2
					3	796.9
			2	Lake Pepin - LP (766 - 785)	4	752.8
			3	Chippewa River - CR (634 - 765)	5	738.1
					5A	728.5
					6	714.3
					7	702.5
					8	679.2
					9	647.9
			4	Wisconsin River - WR (558 - 633)	10	615.1
		Rock Island			11	583.0
					12	556.7
				Maquoketa River - MR (503 - 557)	13	522.5
	Lower Impounded Reach		5		14	493.3
				Rock Island Gorge - RI (456 - 502)	15	482.9
					16	457.2
				Iowa River - IA (375 - 455)	17	437.1
			6		18	410.5
				Keokuk Gorge - KG (364 - 375)	19[b]	364.2
			7	Des Moines River - DM (315 - 363)	20	343.2
					21	324.9
				Quincy Anabranch - QA (268 - 314)	22	301.2
		St. Louis	8	Sny Anabranch - SA (229 - 267)	24	273.4
					25	241.4
				Columbia-American Bottoms - AB (177 - 228)	Mel Price	201.1
	Unimpounded Reach		9 & 10		N/A	0.0
				Jefferson Barracks - JB (122 - 176)		
				Kaskaskia River - KR (48 - 121)		
				Thebes Gap - TG (41 - 47)		
				Lower Mississippi - LM (0 - 40)		
Illinois Waterway (Illinois & Des Plaines Rivers)	Illinois Reach	Rock Island	11	Upper Illinois - UI (216 - 327)	Lockport	291.0
					Brandon Road	286.0
					Dresden Island	271.5
					Marseilles	247.0
					Starved Rock	231.0
			12	Lower Illinois - LI (0 - 215)	Peoria	157.7
					LaGrange	80.2
		St. Louis			Mel Price	0.0

The Holocene

Climate transition during the Holocene shifted the river's water source from steady clear-water lake outflows punctuated by episodic catastrophic breakout events to an interglacial mode of regional weather control on water and sediment discharge (Bettis et al., 2009). The river assumed an island-braided form of coarser sediments in channels and overbank floodplain sedimentation shifted to finer material as river discharge and sediment transport energy dropped when glaciers melted and river flow variability decreased (Bettis et al., 2009). Early to middle Holocene overbank flooding was focused in abandoned glacial channels, similar to contemporary floodplain overflow channels, which filled with sediment first (Bettis et al., 2009) and later became undifferentiated from other floodplain areas as the rivers settled into a narrower channel belt. Channel meanders below the Missouri River decreased in amplitude with reduced discharge and sediment transport and left elaborate meander scroll morphometry and many oxbow lakes. Channel position throughout the river has been relatively stable except at tributary alluvial fans since about 7,000 years BP (Bettis et al., 2008). Sand bars, shoals, and islands were annually transient in active channels in the Middle Mississippi River (Collot, 1826), but some islands on the upper river are thousands of years old (Knox, 2006).

Climate

Climate is a boundary condition that dictates rainfall patterns and hence annual and seasonal discharge. Several climate shifts have occurred in the UMRS since glacial retreat (Knox, 1993) and there are expectations for future shifts (US Global Change Research Program, 2000; Gutowski, 2008). Discharge and large floods have generally increased basin-wide since the 1930s (Figure 11; Changnon, 1983; Knox, 1993; Wlosinski, 1999; Zhang and Schilling, 2006).

At large scales plant community composition in the UMRS is structured by climatological gradients interacting with conditions across seven ecoregions (Omernik, 1987). At smaller scales, local channel and floodplain morphology and hydrology determines the distribution of floodplain and riparian plants (Junk et al., 1989; Sparks, 1995; Nelson et al., 1996; Poff et al., 1997; Ward et al., 1999). The UMR basin has a sub-humid to humid continental climate. It is characterized by cold, dry winters and warm to hot, moist summers. Average annual precipitation in the basin varies from about 24 inches in the northwest to about 45 inches in the southeast. About three-quarters of total annual precipitation over the basin occurs between April and September. Flooding is seasonal and associated with spring snowmelt and rainfall, but summer floods do occur. The Missouri River is an important influence at downstream from St. Louis, Missouri. Flow on the Missouri is Bimodal with a spring rain and snowmelt peak followed by a mountain snowmelt peak (Hesse et al., 1989). Typically, average monthly temperatures in the basin are lowest in January and highest in July. Climate has calmed through the Holocene, historic annual floods were more similar to our infrequent extreme events (Knox, .1984, 1996).

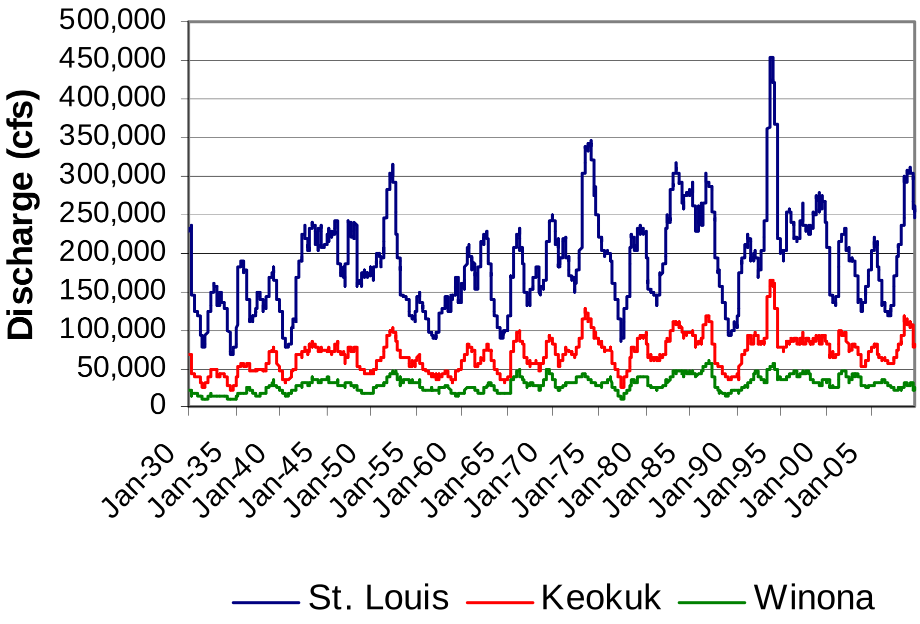


Figure 11. Long term 3-year moving average discharge (cubic feet per second, cfs) for gauges in the upper (Winona), middle (Keokuk), and lower (St. Louis) regions of the Upper Mississippi River System.

Contemporary Conditions

Upper Mississippi and Illinois River basins and tributaries have been logged, plowed, and channelized to support regional development and intensive corn and soybean row crop agriculture. More than 80 percent of the total basin area is developed, predominantly by agriculture (over 60%; Gowda, 1999; USEPA, 2008). As much as 26 million acres of wetlands have been drained in the Upper Mississippi and Missouri River Basins (Hey and Philippi, 1995). Illinois and Iowa have each lost 95% of their presettlement wetlands (Dahl, 1990). Land grading and clearing, tile drainage systems, ditches, and stream channelization all contribute to an increased rate of water delivery from the basin to the main stem rivers (Sparks, 1992; DeMissie and Khan, 1993; Sparks et al., 1998; USEPA, 2008). Development in the Upper Mississippi and Illinois River watershed contributes to the formation of a large hypoxic zone in the Gulf of Mexico, and the states of Illinois and Iowa are the greatest contributors of nutrients driving the hypoxia (USEPA, 2008).

Median long-term discharge in the main stem Mississippi River increases from 32,000 cubic feet per second (cfs) (905 cubic meters per second (cms)) at MRM 725, Winona, Minnesota (km 1166) to almost 200,000 cfs (5,600 cms) south of the Missouri River confluence (Figure 12). The Illinois River proper flows 273 mi (439 km) to the confluence with the Mississippi River, but the entire Illinois Waterway (including tributaries and canals linking it to Lake Michigan) is 327 mi (526 km) long (see Figure 8). Median discharge in the Lower Illinois River is 28,500 cfs (803 cms) (Figure 12). The Upper Mississippi River floodplain widens from 1 – 3 mi (2 – 5 km) wide north of MRM 452 (km 728) in Minnesota and Wisconsin to 5 – 7 mi (8 – 11 km) wide from MRM 452 to MRM 178 (km 728 to km 286) in Iowa, Northern Missouri, and Illinois, and 7 – 10 mi (11 – 16 km) wide south of MRM 178 (km 286; see Figure 8) in Southern

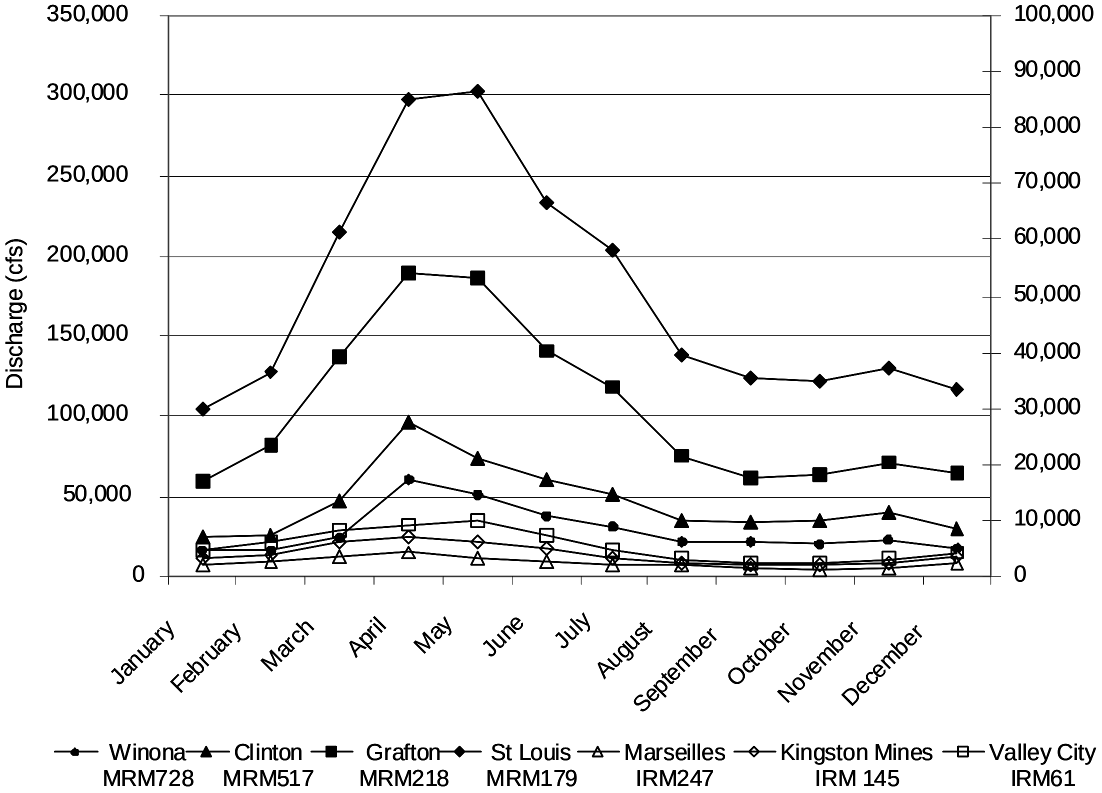


Figure 12. Average annual discharge at gauges throughout the Upper Mississippi River System.

Illinois and Missouri. The Lower Illinois River floodplain is 4 – 5 mi (6 – 8 km) wide (see Figure 8) and the river has a very low gradient (0.2 ft/mile; Fremling and Claflin, 1984; Starrett, 1972).

Steam mechanization in the late 19th Century enabled large scale floodplain wetland conversion to agriculture (Thompson, 2002). Local cooperatives and government support have evolved over time to various levels of organization on the UMRS as opposed to uniform Federal flood protection on the Mississippi River south of St. Louis, Missouri. The distribution of isolated floodplain area (see Figure 2) relative to historically connected floodplain area among major river reaches is:

• Pools 1 – 13	3%
• Pools 14 – 26	50%
• Unimpounded Reach	83%
• Lower Illinois River	61%.

Levees prevent lateral animal migrations, disrupt important energy pathways, concentrate sediments, and increase moderate flood peaks and stage variation (Belt, 1975; Bellrose et al., 1983; Ward and Stanford, 1983; Bailey, 1991). Levees in southern river reaches have been shown to increase flood stages and restrict the flood zone (Belt, 1975; Chen and Simons, 1986; Pinter et al., 2000).

The cross-sectional distribution of surface and ground water across the floodplain is related to river stage, and it changes in response to development like mainstem channelization (Chen and Simmons, 1986; Franklin et al., 2003; Brauer et al., 2005), levees (Thompson, 2002; USACE, 2006), and mainstem impoundments (Figure 13; Grubaugh and Anderson, 1988; Fremling et al., 1989; WEST Consultants, Inc, 2000; Franklin et al., 2003) also helps characterize the reaches. Surface water flow is

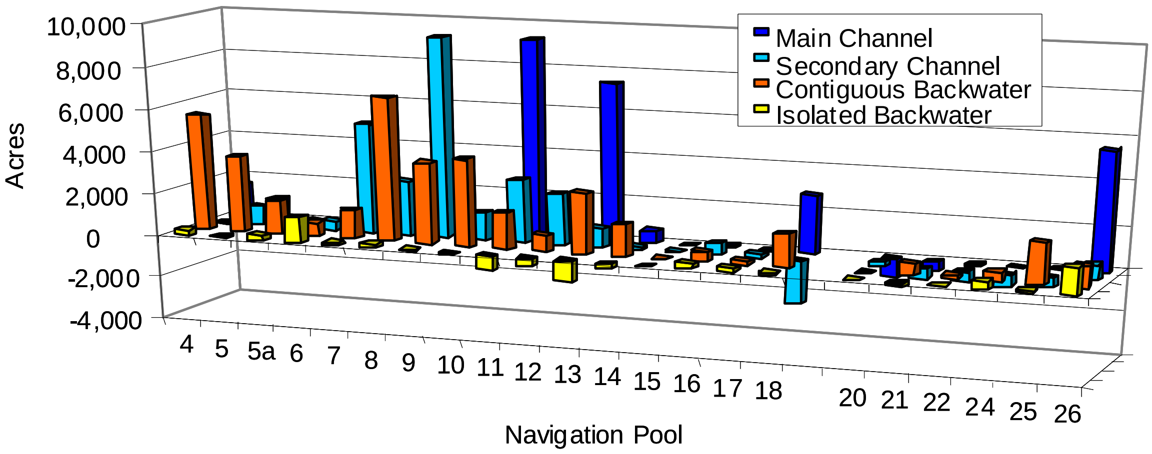


Figure 13. Contemporary aquatic habitat distribution relative to pre-dam condition in Upper Mississippi River navigation pools 4 to 26, excluding 19.

distributed among main channels, side channels, bars, islands, backwaters, and floodplains to create diverse aquatic conditions that can be classified, measured, and compared as surface area, mean depth, mean current velocity, susceptibility to wind-waves, and other parameters.

The Upper Mississippi River navigation system evolved over 100 years of incremental development that culminated in the construction of 29 locks and dams on the Mississippi River and 8 on the Illinois River during the 1930s (see Figure 1; Anfinson, 2003; WEST Consultants Inc., 2000). Navigation dams are used to increase low and moderate discharge water surface elevations to the 9-ft. (2.7 m) depth necessary for modern commercial towboats and barges. UMRS navigation dams do not hold back flood water during high flows and consequently cannot affect flood discharge. Substantial differences in surface water response to impoundment occur among river reaches and within pools (see Figure 13), but dams effectively remove the low signals of the annual stage hydrograph without affecting the high signals. Surface water distribution among aquatic areas (i.e., channels and backwaters; see Figure 13; Wilcox, 1993) are substantially altered by river regulation in northern river reaches and relatively little changed in southern reaches. River stage and discharge relationships are also affected to different extents depending on location in the system (WEST Consultants, Inc., 2000; Brauer et al., 2005; Theiling and Nestler et al., 2010). Groundwater levels, flooding, and soil permeability determine the distribution of isolated floodplain lakes. Groundwater dynamics have been highly altered by low head navigation dams and extensive levee and drainage district systems to support floodplain agriculture in the southern reaches of the river (Thomson, 2002; USACE, 2006).

Landform Sediment Assemblages

My analysis combines Landform Sediment Assemblage (LSA), large-scale geomorphic mapping units from four separate archeological investigations (Bettis et al., 1996; Madigan and Schirmer, 1998; Hajic, 2000, Hajic, unpublished) into a common ecologically relevant classification for the entire river system (Table 3). Landform Sediment Assemblages consist of mappable landforms and their underlying deposits that occur in ordered and predictable sequences of characteristics (Hajic, 2000). Soil sequences can be dated and related to other characteristics of the landscape (Hajic, 2000). They were developed to help identify locations of cultural artifacts, but the landscape characteristics used in the classification are well suited for ecological investigations also.

Geomorphic mapping in the valley has followed the general protocol defined by Bettis et al. (1996) with slight regional variations. The methods in most cases are a first approximation and open to further interpretation, as are my results presented herein. Mississippi River mapping in the Rock Island and St. Louis, Missouri Districts were low resolution investigations devised to age landforms for their origin and age. Hajic (1990) completed a detailed investigation of the Illinois River and adapted the results to the LSA scheme (Hajic, 2000). Work in the St. Paul District Mississippi River was intermediate in resolution with distinctions for vertical and lateral accretions that helped assess water retention and soil moisture. Mapping under modern aquatic areas was not possible, so most of the low elevation features (active floodplain and some paleo-floodplain) were inundated in the lower ends of navigation pools. I took the individual district-scale LSA data sets and unioned and reclassified them using a common ecological class scheme in GIS. The data were clipped to the extent of the 2000 LTRMP land cover extent which was delineated to the base of the bluffs using aerial photography (LTRMP, 2008).

Table 3. Habitat characteristic cross-referenced to four separate geological survey landform classifications.

	St. Paul		Rock Island		St. Louis		Illin
Habitat Characteristics	Code	Landform	Code	Landform	Code	Landform	Code
Modern Channel	MCMR	Main Channel	Mississippi River	Channel			
Modern Backwater	MVC	Lake	Mississippi River				
	W	Water					
Active Floodplain - Wet	MVM	Marsh	TRIFA	Tributary Floodplain	LAHOL	Active Floodplain	F
Frequently Flooded, Poorly Drained	MVU	Floodplain	ISLAN	Main Channel Island			FP
silt-loam-clay grading to sand and	TF	Tributary Floodplain	LAHOL	Active Floodplain			FC
pebbly sand	TFD	Tributary Fan/Delta			TRIFA	Tributary Floodplain	I
Inundated in lower part of most pools							
Active Floodplain - Dry	MLB	Scroll/Bar					AF
Frequently Flooded, Well Drained	MCI	Main Channel Island					DE
abandoned sand bars, channels over	TY	Tributary Meander Belt					
pebbly sand,	TAF	Tributary Alluvial Fan					
Paleo-Floodplain - Wet	IVM	Inactive Marsh/Slough	EMHOL	Inactive Floodplain	CBIB	Inactive Floodplain	CBO
Infrequent Flooded, Poorly Drained	IVS	Inactive Lake			CBLMB		FB
silt-loam-clay grading to sand and	IVU	Inactive Floodplain			CBLMC		FS
pebbly sand	IC	Inactive Channel			EMHOL		
Inundated in northern pools							
Paleo-Floodplain - Dry	ILB	Inactive Scroll/Bar	YAZOO				CS
Infrequent Flooded, Well Drained,	ICI	Inactive Minor Channel Island					CB
sand, mixed alluvium under silt-loam							CSP
cap							FD
Natural Levees	UH	Hilltops	LEVEE	Natural Levee			
Natural Levees and High Spots	MVL	Natural Levee					
cross-bedded loam, slay, silt sand							
Colluvial Slope	TS	Tributary Scarp	FANCO	Colluvial Slope	FANCO	Colluvial Slope	CA
Steep fingering over other LSAs	VCS	Colluvial Slope					CB
Upward fining soil							
Glacial Terrace	EDT	Dunes Over Terrace	CUIVER	High Terrace	SAVAN	Intermediate Terrace	B
High, Flat, and Dry	GSC	Glaciofluvial Channel	GILEAD		STCHG		D
Mixed soil: loess to gravel till,	GSS	Glaciofluvial Scarp	SAVAN	Intermediate Terrace	TMOAF1		ER
aeolian dunes, fining toward channel	GTH	High Terrace			TMOAF2		ST
and downstream	GTL	Low Terrace					FE
	GTM	Intermediate Terrace					MC
	TVT	Tributary Valley Terrace					OB
							P
							T

The ecology-based geomorphic classification I developed has nine classes (Table 3, Figure 14). Characteristics were derived from Bettis et al. (1996), Madigan and Schirmer (1998), and Hajic (2000) as follows:

- **Modern aquatic classes** (Modern Channel, Modern Backwater) range from a few hundred to over 1,800 acres per river mile (Figure 15). Aquatic area is <500 acres except at Illinois River miles where large lakes occur and on Mississippi River miles where impoundment effects are pronounced. Modern aquatic area covers a considerable proportion of the floodplain in the northern one-half of the Upper Mississippi River (Figure 15). Impoundment inundated low elevation active and paleo-floodplain geomorphic classes leaving levees exposed as islands in impounded aquatic areas and terraces laterally. Aquatic area is generally <10 percent of the total floodplain area in the south, but 20 to 60 percent in the north.

- **Active Floodplain – Wet** is frequently flooded low elevation floodplain of vertical accretion origin. Soils are likely silt, loam, clay mixes that grade downward to coarser sand and pebbly sand. Fine sediments may be 1 – 2 meters deep over coarser sediment. These surfaces are likely inundated in the lower portions of all navigation pools. Some of these areas occur riverward of the flood control levees, some are protected by levees, and both occur at tributary fans. They are most abundant in the mid valley Mississippi River reaches and lower Illinois River, but that is due to impoundment effects not so pronounced in these reaches and to agricultural drainage districts (Figure 15). These geomorphic classes are of late Holocene origin.
- **Active Floodplain – Dry** is frequently flooded low elevation floodplain of lateral accretion origin. It is of Late Holocene fluvial origin and likely to have sand and gravelly sand overlaid by finer alluvium. Despite high frequency inundation, it does not retain water. Dry active floodplain may also be associated with alluvial

fans and deltas. Dry active floodplain is common on the Illinois River and occurs in patches in the St. Paul District (Figure 15). The class was not mapped in the Rock Island and St. Louis, Missouri Districts.

- **Paleo-Floodplain – Wet** is infrequently flooded mid elevation floodplain of vertical accretion origin. These floodplain areas contain former channel and lake features that have transitioned to terrestrial area. Soils are variable with fine silt, loams, and clays overlying pebbly sand. These areas are of early to middle Holocene origin (Figure 15).
- **Paleo-Floodplain – Dry** is infrequently flooded mid elevation floodplain of lateral accretion origin. These floodplain areas include inactive scrolls, bars, meander belts, and splays. Soils are variable with fine silt, loams, and clays overlying sand channels and pebbly sand. These areas are of early to middle Holocene origin. Paleo-Floodplain is mapped mostly in the Rock Island and St. Louis, Missouri Districts (Figure 15). In the Rock Island District it is an association with early and mid Holocene surfaces that define the wet areas and paleo-channels that derive the dry areas (Table 3). In the St. Louis, Missouri District ancient meander scrolls comprise these areas (Table 3) and are a major proportion of the floodplain area (Figure 15). There is almost no paleo-floodplain in the St. Paul District because of the frequent reworking of the alluvial substrate in the valley floor. Older surfaces in the St. Paul District occur as terraces.
- **Natural Levees** are naturally adjacent to many channels (Leopold et al., 1964). They develop as heavier sediment drops out of suspension adjacent to the channel when current velocity drops in overbank areas. Levees are typically planar, cross-bedded loam, sand, silt, clay, and pebbly sand. Many are discontinuous linear features, but crevasse splays can cause variations. Levees are most abundant on the Illinois River (Figure 15). This is a matter of data resolution because the Illinois River geomorphology was investigated in more detail (Hajic, 1990).

Several large levee patches are mapped in the Rock Island District and they are common along the channel in the St. Paul District where they are not submerged.

- **Colluvial Slopes** are at the valley margin where material runs off, slumps, or slides from the buffs to the valley floor. The slopes may be many tens of meters thick with the youngest material on top and away from the bluff. Material is graded with coarse material at the bottom. It can be a quite xeric environment. Colluvial slopes are at all valley margins, but they may not be mapped along the entire length. The most notable abundance of slopes occur in Illinois near Quincy where there are other high floodplain features (Figure 15).
- **Glacial Terraces** occur throughout the river and are related in age and height sequences to glacial processes (Knox and Schumm in West Consultants, Inc., 2000). They are most abundant in the Illinois, Minnesota, Chippewa, Maquoketa, and Iowa River reaches where outwash and glacial lake drainage events most impacted the floodplain (Figure 15).

Geomorphic Characterization

Geomorphic Reaches

Geomorphic classes were mapped and summarized by river mile (Figure 15), but the river system is so large it is difficult to display in a single map image (see Figure 14). Individual geomorphic reaches are discussed and presented in maps and charts in Appendix A. These geomorphic reach definitions are a refinement of the classification defined by Knox and Schumm (in WEST Consultants, Inc., 2000). Knox and Schuum examined a river bed profile and regional geology to identify changes in the slope and the probable cause. They identified ten reaches on the Mississippi River and 2 on the Illinois River using navigation dams as break-points. I refine the classification to more closely locate reach divisions at their geomorphic control, which was either a tributary or change in bedrock composition. The Illinois River reach classification could be further refined to at least three, and perhaps 5, reaches.

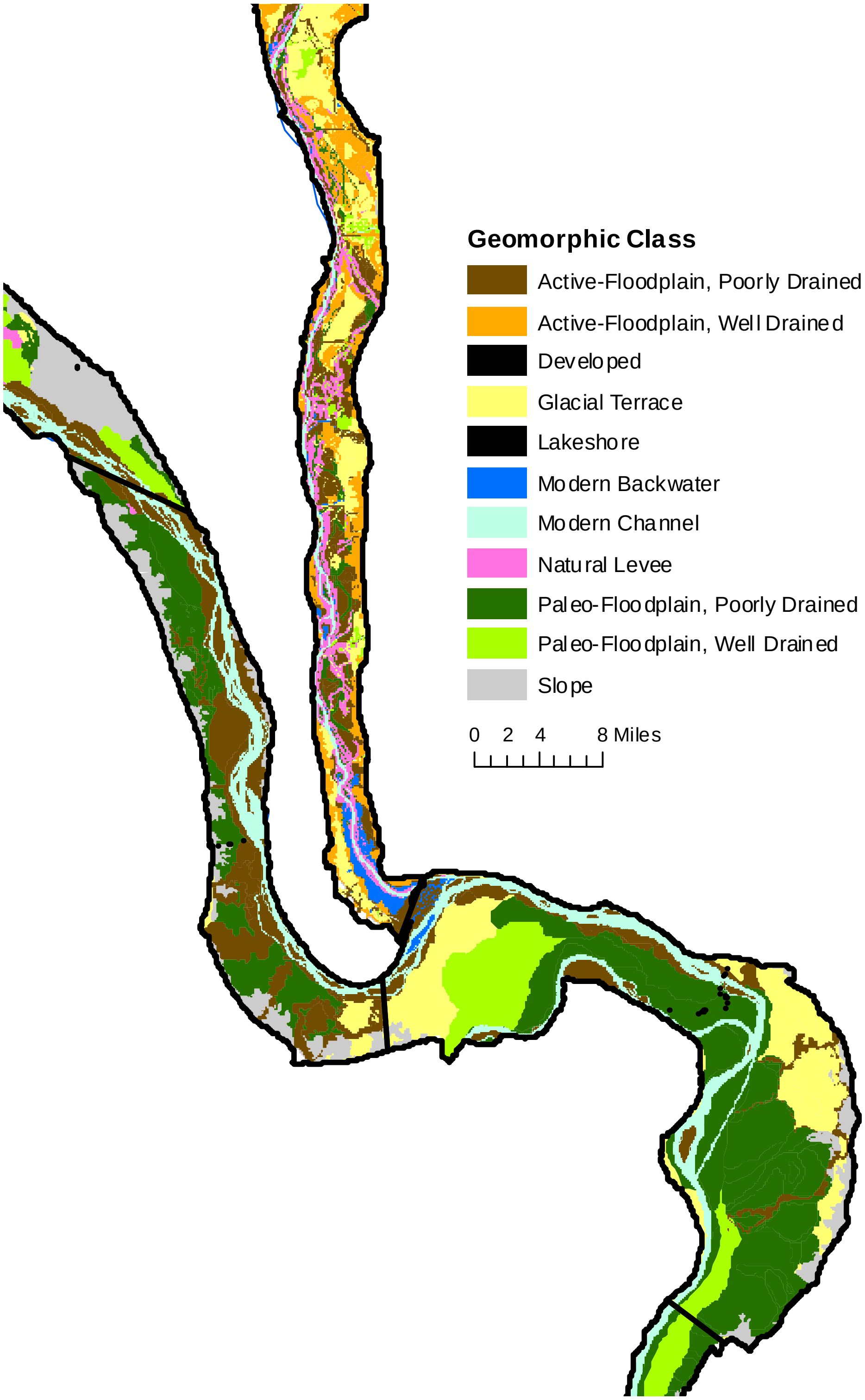


Figure 14. Geomorphic classes in river reaches at the confluence of the Illinois, Mississippi, and Missouri Rivers.

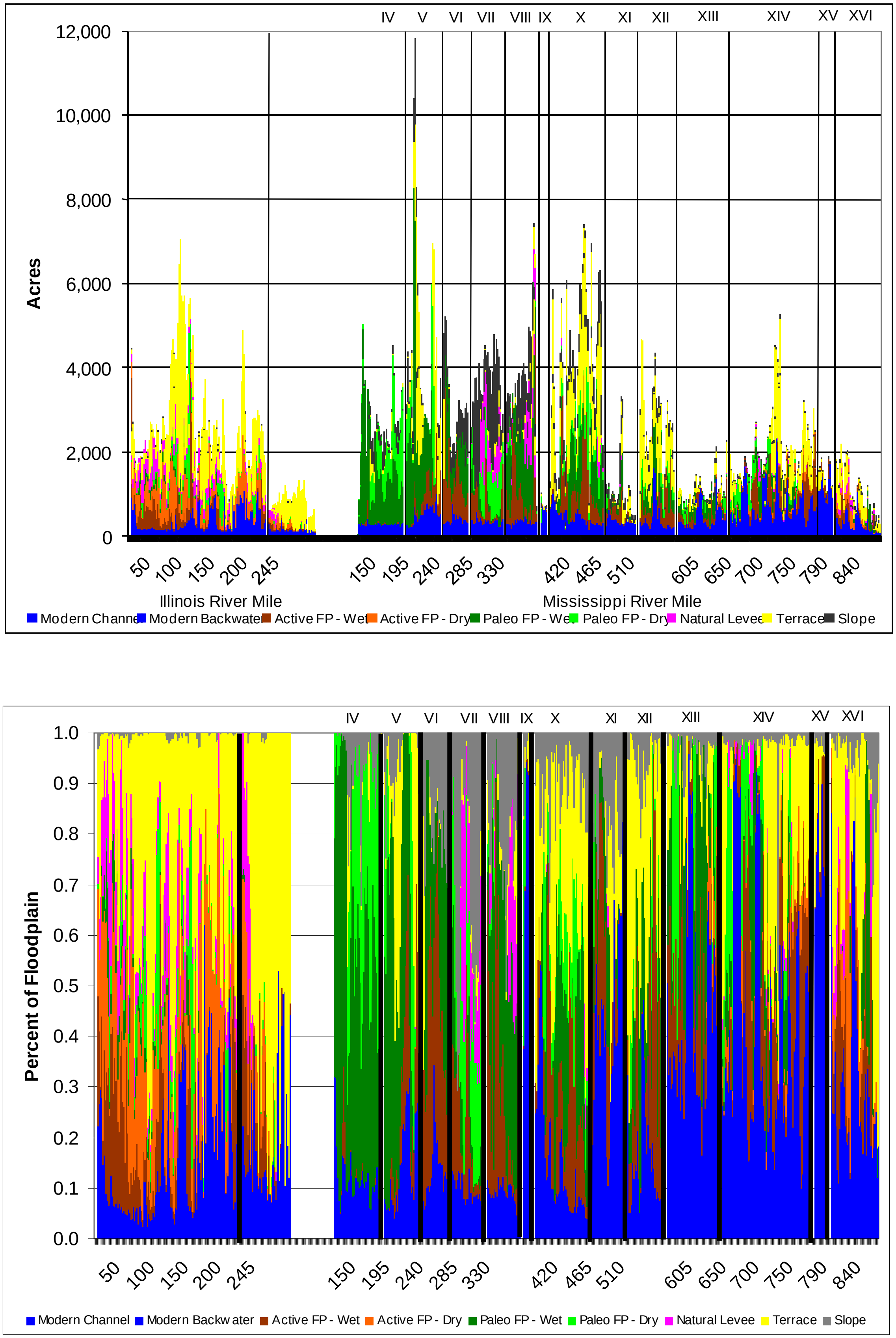


Figure 15. Geomorphic class distribution by river mile.

Geomorphic Area Spatial Ordination Analysis

I converted the GIS LSA vector coverage to raster, and extracted each class as a separate raster layer. Each UMRS LSA class was summarized and entered into a spreadsheet of LSA class by geomorphic reach. I also extracted geomorphic classes by a mask of UMRS levees to assess changes from floodplain development. The geomorphic classes in leveed areas were subtracted from each geomorphic reach total extent and reclassed as total leveed area regardless of LSA class. I used the Multivariate Statistical Package (MVSP, Kovach Computing, Inc., 2008) where geographic relationships among large LSA classes and UMRS geomorphic reaches were explored using correspondence analysis (see Methods in Chapter 1). Modern main channel and modern backwater classes were excluded from analysis because they inundate and mask the true geomorphic surface. Excluding these classes is most pronounced in the Minnesota River and Chippewa River geomorphic reaches where impoundment effects were greatest. Cluster analysis was used to explore similarity among reaches and also among time periods (see Methods in Chapter 1).

Cluster analysis of the entire LSA data set spatial extent was conducted to assess the natural distribution of geomorphic surfaces. The analysis revealed a group of geomorphic reaches with broad valleys in the central and southern regions (Figure 16). There were several narrow valley reaches clustered in the center of the dendrogram. The Maquoketa and Chippewa Reaches are diverse in that each reach consists of both narrow and wide floodplain segments. These reaches each have zones of erosive shale and the Maquoketa Reach is the location where the Mississippi diverted back and forth to the Illinois Valley.

Correspondence analysis ordination results of LSA classes and geomorphic reaches are centered on Active Floodplain Poorly Drained (AFPD) and Paleo-Floodplain Well Drained (PFWD) which are widely distributed geomorphic surfaces established during the Holocene (Figure 17). The Middle Mississippi River Reaches at the upper left of the CA biplot are characterized by Paleo-Floodplain Poorly Drained (PFPD) which is older material settled in the broad alluvial valley below the Missouri River that has been reworked by meandering channels. Glacial Terraces (GT) and Active Floodplain Well Drained (AFWD; i.e., alluvial bars) dominate the Illinois River reaches that transported large amounts of sand in glacial torrents from the Kankakee River. The Minnesota River, Lake Pepin, and Chippewa River Reaches are distributed to the right on Axis 1 because of their abundant GTs. Natural Levees (NL) influence those reaches, the Lower Illinois, and the next set also, but Colluvial Slopes (SLOP) most influence the Quincy Anabranch, Keokuk Gorge, Rock Island Gorge, Des Moines, and Sny Botttoms Reaches.

A second cluster and correspondence analysis separated levees out of the coverage to assess changes in connected floodplain characteristics because levees account for 50 to 80 percent or more of the total floodplain area in river reaches south of Rock Island, Illinois. Isolating leveed area as a separate geomorphic class increases the homogeneity among reaches, as more reaches cluster toward the center of the CA biplot (Figure 18). Total Levee area (TOTAL_LEV) is at the center of the ordination with AFWD inferring its importance in the ordination. The Middle Mississippi River reaches, Kaskaskia River (KR), Jefferson Barracks (JB), and Columbia-American Bottoms (CB), all move down toward the origin compared to the no levee plot. Similarly, several Lower Impounded Reaches, Quincy Anabranch (QA), Sny Anabranch (SA), and Des Moines River (DM), move up toward the origin compared to the no levee plot. The importance of Colluvial Slopes (SLOP) changes with levees included, as the levees incorporate most slopes into the protected areas.

A final multivariate analysis combined the total floodplain area data with the modern connected floodplain area to assess the impacts of development among reaches. Aquatic habitats were excluded from the analysis. There was little change detected among most geomorphic reaches because six reaches clustered adjacent to each other

(Figure 19). These included the gorges, Lake Pepin, and other narrow reaches. The Lower Illinois and Iowa River Reaches did not separate too far. The remaining reaches in the Lower Impounded Floodplain Reach further south showed the most separation between their pre-development and contemporary characteristics (Figure 19). The cluster analysis confirmed the lack of change with most reaches falling very close together for both analysis periods (Figure 19). The sites that separated in the cluster analysis separate in the CA biplots also (Figure 20).

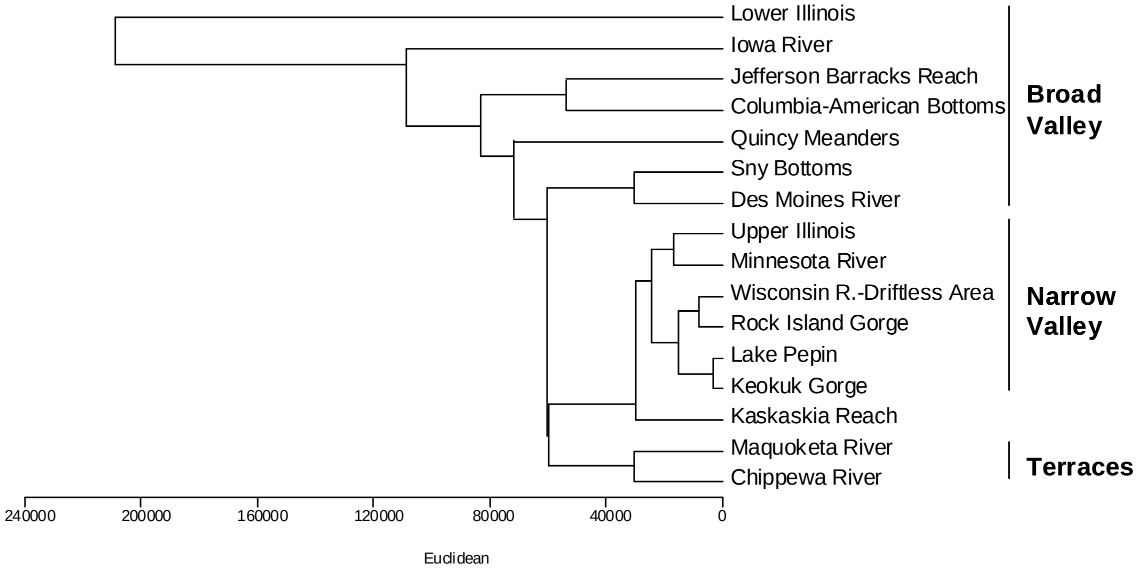


Figure 16. Cluster analysis of Upper Mississippi River geomorphic reaches based on their Landform Sediment Assemblage geomorphic characteristics.

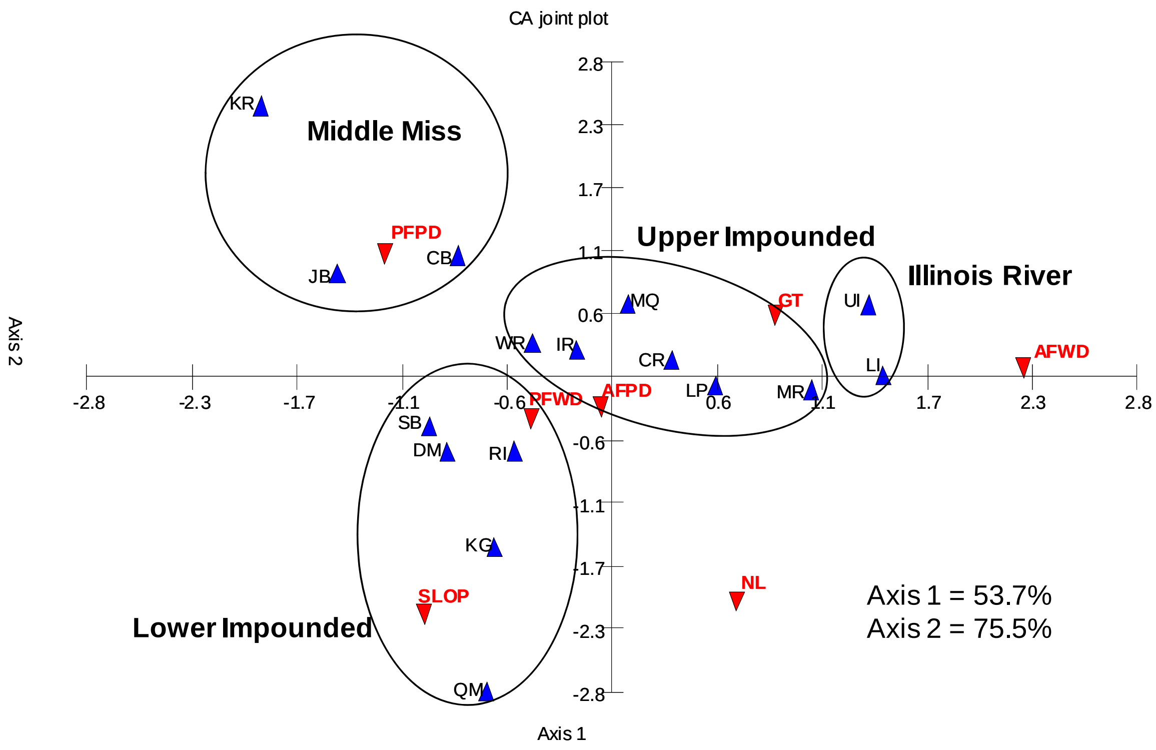


Figure 17. Landform Sediment Assemblage unit correspondence analysis among geomorphic reaches. Abbreviations as in text and Table 2.

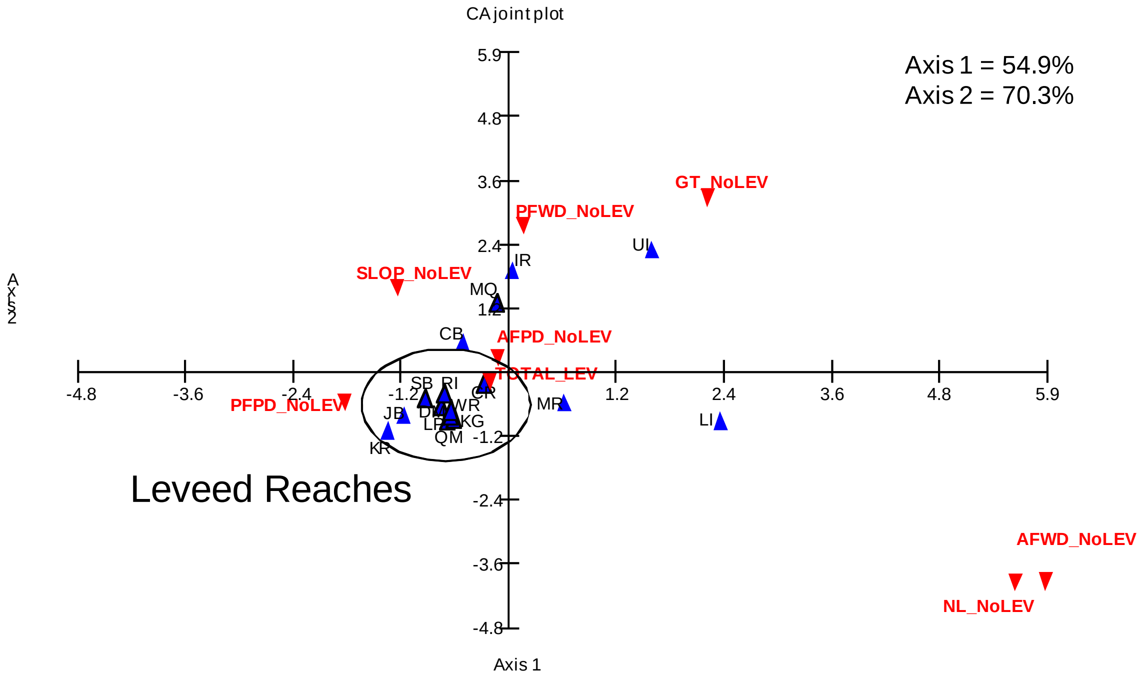


Figure 18. Landform Sediment Assemblage units with leveed areas classified separately (TOTAL_LEV) for correspondence analysis among geomorphic reaches. Abbreviations as in text and Table 2.

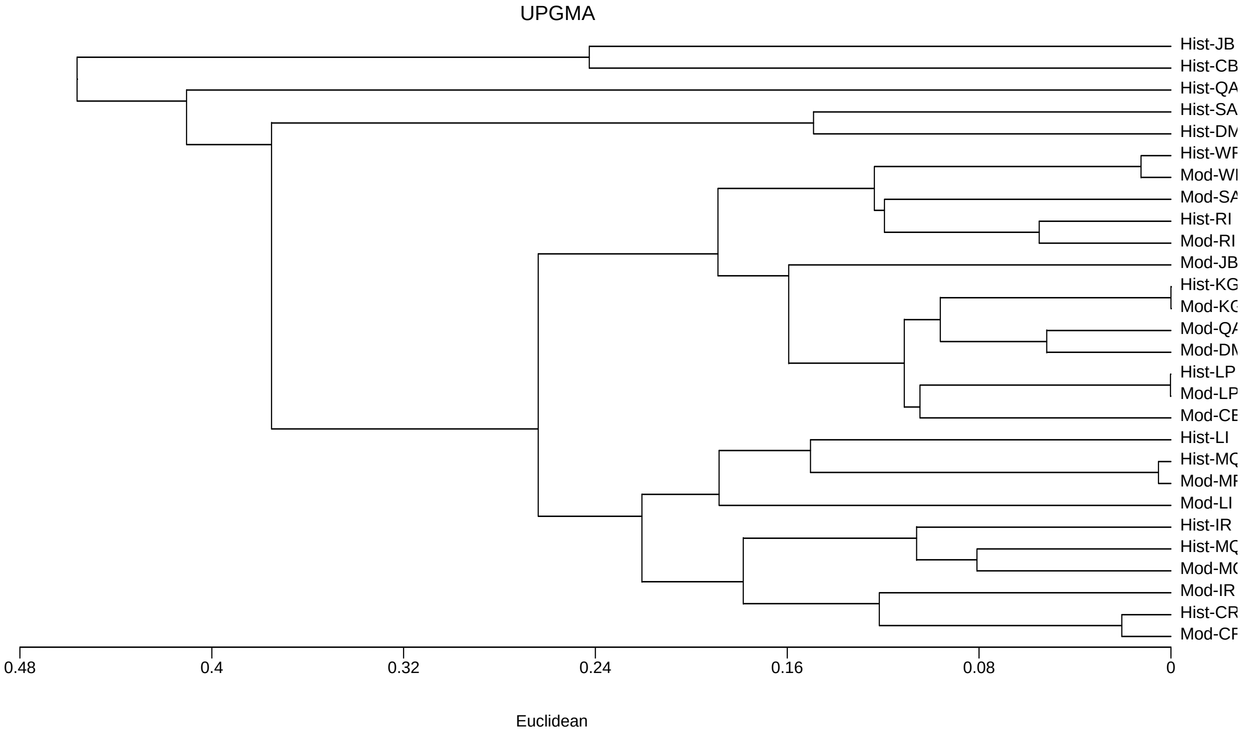


Figure 19. Cluster analysis of the proportional distribution of geomorphic surfaces among geomorphic reaches regardless of levees (Hist-XX) and considering only connected floodplain (Mod-XX). Abbreviations as in Table 2.

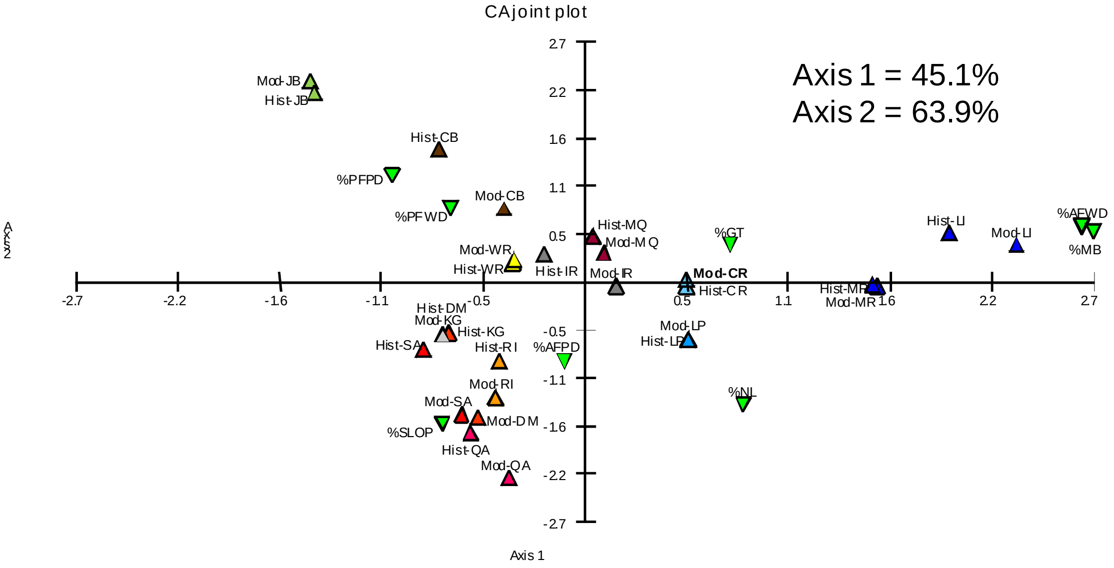


Figure 20. Correspondence analysis biplot of the proportional distribution of geomorphic surfaces among geomorphic reaches regardless of levees (Hist-XX) and considering only connected floodplain (Mod-XX). Abbreviations as in text and Table 2.

Aquatic Areas

Pre-dam Aquatic Areas

My analysis of pre-dam is restricted to Pools 4 through 26 of the UMR because Brauer et al., (2005) have already completed a comprehensive analysis of the MMR and also because pre-development aquatic habitat data for the Illinois River have not been digitized. Pre-dam aquatic areas were digitized from Mississippi River Commission maps compiles in 1891 following a generalized classification of Wilcox (1993). Post dam aquatic area data were available from the Long Term Resource Monitoring Program 1989 land cover.

Pre-dam aquatic habitat was primarily main channel and secondary channel area (Figure 21; Appendix B). Sand, as bars and banks, was common south of the Chippewa River Reach (~RM650), whereas wooded islands only were more common in the reach dominated by bed load from the Chippewa River (Figure 21). There is uniformity in the total area of channel habitat along the entire river. Except where island area skews results in the Chippewa River Reach and Water area skews the Lake Pepin Reach, channel habitat was between 40 and 60 percent of total aquatic habitat (Figure 21). Backwater abundance is uniform also, with contiguous backwaters in the north and isolated backwaters in the south. The large spike in backwater area ~RM 350 is a single large floodplain lake, Lima Lake. Lake Pepin is a large mainstem lake between RM 765 and 785. Maps for individual reaches provide images that can be used by restoration planners (Appendix B), total area for each class is summarized by reach (Figures 22 and 23). Island characteristics were summarized by reach (Figure 24) because they are geomorphic features that increase structural diversity in the aquatic landscape (Shields and Smith, 1992; Gore and Shields, 1995). The Chippewa River Reach is unique in its total number and acreage of islands with three times more islands and acres than the nearest reach because of a huge sand bed load delivered from the Chippewa and Black Rivers (WEST Consultants, Inc., 2000). Island characteristics among other river reaches are rather uniform (Figure 24). The narrow gorges have fewer islands, and Iowa River bed load increases island abundance in the reach below the Rock Island Gorge which also funnels sediment from the Wapsipinicon and Rock Rivers. The Kaskaskia River Reach is unique in the size of islands because of the presence of Kaskaskia Island which existed before the Mississippi River had a large avulsion that captured the Kaskaskia River in a new channel (Brauer et al., 2005).

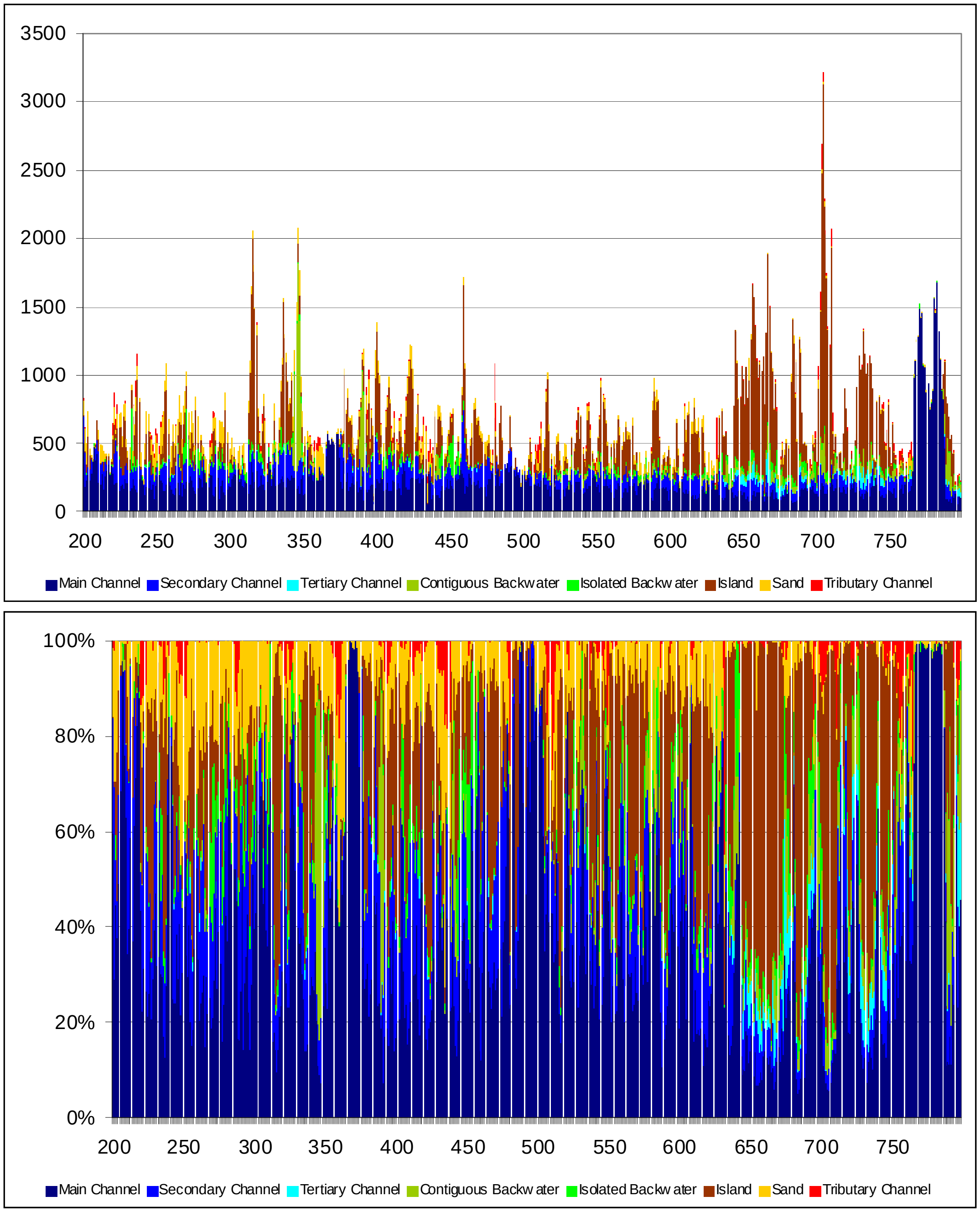


Figure 21. Pre-dam (1890) aquatic area distribution in acres (top) and as percent of aquatic area for Upper Mississippi River Pools 4 through 26 displayed by river mile.

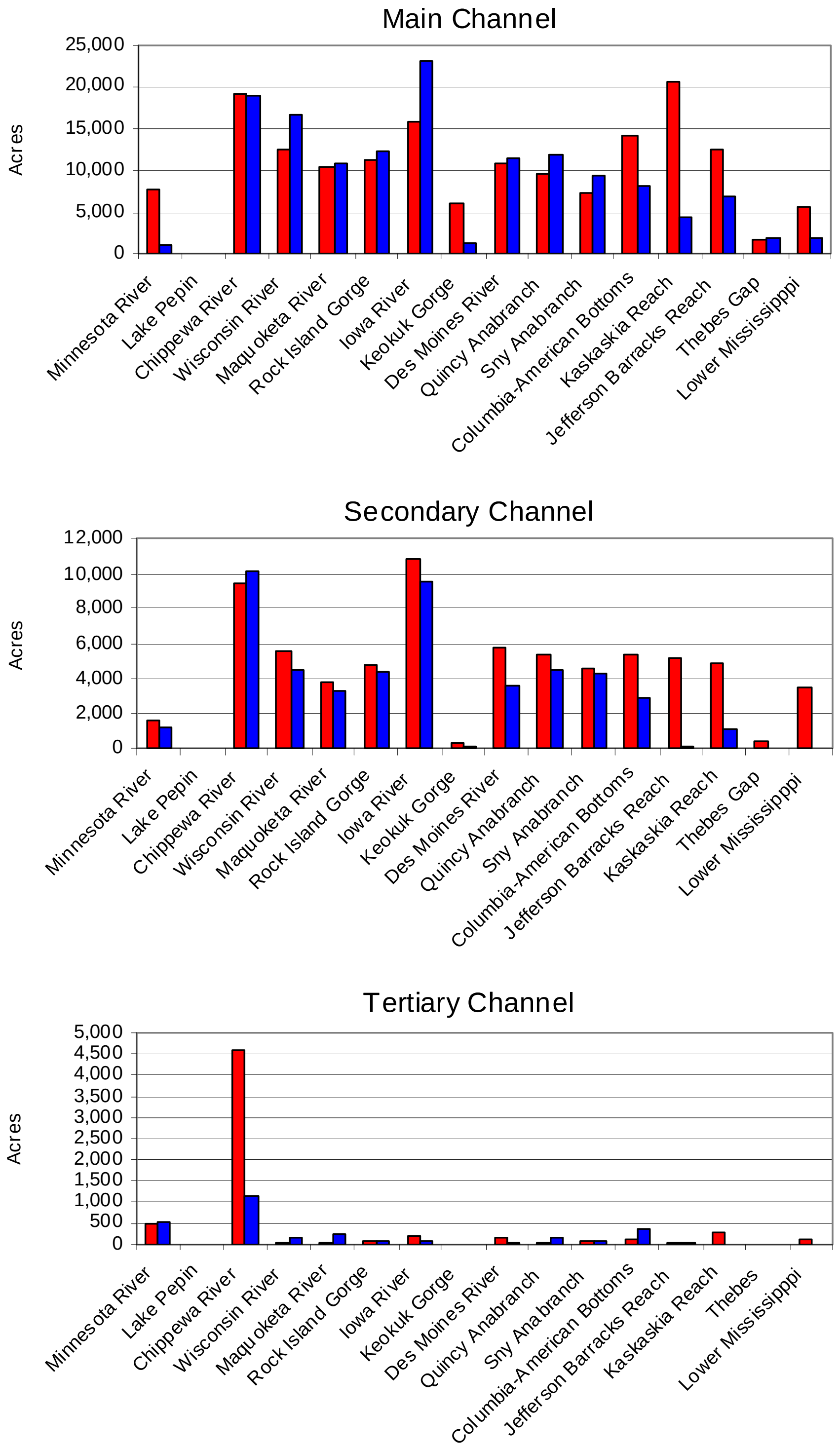


Figure 22. Upper Mississippi River 1890s (red) and 1989 (blue) main channel, secondary channel, and tertiary channel area summarized by geomorphic reach.

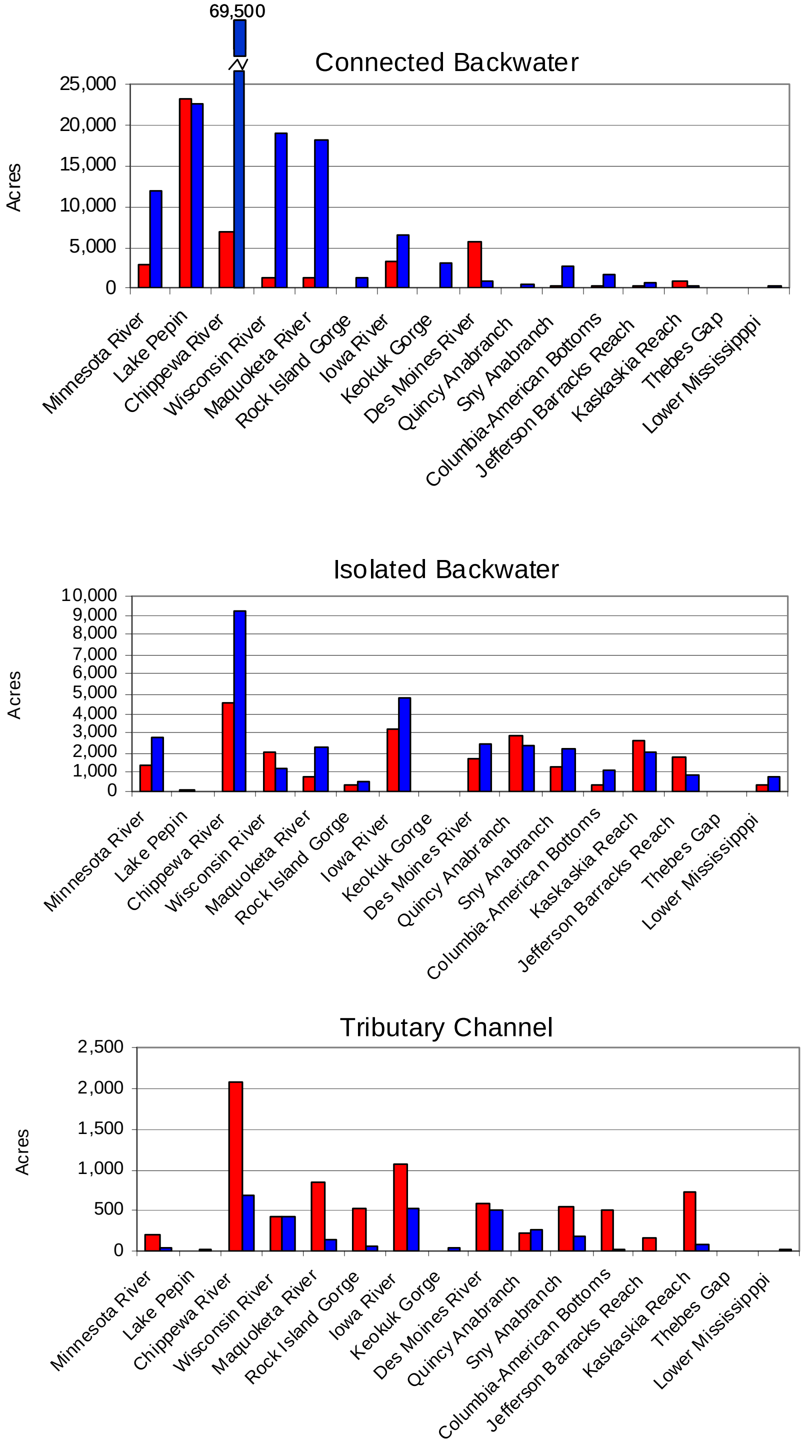
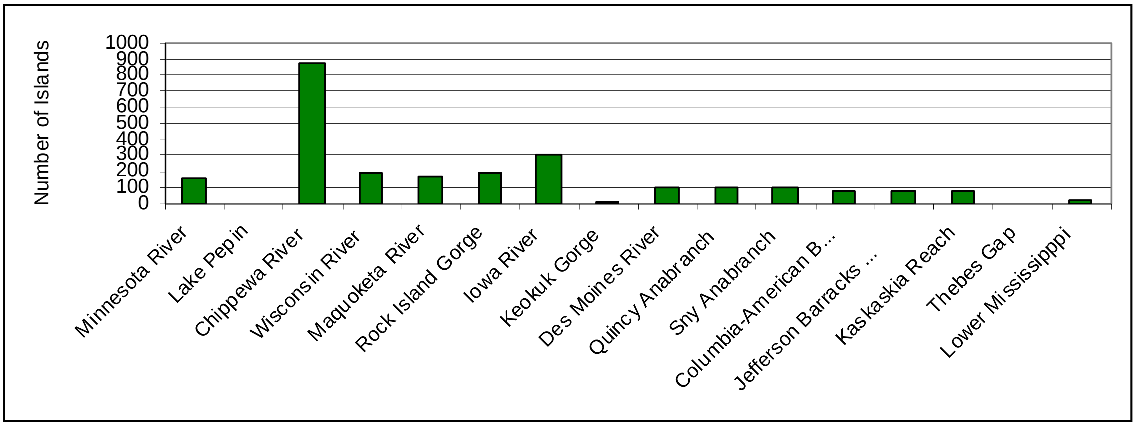
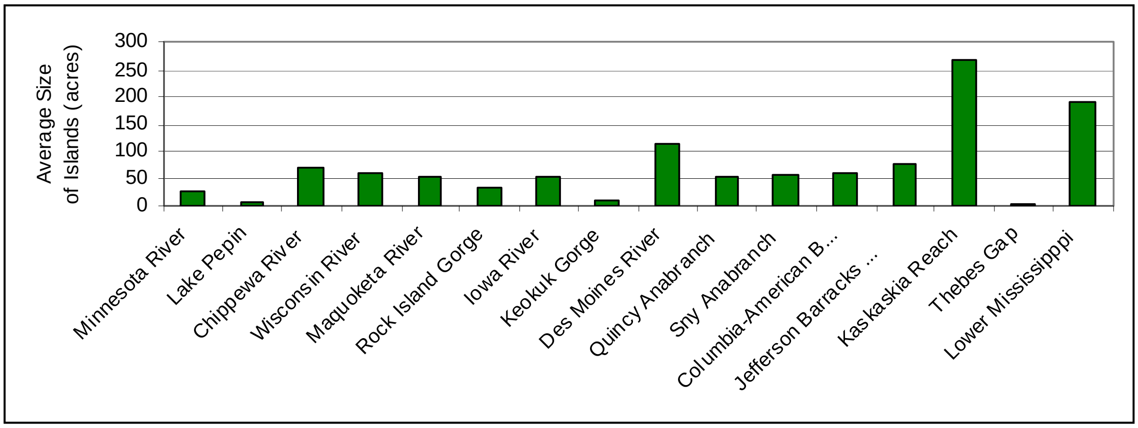


Figure 23. Upper Mississippi River 1890s (red) and 1989 (blue) contiguous backwater, isolated backwater, and tributary channel area summarized by geomorphic reach.





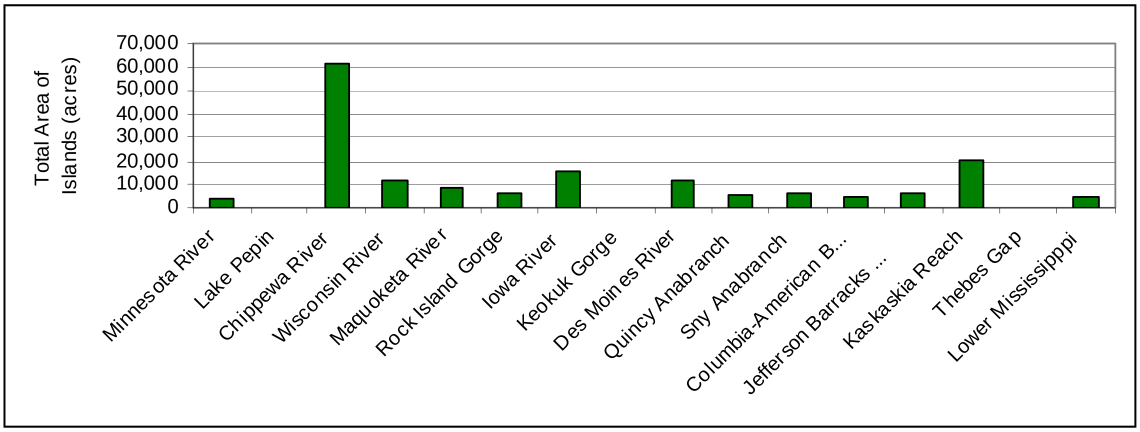


Figure 24. Upper Mississippi River 1890s island characteristics, number, size, and area) summarized by geomorphic reach.

Post-dam Aquatic Areas

Navigation dams increased low flow river stages to a minimum 9-ft. channel between RM 200 and 857 and through the entire IWW. Each dam has specific local effects (see Figure 2) but the general pattern of surface water distribution among aquatic classes clearly differs above and below RM 500. Total aquatic area increased throughout the river with minor changes reflected as channel area south of RM 500 and large increases in aquatic area as backwater areas due to impoundment north of RM 500 (Figure 25). Sandbars were inundated in the south, wooded islands and floodplain were inundated in the north (Figure 26). Isolated backwaters remain isolated in the south (but by levees) and they have been converted to contiguous backwaters in the north. Lake Pepin (RM 765-785) was classed differently in the two periods, but was unchanged by river regulation.

Pre-dam and Post-dam Comparison

Main channel and secondary characteristics remain relatively constant between pre-dam and post-dam periods in impounded reaches (see Figure 22). Tertiary channels were only common in the Chippewa River Reach which has an island-braided morphology characterized by intermingled channel complexes (see Appendix B). Most tertiary channels in the lower two-thirds of the pools in the Chippewa River Reach were inundated (see Figure 23). Islands that remained as islands following impoundment were dissected by current and eroded by wind-generated waves. Alluvial material eroded from islands was transported short distances to fill former floodplain lakes and channels to a uniform level in many backwaters. Backwater sedimentation gets increasingly worse progressing downstream from RM 500 where excessive sedimentation and loss of low river stage because of impoundment hae degraded backwater habitat quality.

There were very large increases in connected backwaters in the Chippewa River Reach (see Figure 23). Increases in backwaters were also notable in the constricted Wisconsin River and Maquoketa River Reaches. Most modern backwater area is in the impounded backwater class immediately upstream from the dams. Pools 8 to 13 in particular have very large impounded areas (see Appendix B). Isolated backwater area also increased in the mid- and upper parts of pools in the Chippewa River Reach. The open water impounded areas transition upstream through island-braided midpool segments and then to riverine segments at the upper ends (see Appendices B and D; Theiling and Nestler, 2010).

Tributary channel area is reduced throughout the river. Most tributaries have been altered many ways in the historical record. They have been channelized, used to float logs, filled with sediment, and leveed. The loss of tributary channel area is likely most attributable to channelization and levees across the floodplain and tributary fans.

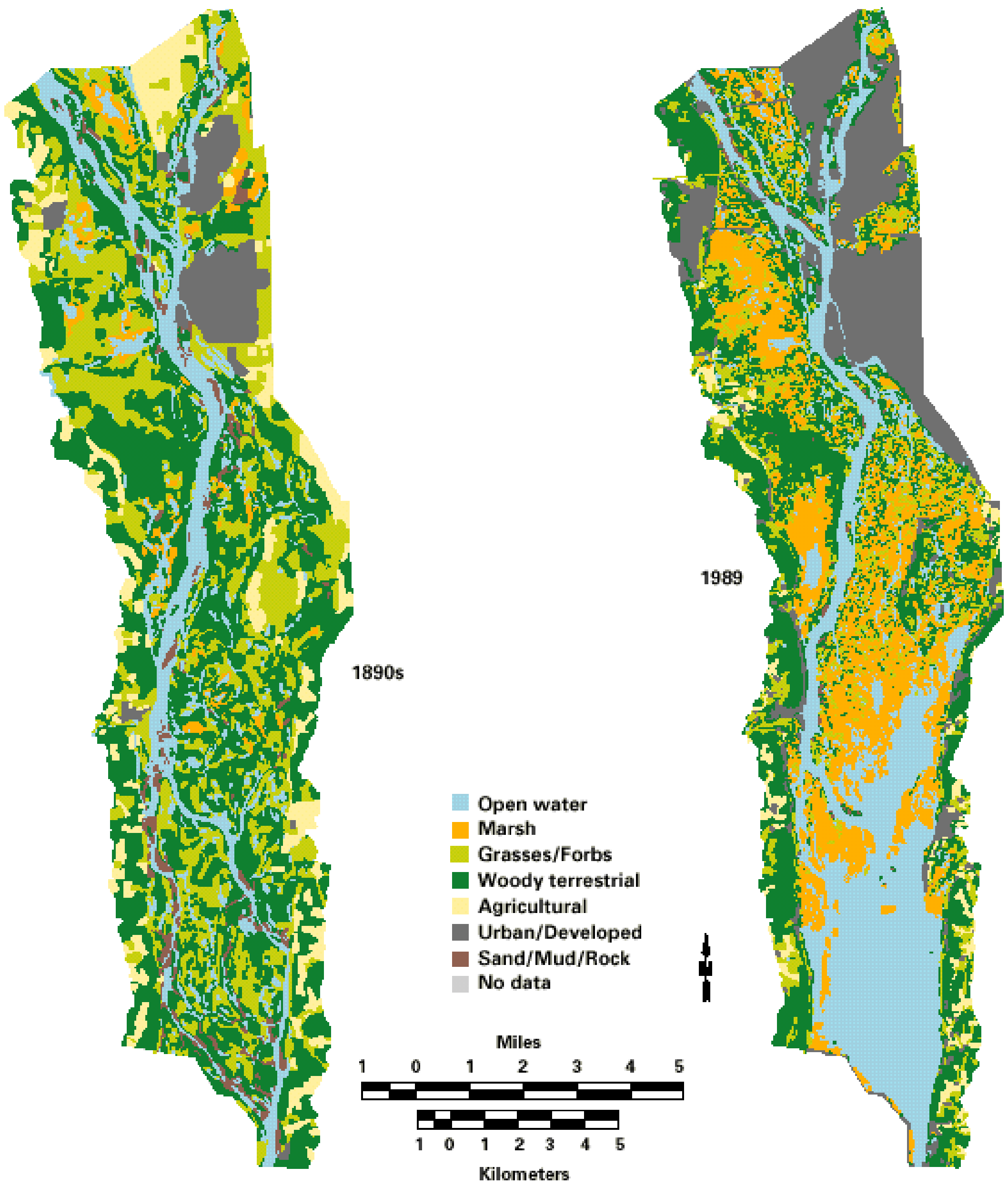


Figure 25. Pool 8, Upper Mississippi River System demonstrates impoundment effects quite clearly.

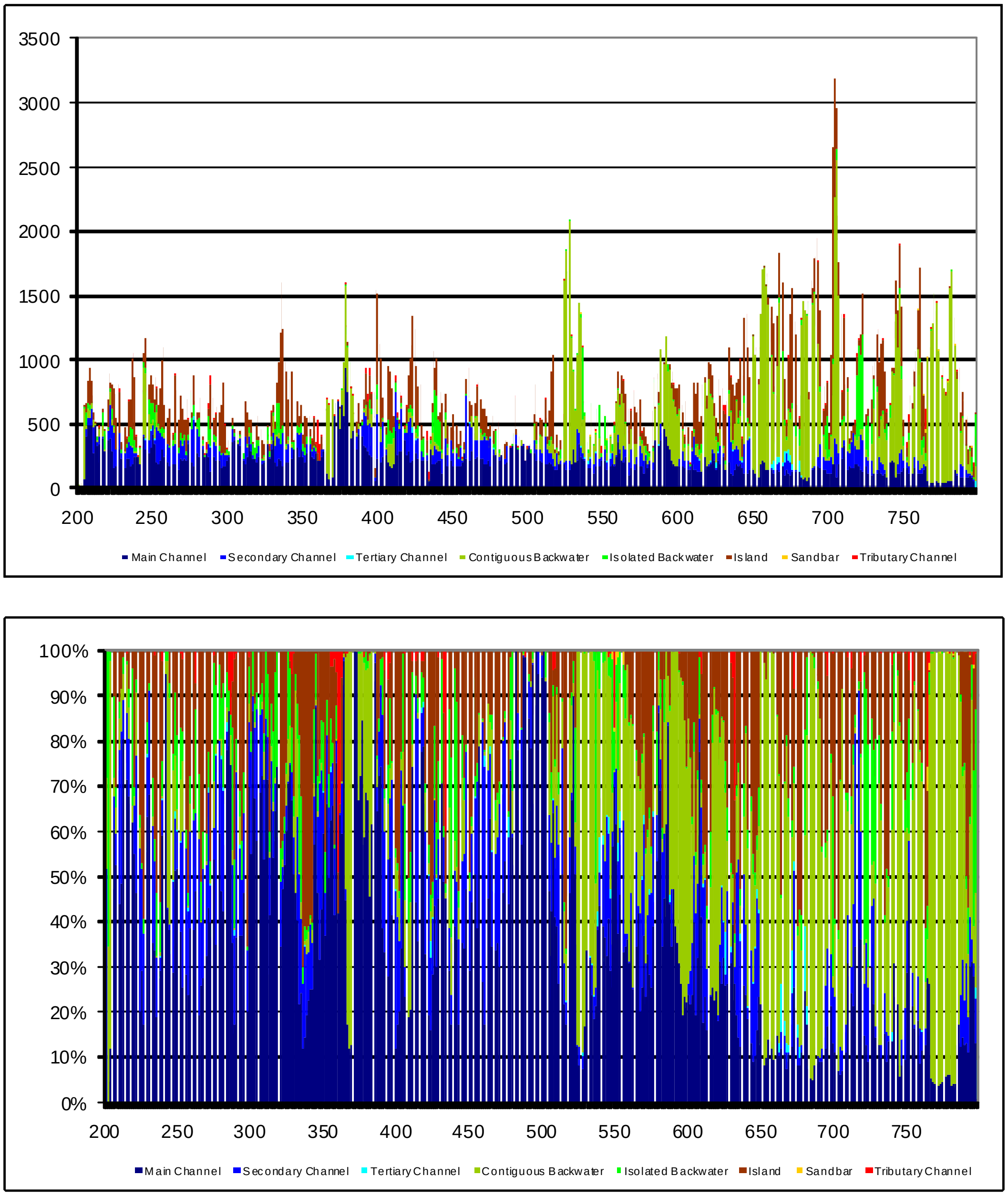


Figure 26. Contemporary (1989) aquatic area distribution by river mile in the Upper Mississippi River System Pool 4 through 26.

Aquatic Area Ordination Analysis

Aquatic Area Ordination

Pre-dam and post-dam aquatic areas were standardized to five simple classes: Main Channel, Secondary Channel, Tertiary Channel, Connected Backwater, and Isolated Backwater. The GIS vector coverage was converted to raster, and each class was extracted as a separate raster. Each UMRS Aquatic Area class was summarized by geomorphic reach and entered into a spreadsheet of Aquatic Area class by geomorphic reach for each time period, and also coded uniquely in a combined spreadsheet. Data were imported to the Multivariate Statistical Package (MVSP, Kovach Computing, Inc., 2008) where correspondence analyses were used to explore geographic relationships among large scale geomorphology represented by UMRS geomorphic reaches (see Methods in Chapter 1). Lake Pepin, Keokuk Gorge, and Thebes Gap were dropped from correspondence analysis because they acted as strong outliers masking other comparisons. Cluster analysis was used to explore similarities in aquatic area abundance among geomorphic reaches.

The correspondence analysis of the pre-dam 1890 Aquatic Areas reveal a clustering of most reaches near the origin of the CA biplot with Main Channel abundance dominating the group (Figure 27). The Minnesota River Reach (MR) and Chippewa River Reach (CR) are distributed up Axis 2 along a Secondary Channel, Contiguous Backwater, and Tertiary Channel gradient characteristic of the island-braided reaches. The Sny Anabranch (SA), Jefferson Barracks (JB), and Quincy Anabranch (QA) reaches separate slightly along Axis 1 toward Isolated Backwaters because of the presence of larger floodplain lakes. Many of these lakes apparent in the <1850s land cover south of St. Louis, Missouri were already drained by 1890 and are not present in this data set.

Regional similarities in pre-dam aquatic area distribution were also examined using cluster analysis (Figure 28). The lower group includes closely associated geomorphic reaches that are located below large tributary confluences. The upper group of geomorphic reaches is gorges, below gorges, or the unique Missouri River Confluence near St. Louis, Missouri.

The post-dam distribution of geomorphic reaches is looser than the pre-dam results, but many of the results are similar. Most geomorphic reaches cluster near the origin near the Main Channel Aquatic Area class (Figure 29). The Minnesota River Reach (MR) and Chippewa River Reach (CR) switch positions along Axis 2, with MR located farther along the Tertiary Channel (TC), Secondary Channel (SC), and Contiguous Backwater (CBW) gradient. The Lower Mississippi (LM) and Jefferson Barracks (JB) Reaches are located along Axis 1, Isolated Backwaters (IBW) because of several large oxbow lakes managed as wildlife areas. The Quincy Anabranch (QA), Des Moines (DM), and Kaskaskia River (KR) Reaches have remnant backwaters and ditches in leveed areas.

The combined pre-dam and post-dam Aquatic Areas correspondence analysis was color coded by geomorphic reach to emphasize change at each site (Figure 30). The patterns detected in the individual analysis were retained in the combined results. The Minnesota River Reach (MR) separated farther along Axis 2 because of a large increase in Contiguous Backwater and Tertiary Channel area. The Chippewa River Reach (CR) responded similarly to impoundment, but had more backwaters and small channels than other river reaches initially so the change is not so pronounced. All of the reaches that had been influenced by isolated backwaters in the pre-dam period were less-so influenced in the post-dam period as noted by their shift to the left along Axis 1.

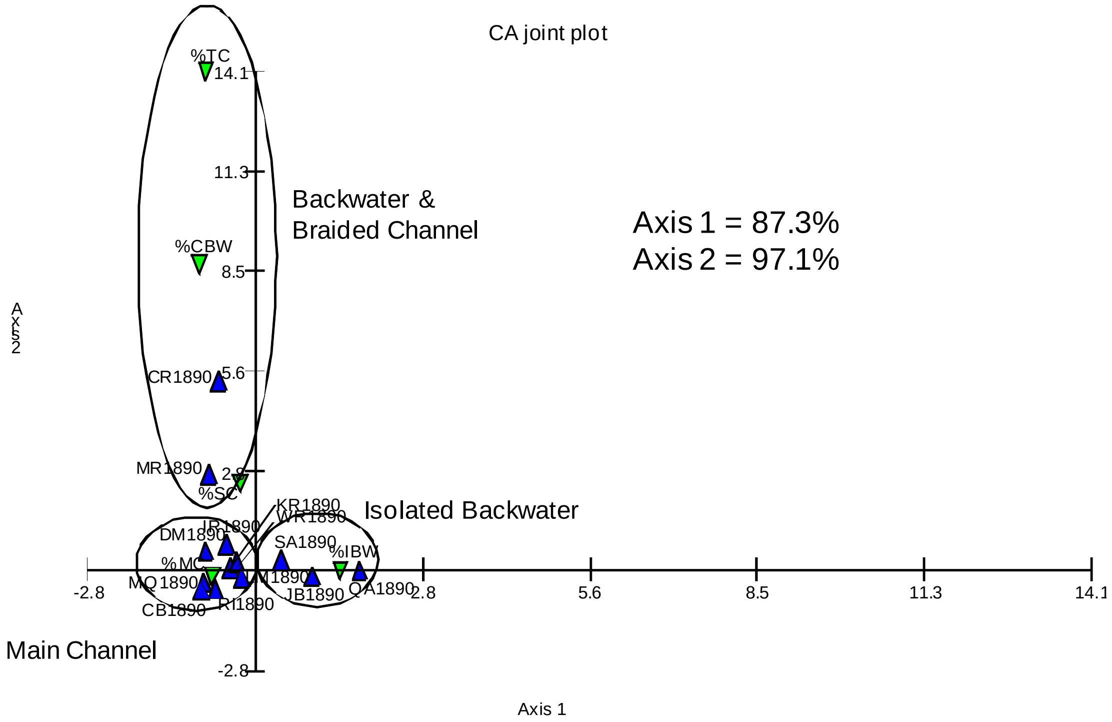


Figure 27. The correspondence analysis biplot of pre-dam aquatic area proportional distribution clusters most geomorphic reaches near the origin and Main Channel except for the northern reaches that separate on tertiary channels and contiguous backwaters and some southern reaches that separate on large isolated backwater lakes. % = percent; IBW = Isolated Backwater, CBW = Contiguous Backwater, TC = Tertiary Channel, SC = Secondary Channel, MC = Main Channel; Geomorphic Reach abbreviations as in Table 2.

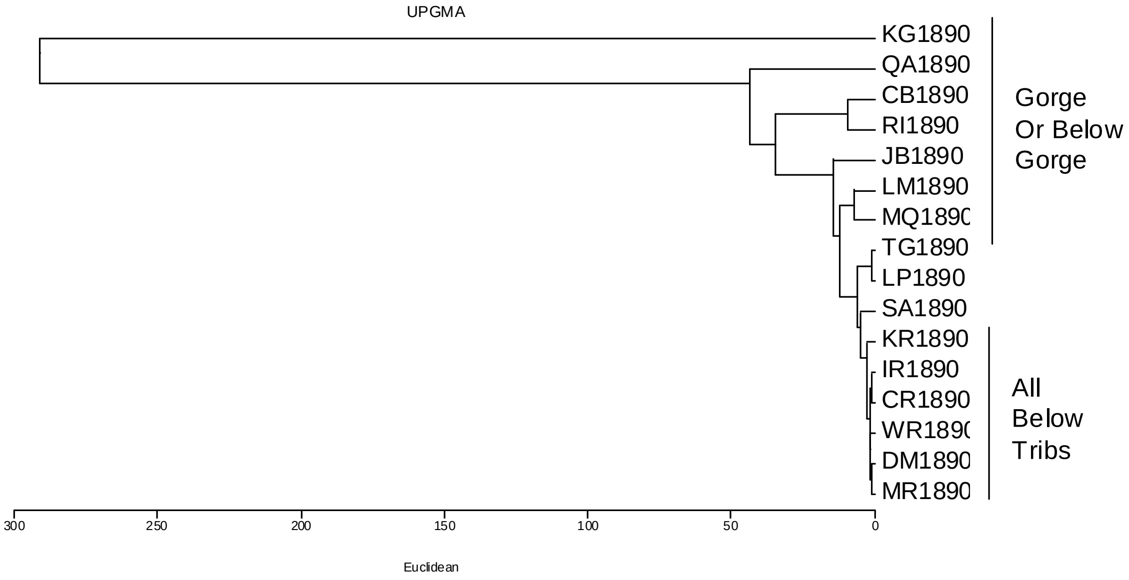


Figure 28. Cluster analysis mixes geomorphic reaches based on geography, but reaches in the lower cluster all occur below major tributaries and the reaches in the upper clusters are either a gorge, below a gorge, or at the unique Missouri River confluence (Geomorphic Reach abbreviations as in Table 2).

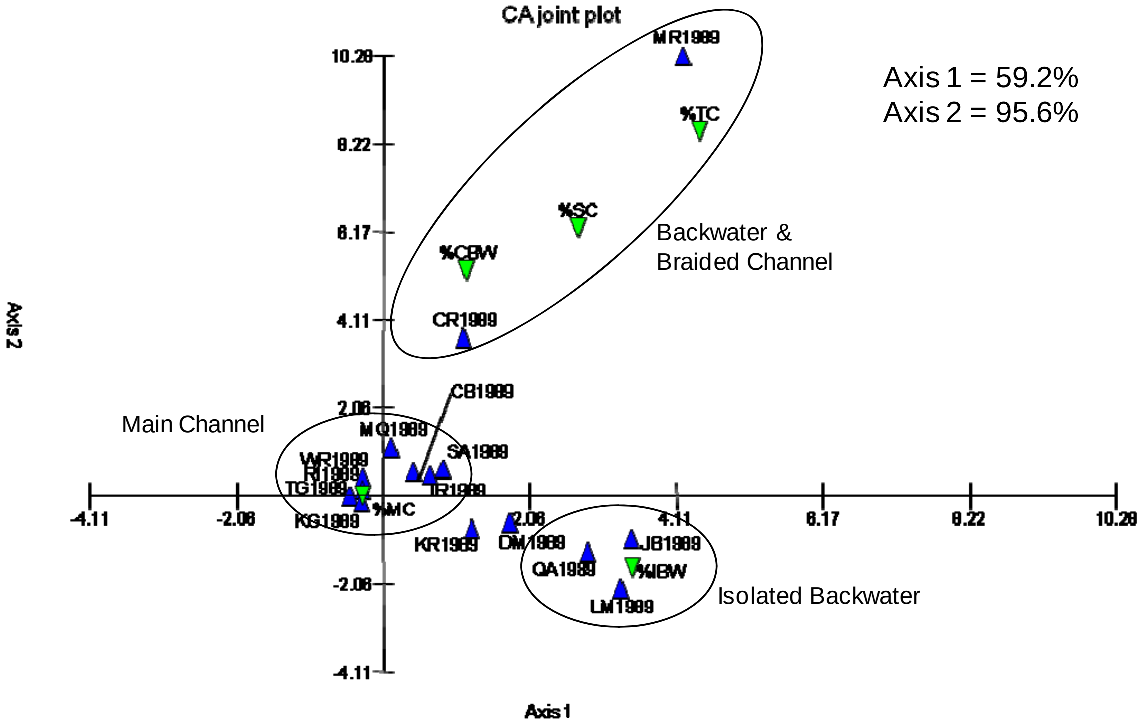


Figure 29. The post-dam aquatic area correspondence analysis biplot ordination resulted in separation of the Minnesota and Chippewa Reaches along a Tertiary Channel, Secondary Channel, Contiguous Backwater gradient and several southern reaches were influenced by Isolated Backwater (Geomorphic Reach abbreviations as in Table 2).

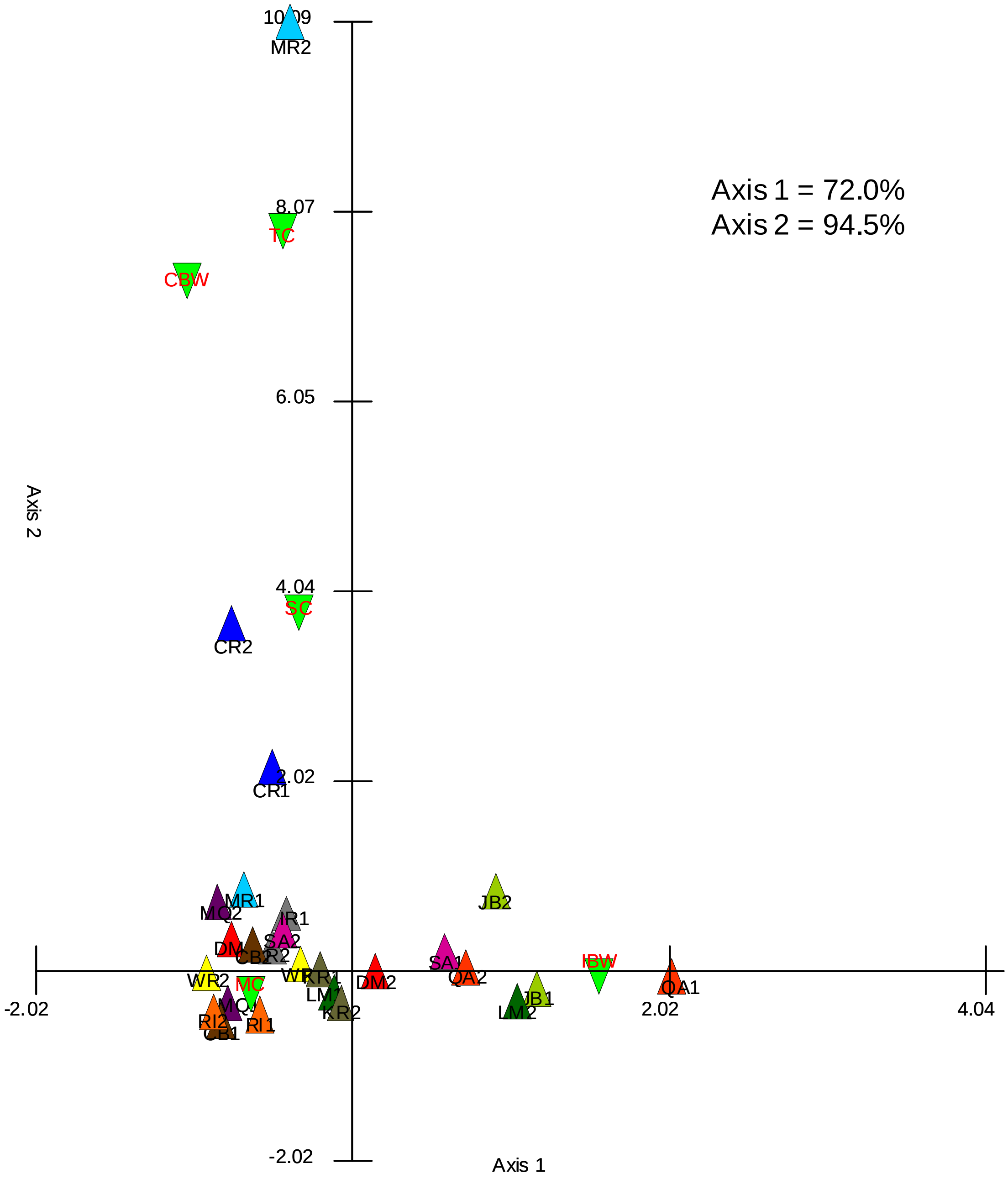


Figure 30. The combined pre-dam and post-dam Aquatic Areas correspondence analysis results were color coded for each reach to identify changes between time periods. Labels ending in 1 are pre-dam, those ending in 2 are post dam; Geomorphic Reach labels are as in Table 2; Aquatic Area variables are all bright green with red labels.

Discussion:

Implications for River Management

An earlier section reviewed some of the social influences that have so profoundly affected the river environment for nearly 200 years. People were intent to exploit the region prior to industrialization, but the introduction of steam power changed the scale of human activity and influence on the ecosystem. Navigation and flood control projects became large enough to effect the river-floodplain ecosystem by substantially changing the natural hydrogeomorphology. The ecological effects of dams, channelization, and levees are described in more detail below.

Flood Control

Flood control levees are typically earthen structures along river banks that prevent flood flows from spreading across low elevation floodplains. They were initially built on a small scale during the mid-1800s, connecting natural levees and building them to a level height. Government involvement through the Swamplands Act (1850) and landowner cooperation through levee and drainage districts fostered larger projects in the late 1800s. Steam power and large groundwater pumping capability accelerated development. Levees are most prevalent in the Upper Mississippi River south of Rock Island and in the La Grange and Alton pools on the Illinois River (see Figure 3) where the majority were constructed to protect agricultural areas from moderate floods. The environmental impacts of levees and the development they allow are extensive (Theiling, 1999). Natural vegetation in leveed areas has been removed and largely converted to agriculture (Theiling et al., 2000). Wetlands were filled and the floodplain behind levees has been drained and leveled. Floodplain lakes have been isolated from the river and tributaries have been channelized between levees. The areas protected by levees have lost much of their habitat value because they specifically exclude the ecologically important 2-yr average.

Levees also alter physical and biological processes in the rivers. River stages are higher for commensurate flow volume than they were before levees were widespread (Belt, 1975; Bellrose et al.,1983; Wlosinski, 1999). Levees also concentrate river flow and the particulates carried in suspension. Sediment is constrained in the remaining contiguous floodplain where it settles out, causing rapid filling in backwater lakes riverward of the levee system (Bellrose et al., 1983). The effects are particularly pronounced below large tributaries. Levees reduce river-floodplain connectivity, which may limit production of floodplain spawning fishes and reduce nutrient transfer between the rivers and their floodplains (Sparks, 1995; Ward et al., 1999).

Channelization:

The Middle Mississippi River is an interesting case study in the evolution of channel engineering. The initial channel improvements changed the river morphology from its natural dynamic form to a much different and undesirable dynamic form. Subsequent channelization has reshaped bank configurations similar to the historic bankline position, but the in-stream habitat structure is reduced in abundance, simplified, and stabilized compared to historic conditions.

Contemporary navigation on the Middle Mississippi River is maintained without dams because the river is much deeper with the additional flow from the Missouri River. Channelization activity, on the other hand, is extensive. Channelization was more common on the upper river also prior to lock and dam construction and there are thousands of legacy structures that are now submerged by the 9-ft. channel project (WEST Consultants, Inc., 2000). As river engineers gained experience they reduced dredging requirements by building dikes designed to narrow the river to concentrate flow and scour the channel deeper using the river’s own energy. Early river engineers were creative and extremely effective at building channels (Degenhardt, 1973), modern engineers are being equally creative with innovations for environmental restoration (Neimi and Strauser, 1991; Theiling, 1995).

Dams:

UMRS low head dams impounded water onto low elevation floodplains to maintain navigable waterways 9-ft deep (i.e., the 9-Ft. Channel Project) and locks step boats and barges past the dams (see Figure 2). The effects of dams are detectable in the stage hydrograph where river stage is greatly modified in the lower parts of each navigation pool, but less so in the upper parts of the pools (see Figure 25; Theiling and Nestler, 2010). Large scale changes in the distribution of water differ upstream and downstream of Rock Island. Most river miles upstream from Rock Island have much more aquatic area, three times as much or more, in most areas than pre-dam conditions. There is a within-pool pattern that generally inundates the lower region of pools, partially inundates mid-pool reaches, and has relatively little planform change in the upper pool (see Figure 25) that is clearly visible in the Chippewa River Reach. The planform distribution of water in river reaches below Rock Island are not changed as much except in the lower parts of Pools 16, 17, and 18.

Dams create physical hydrogeomorphic changes that propagate through other ecosystem components. They initially inundated topographically diverse floodplain areas that responded with a highly productive “new reservoir” effect (Fremling et al., 1989). Islands were created from the natural levees and ridges on the floodplain after impoundment, but the alluvial soil was eroded by wind generated waves in the open water environment. Sediment from island erosion and increased sediment transport from the watershed was focused into deeper channels and backwaters reduced depth diversity in much of the river. There are many site-specific examples of several feet of sedimentation directly adjacent to areas where 70 year old stumps still protrude from the sediment. Backwater habitats naturally accumulate fine sediment, but the navigation system prevents the low river stages required to expose, compact, and transform backwater sediments to maintain high sediment and water quality. “Pool aging,” as these cumulative effects may be referred to, (Lubinski, 1999) is more advanced in the Lower Impounded Reach and Lower Illinois River because of their high concentration silty sediment load.

Habitat Management:

Natural resource management has been a concern of many individuals and groups since the 1800s, but the motivation for economic development has typically determined development on the river. The Issac Walton League was concerned about the condition of the river during the early 1900s as drought struck the region and urban pollution and channelization were changing the river quickly. They were able to secure the Upper Mississippi Wildlife and Fish Refuge in 1924 "as a refuge and breeding place for migratory birds, fish, other wildlife, and plants." The Upper Mississippi Refuge is a nearly continuous floodplain corridor for 260 miles (>230,000 acres) in the northern part of the river. In the Lower Impounded Reach the are several refuges along the river totaling about 30,000 acres and other public land adding to more than 160,000 acres. The Corps of Engineers purchased almost 200,000 acres adjacent to the river providing a riparian corridor that it mostly outgrants to states and USFWS for management. Public land is much less common on the Illinois (~75,000 acres) and Middle Mississippi River reaches (50,000 acres). In total there are more than 500,000 acres, about 17 percent of the total floodplain area, in some form of public ownership and natural resource management.

Several new types of river engineering structures have been designed and built to achieve both navigation and ecosystem objectives in the last 10 years (USACE Applied River Engineering Center, 2008). Chevron dikes are artificial islands constructed in series at the mouth of a secondary channel to deflect flow into the main channel. They provide the hydraulic function of a closing structure, without completely blocking the secondary channel. Their long-term impact has not been evaluated, but they should reduce dredging requirements in the main channel (Theiling, 1995). Various types of rock piles, called round points, are being investigated for their ability to replace wing dams. Constructed in groups perpendicular to the flow, they should increase physical diversity in a dike field, while still maintaining the main channel (Brian Johnson, U. S. Army Corps of Engineers – St. Louis District, St. Louis. Missouri, personal communication). Bendway weirs are stone structures constructed on the bottom of the river to deflect flow through river bends. The bends are historically troublesome for navigation because sand bars that form on the inner side of the bends gradually encroach into the main channel. Dredging has been reduced where bendway weirs have been built (Davinroy, 1990). Wing dams have also been modified to improve river habitat. They have had extensions built to create artificial backwaters in L-dikes, have been notched to direct flow into the dike field and scour sediment deposits, and have been raised or lowered to scour areas downstream differently at high and low river stages (Niemi and Strauser, 1991). Islands are being built by constructing dikes away from the bankline to create side channels between islands and banks.

Conclusions

The anthropomorphic influence on the UMRS ecosystem is exceptionally high considering the size of the system. Millions of acres have been affected by altered hydrology and direct landscape manipulations. Ecological impacts of direct conversions to agriculture or impoundments are relatively easy to document, but the more subtle changes to sediment transport and deposition or water table alterations are more difficult to detect. Several hydro-geomorphic changes have altered the forest composition and wetland abundance throughout the system.

It is time to reconsider human activity on the river-floodplain. By understanding ecological response to altered physical structure and function of the system, it may be possible to define a more desirable future alternative condition. It is likely that the multiple uses on the river can be integrated to increase the efficiency and effectiveness of all river management activities.

CHAPTER 3: CAN HYDRODYNAMIC PATTERNS BE DEFINED FOR THE UPPER MISSISSIPPI RIVER SYSTEM?

Introduction

Hydrologic Modeling

Large river hydrology is a function of climate determining the quantity of water and geomorphic factors and their position in the hydrologic network determining the distribution of water at any location. The issue is important in large river ecosystem management because hydrology is a strong driver in river ecosystems (Poff and Ward, 1989; Richter et al., 1997; Poff et al., 1997; Sparks et al., 1998). Hydrology is commonly discussed in terms of discharge volume and river stage elevation, but hydraulic factors like distribution of flow and current velocity are also important because they determine local aquatic habitat conditions, soil moisture, water table depth, propagule distribution, etc. (Malanason ,1993). Hydrologic characteristics change dramatically from one end of the UMRS to the other and hydraulic characteristics differ spatially across the river-floodplain continuum. Both hydrologic and hydraulic conditions change seasonally with variation in flow. Dams, levees, diversions, and upland development have changed the UMRS hydroscape significantly.

Natural hydrologic processes and hydraulic patterns (H&H) fundamentally influence the high productivity characteristic of river floodplain ecosystems (Vannote et al., 1980; Ward & Stanford, 1983; Junk et al., 1989; Poff et al., 1997; Ward et al., 1999; Postel & Richter, 2003). Many large river species and communities are adapted to predictable seasonal hydrologic variation (Welcomme, 1979; Cross and Vohs, 1988; Junk et al., 1989; Bayley, 1995; Poff et al., 1997; Ward et al., 1999; Koel, 2001). The importance of natural hydrologic patterns for biodiversity conservation and sustainability suggests that naturalization of the hydrologic regime should be an objective for ecosystem restoration (Poff et al., 1997; Richter et al., 1997; Sparks et al., 1998). Describing and understanding how water resource development activities have affected the magnitude, timing, frequency, duration, and change rates of hydrologic events that characterize the natural hydro-geomorphic template of rivers should be among the first, critical steps in large scale ecosystem restoration (Collwell, `1974; Poff et al., 1997; Richter et al., 1997, 1998).

There are ample data to characterize river discharge and stage in the contemporary UMRS, and there is reasonably good data to characterize pre-development discharge and stage at many locations also. Hydrologic and hydraulic (H&H) modeling is also quite advanced, so the H&H Essential Ecosystem Component (EEC) is well suited for the MRCA approach. Historic and contemporary river discharge and stage conditions were analyzed by Theiling and Nestler (2010) to characterize reach and pool scale indicators of stage alteration and demonstrate the MRCA. In this study I simulated the system-wide flood inundation spatial extent for the 1994 flow frequency river stage estimates (USACE, 2003and 2004b). My analysis defines the surface water distribution of the 50 percent to 0.2 percent (i.e., 2-yr to 500-yr) flood stage over high resolution floodplain topography to provide the first quantitative approximation of flood extent for the UMRS at this scale. The results can be modeled in GIS to represent historic, contemporary, or simulated alternative reference conditions. Surface water overlays are analyzed with land cover in Chapter 5 to analyze plant community distribution in relation to hydrology and development.

Many studies consider river total discharge to characterize seasonal and annual phenomena (Richter et al., 1998; Galat and Lipkin, 2000). Many ecological studies also consider river stage (Wlosinski, 1999; Pinter and Heine, 2005; Theiling and Nestler, 2010) and stage analysis for flood risk assessment is common. Few ecological studies consider the spatial extent of river-floodplain hydrology over a large scale (Thoms, 2003). Large scale hazard assessments are typically concerned with extreme, infrequent events and thus disregard the extent of small floods. This investigation bridges the gap between stage-frequency hydrology and large flood hazard mapping by combining system-wide high resolution floodplain topography and recently updated river stage frequency analyses to simulate the spatial distribution of flood waters over more than 2 million acres along 1,000 river miles. The “virtual reference” (Lubinski and Barko, 2003) floodplain inundation maps support multiple reference condition analysis (Nestler et al., 2010) of alternative floodplain management scenarios.

Floodplain Inundation Analysis Management Applications

An early application of UMRS floodplain inundation mapping for engineering design was the determination of permanent flooding to be caused by navigation dams (USACE, 1949). A comprehensive topographic survey in 1927 and concurrent river gauging and flow frequency analyses (USACE, 1949) were used to design the lock and dam system and identify real estate requirements because much of the floodplain was in private ownership. More than 200,000 acres of land was purchased outright for the 9-Foot Channel Project and easements were acquired for other lands (USACE, 2004). Existing levee and drainage districts (L&DD) sought and received compensation for increased pumping costs relative to increased river stages in lower pool reaches where dams raised groundwater elevation (USACE, 1949). The existing L&DD infrastructure supports tremendous water management capabilities that could be integrated into many alternative floodplain management scenarios, the visualization and quantitative capabilities of these contemporary floodplain inundation maps and similar site-specific analyses can help estimate the environmental benefits of such scenarios.

Waterfowl managers have regulated water levels in UMRS backwaters and floodplains to optimize wetland habitat for migratory waterfowl since the 1930s at private waterfowl hunting clubs (Havera, 1999). Water management infrastructure was incorporated into waterfowl management and demonstrated great potential to exceed natural wetland production capacity (Havera, 1999), especially in the changing hydrodynamic and sediment transport environment of modern rivers. Currently there are at least 25,000 acres in wildlife management areas with water regulation capabilities. The concept is being adapted to the pool scale by conducting drawdowns in applicable pools during a specific discharge range that accommodates all river uses (Landweher et al., 2004; Kenow et al., 2007). Drawdowns in navigation pools can expose between 500 and 3,000 acres of floodplain inundated by low head navigation dams. Similar water level management strategies could be evaluated at appropriate locations in L&DDs throughout the system.

The juxtaposition of navigation, flood protection, ecosystem management, and other social issues makes modern floodplain management an economically important concern (Galloway, 2008). Extreme flooding in 1993 overwhelmed system capacity and identified the range of potential impacts that could be incurred again (IFMRC, 1994). The policy recommendations went unaddressed and many of the same locations were overwhelmed again in 2008 by another extreme unusual event (Galloway, 2008). Extreme, unusual events are more common than they used to be and they are expected to continue to occur at greater frequency (Changnon, 1983; Zhagand and Schilling, 2006; Gutowski et al., 2008). Floodplain managers need to review the hydrodynamic landscape of the UMRS to optimize land use management. This investigation provides results from large scale assessment of hydrologic alterations of river stage, inundation patterns, and alternative ecosystem restoration scenarios to examine the hydrodynamic landscape in several river reaches and in relation to river-floodplain development.

Inundation Mapping Methods

Floodplain Inundation

High resolution topographic data and updated river stage-discharge relationships were developed following the “Great flood of 1993” when the President directed a comprehensive review of floodplain management (Interagency Floodplain Management Review Committee, 1994). A highly accurate floodplain topography digital elevation model (DEM) was created and used in hydrologic modeling to re-define the river stage frequency rating curves along the entire UMRS. I created GIS overlays of Flow Frequency Study (USACE, 2004) flood stage-discharge rating curves on the high resolution topography to create system-wide spatial data for flood inundation patterns for 8 flood recurrence frequencies: 50, 20, 10, 4, 2, 1, 0.5 and 0.2 percent annual recurrence probability (i.e., 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-yr flood). I also overlayed the Flow Frequency Study rating curves and historic rating curves developed for dam impact assessment during pre-dam time periods (1930s) on 1890s topography in several river reaches to examine impacts to natural stage-discharge relationships that are masked by the regulated pool stage. Historic rating curves represent a low flow period (Anfinson, 2003), while the recent flow rating curves reflect increased basin-wide discharge (Zhang and Schilling, 2006).

Topographic Data

The U.S. Geological Survey National Elevation Database available through the National Map Seamless Server (http://seamless.usgs.gov/index.php) provided online access to vast amounts of digital elevation data in an easily accessible and well documented format. Upper Mississippi, Illinois, and Missouri Rivers elevation data were updated using high resolution stereographic techniques in 1998 by the Scientific

Assessment and Strategy Team, a post Great Flood of 1993 commission on floodplain management (Interagency Floodplain Management Review Committee, 1994; SAST http://egsc.usgs.gov/isb/pubs/factsheets/fs10399.html; David Greenlee, USGS EROS Data Center, Souix Falls, SD, personal communication). These data were available, and readily identifiable in metadata for the majority of the river valley. Mississippi River floodplain ("bluff-to-bluff") digital terrain model data was designed and compiled so that spot elevations on well-defined features would be within 0.67 feet (vertical) of the true position (as determined by a higher order method of measurement) 67% of the time. It is approximately 1/6th of a contour interval (4 foot contours; USACE, 2003). High river stages when photography was acquired limited their utility to visualize and model low river stages in mid reaches of the Mississippi River and prevented their use on the Lower Illinois River. The NED30 updated in the NED2003 was used for the Illinois River floodplain (http://topochange.cr.usgs.gov/TopoChange_viewer/viewer.htm).

Data can be accessed at several levels of resolution, I used the default 1 arc second download format to conserve processing requirements over large geographic regions and because subsequent hydrologic modeling analyses were completed at similar resolution. I defined rectangular tiles covering about 100 miles each were downloaded and extracted data by a mask of the 2000 land cover data set for each pool (USGS http://www.umesc.usgs.gov/data_library.html). I mosaiced the pool scale DEMs into a DEM for the entire floodplain. Metric elevations were converted (i.e., times 3.281 in Raster math) to English units to match stage in feet and cubic feet per second (cfs) which is the vernacular of the FFS.

Flow Frequency Study

The FFS was a high profile investigation conducted and documented with great scientific rigor and transparency. The work herein benefits greatly from the FFS. I use text directly from the report (USACE, 2004b) to describe their work:

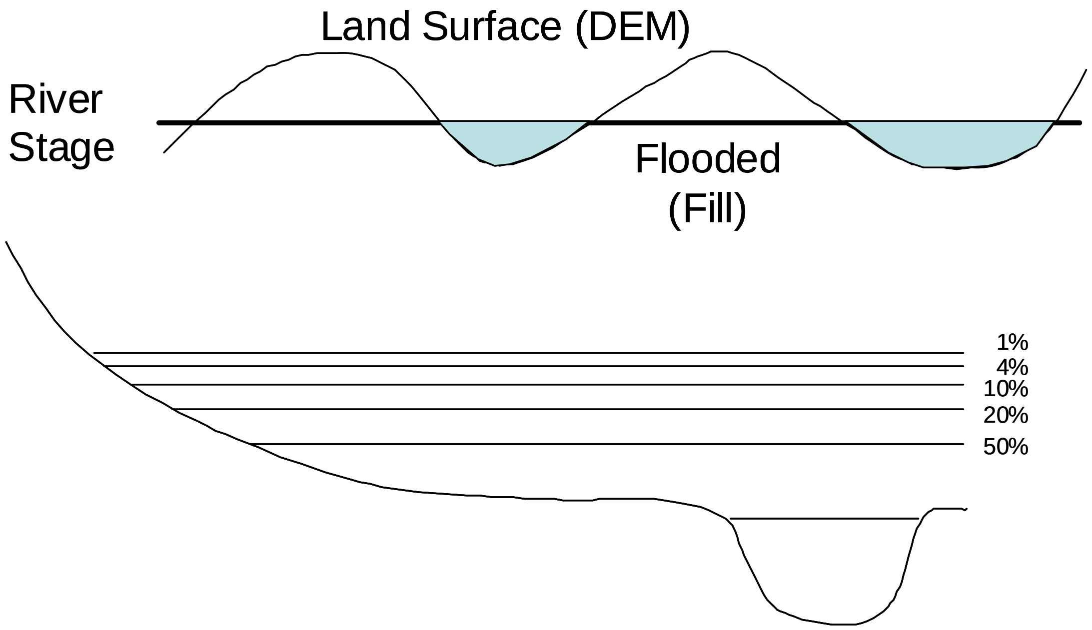
> “Hydrology was accomplished with: 100 years of record from 1898 to 1998; the log-Pearson Type III distribution for unregulated flows at gages; mainstem flows between gages determined by interpolation of the mean and the standard deviation for the annual flow distribution based on drainage area in conjunction with a regional skew; flood control reservoir project impacts defined by developing regulated versus nonregulated relationships for discharges; extreme events determined by factoring up major historic events; and the UNET unsteady flow program to address hydraulic impacts. The result of the hydrologic aspects of the study was a discharge and related frequency of occurrence for stations or given cross sections located along each of the principle mainstem rivers.
>
> “A hydraulic analysis was required to establish the water surface elevation associated with each frequency discharge at each location or cross section along the river reach. The main procedures were to: use the UNET unsteady flow numeric modeling tool; use the recent channel hydrographic surveys (generally obtained for routine channel maintenance) in conjunction with recent Scientific Assessment and Strategy Team (SAST) floodplain digital terrain data collected in 1995 and 1998; and to assume levee failure at the top of existing levee grade based on an upstream and a downstream point. Using these station rating curves and the station frequency flows developed during the hydrology phase, frequency elevation points were obtained for each cross section location. Connecting the corresponding points resulted in flood frequency profiles.

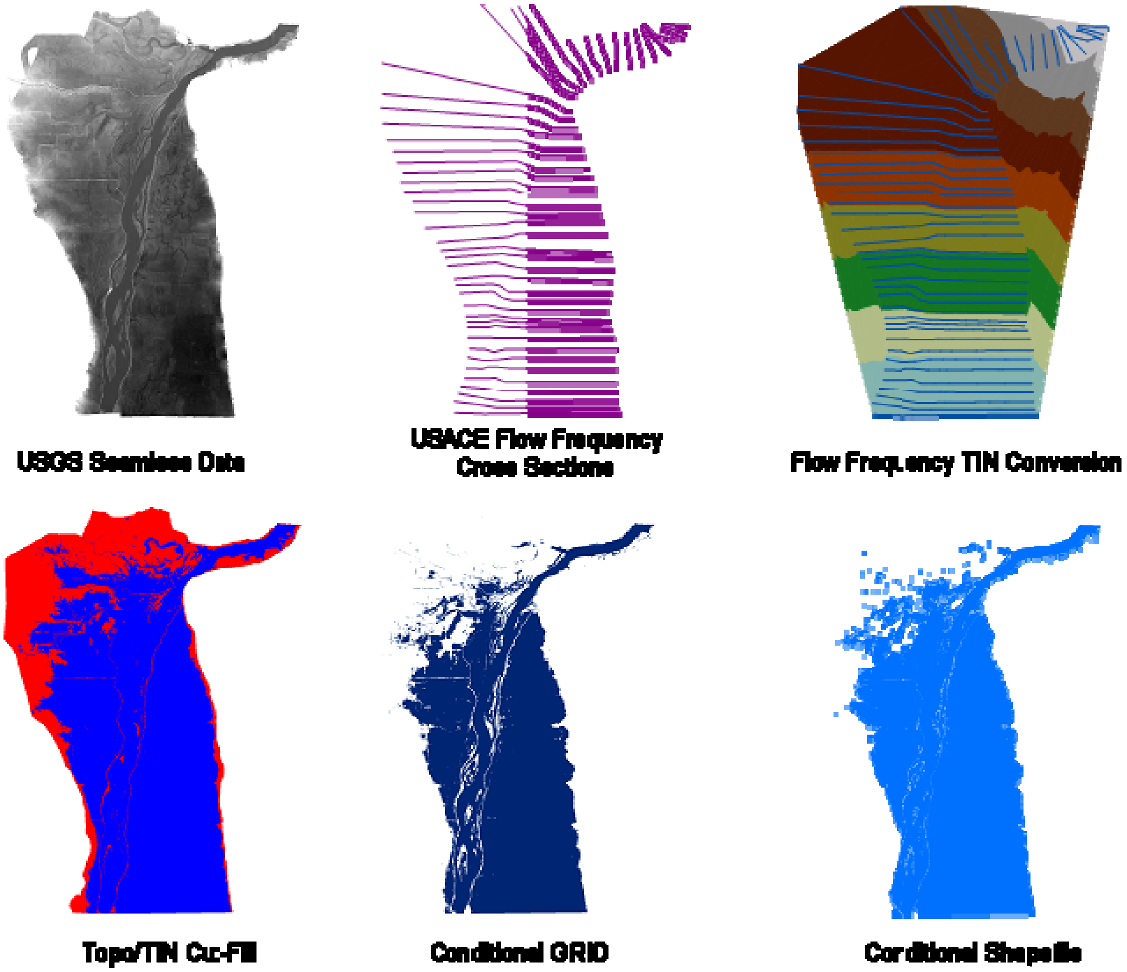
Floodplain Inundation

I used a GIS cut-fill surface analysis to simulated inundation by superimposing a water surface layer across a topographic surface (Ehrhardt, 2001; Figure 31). Terrain above the surface remains exposed, terrain below the surface is “filled” to provide a volume estimate. I created GIS surfaces from the cross-section elevation GIS line features output by the HEC-RAS one-dimensional hydrodynamic model (Figure 32). Triangulated irregular network (TIN) files were created from the cross section feature lines for each separate flood stage attribute (Figure 32). A surface was interpolated across cross sections for each flood stage: 50%, 20%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% recurrence interval (i.e., 2-yr, 5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 200-yr, 500-yr flood).

I used a 20m grid size for the analysis. The area represented as inundated by the cut-fill was separated out as a conditional GRID analysis that selected areas with volume > 0 and output a single GRID with a count of the 20X20 cells below the elevation of the water surface elevation. This value was exported to a spreadsheet where grid counts were converted to area estimates (acres) at the navigation pool scale at which they were created. The resulting GRID was converted to a shapefile to merge with other layers (Figure 32). Features within each water surface inundation polygon layer were assigned a binary value = 1 to identify their unique spatial extent. Non-inundated areas would automatically assigned a 0 in subsequent merges. I merged all the pool-scale stage inundation maps to create system-wide coverages that can be manipulated in GIS. The eight separate flood inundation shapefiles and the LTRMP water area shapefile provide a complete range of inundation maps from low controlled river stage to simulated flood stage up to the 0.2 percent annual recurrence frequency flood stage for most of the Upper Mississippi River System.

Figure 31. Schematic representation of the cut/fill procedure to estimate inundation from surface topography and flood stage estimates after Ehrhardt 2001. Increasingly larger floods inundate larger areas, but the most frequent floods could potentially inundate large portions of the floodplain in the absence of impoundment or levees.





USGS Seamless Data

USACE Flow Frequency Cross Sections

Flow Frequency TIN Conversion

Topo/TIN Cut-Fill

Conditional GRID

Conditional Shapefile

Figure 32. Analysis layers used in flood inundation mapping. See text for details.

Scale Limitations

Models are, by definition, abstractions of real-world systems and are inherently simpler than the real systems that they represent. The FFS river stage estimates represent existing watershed and floodway conditions as represented by the boundary conditions established in the model. The set of circumstances represented in these images and statistics will never occur precisely the way depicted because any of the multitude of changes in the system (e.g., different rain distribution, watershed development, levee push-ups, etc.) that will change model conditions. Large scale flood characteristics and patterns are represented well by the data sets compiled for this analysis, but site-specific planning requires much more detailed survey, monitoring, and design. These floodplain inundation surfaces were not intended for use in flood hazard assessment, their principle ecological value is the depiction of the 2-yr flood. My objective for this analysis is to define the physical drivers that structure plant and animal habitat and large scale landscape patterns to estimate their future potential response to ecosystem restoration and floodplain management actions.

Temporal scale limitations are significant in that the 1994 Flow Frequency Study represents the leveed system and contemporary discharge regime. Today's discharge is greater than in the period of the historic land cover data. The early 1800's was a cool, wet period (Art Bettis, University of Iowa, Iowa City, Iowa, personal communication), but accurate discharge models for the period are not available. My results therefore allocate historically dryer plant communities into contemporary inundated areas. The effect is likely most pronounced in the 2-yr inundation zone because of the relatively greater surface area encompassed by the frequent floods. We have some examples of modeled pre-dam inundation that could refine these estimates (Pinter and Heine 2005; Remo and Pinter, 2007; Dan McBride, USACE Rock Island District, Rock Island, Illinois, personal commnication). The topographic and discharge data required to model the entire pre-dam hydrology are available.

Results

Stage-Discharge Relationships

My analysis in this research concerns the spatial distribution of water during high discharge events, whereas another related stage impact analysis documented changes in the very critical low discharges where dam effects are exhibited (Theiling and Nestler, 2010). The results from the stage analysis are important for some of the inundation concepts, so I summarize some of the most important results here. First, impoundment alters the natural stage discharge relationship (Figure 34). I showed that unregulated historic river stage variation was related to the earliest discharge records and that the association during the modern era declined depending on location within a navigation pool (Figures 34 and 35). Impacts to river stage predictability, seasonality, variability, and flashiness changes were detected in pre- and post dam comparisons as well as along a within pool hydrologic gradient that is stable near the dam and variable upstream toward the next dam (Figure 36).

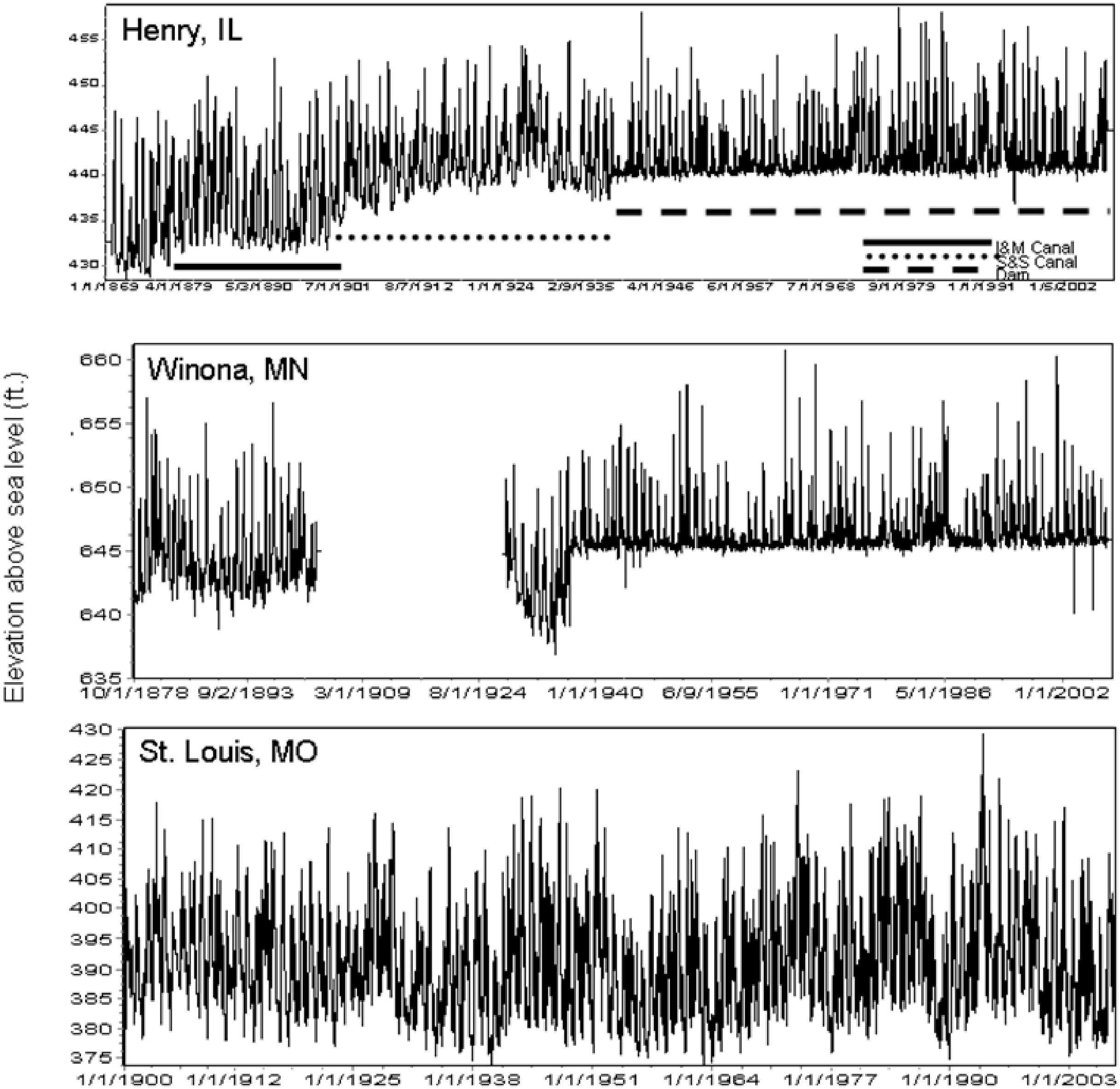


Figure 33. Long term daily stage hydrographs at Upper Mississippi River System locations on the Illinois (Henry), Upper Impounded (Winona), and Unimpounded (St. Louis) Reaches.

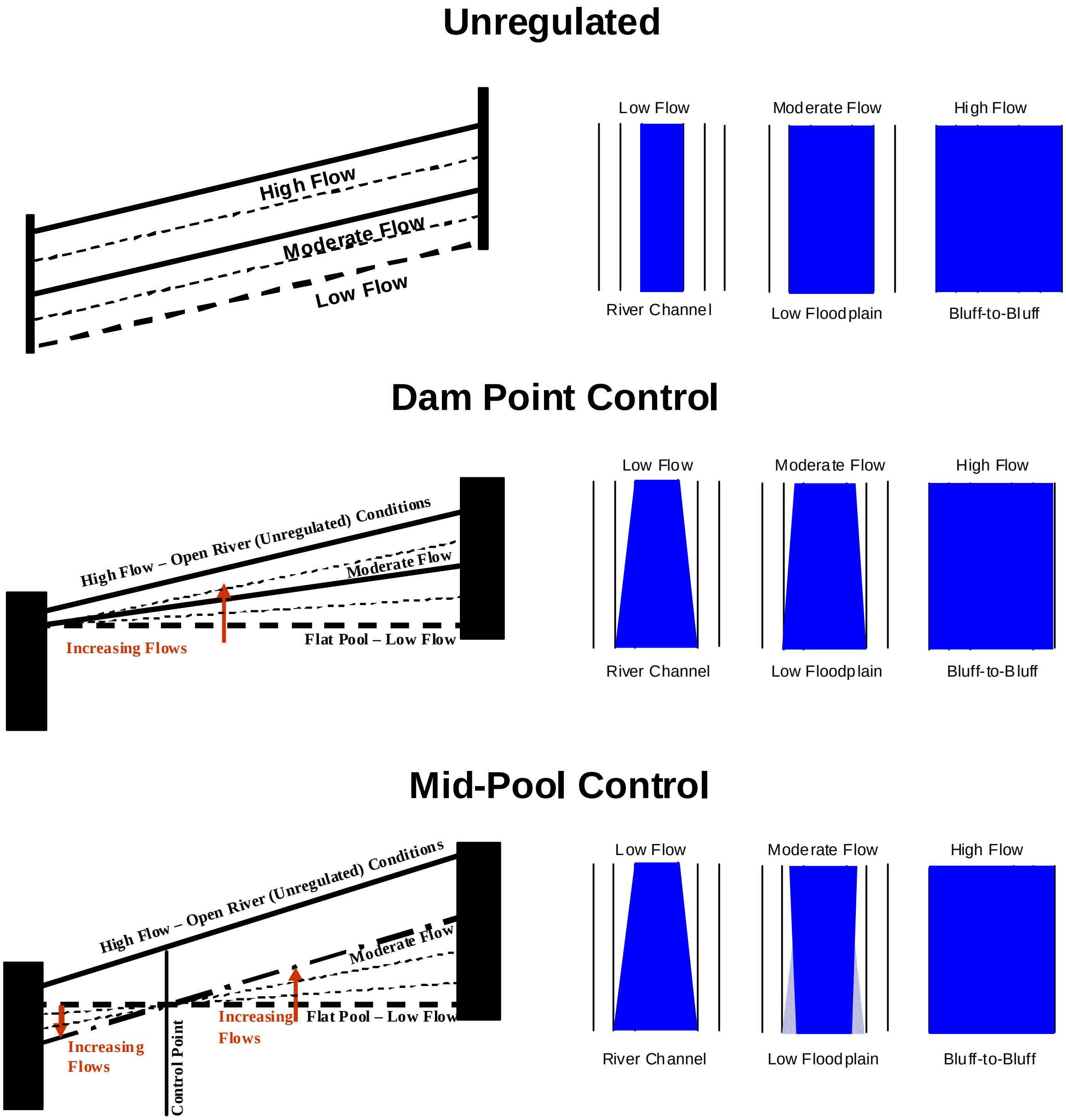


Figure 34. Schematic representation of river stage (left) and planform surface water distribution relative to dams and dam operating procedures. The hatched area in the lower middle planform figure represents a drawdown zone where the river bottom is exposed.

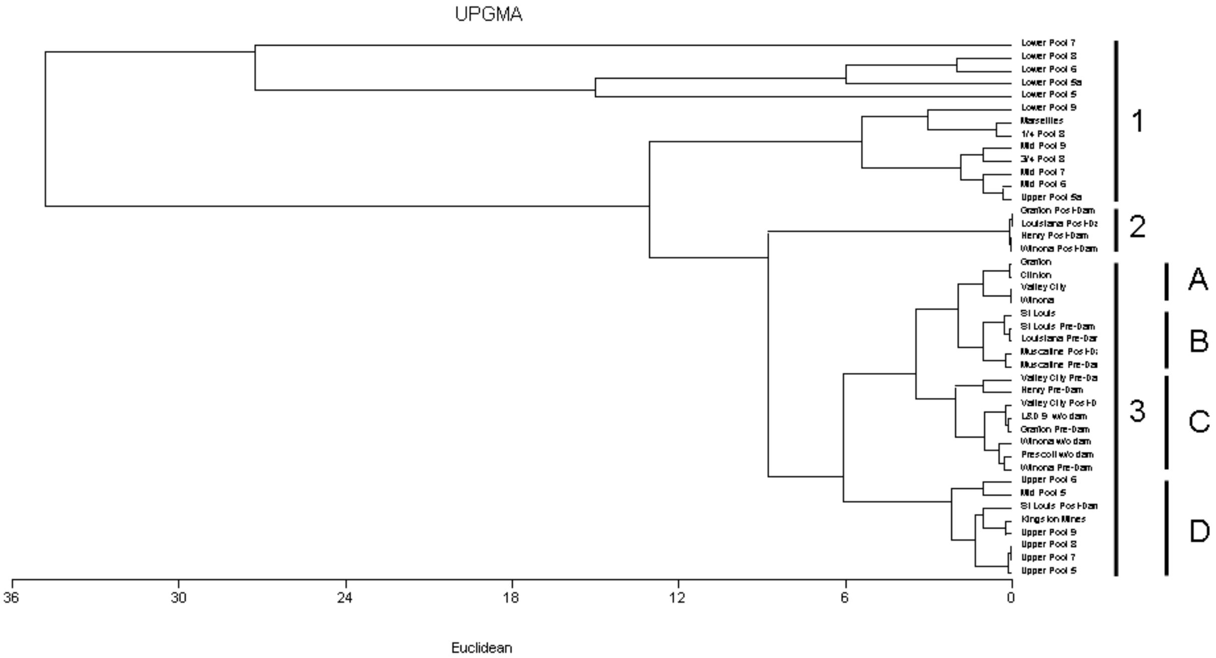


Figure 35. Cluster analysis using coefficient of variation, predictability, constancy, and flashiness parameters (see text) to classify Upper Mississippi River System hydrologic records and several types of gauges.

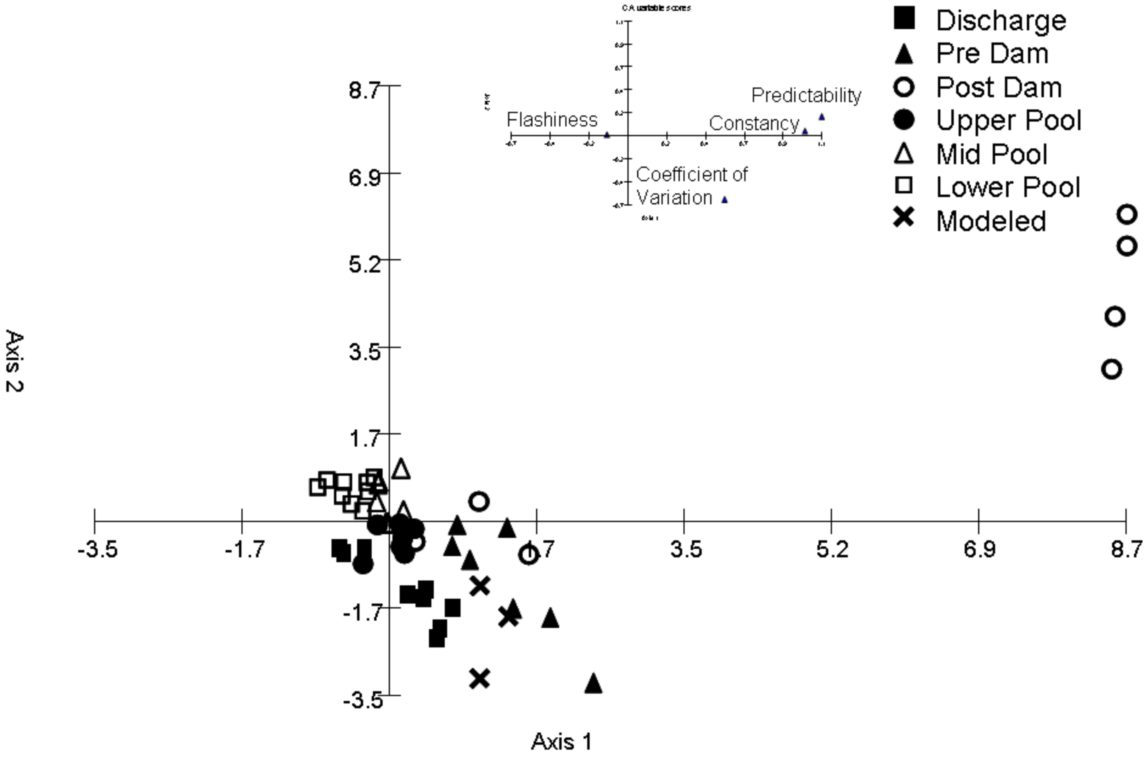


Figure 36. Correspondence analysis scatter plot of a variety of Upper Mississippi River stage, discharge, and modeled gauge records against coefficient of variation predictability, constancy, and flashiness parameters.

Inundation Mapping

The Upper Mississippi River System is 1,181 river miles long, and floodplain inundation mapping was completed for 1,031 of them. Nearly the entire Upper Mississippi was mapped (excluding Pools 1 and 2), but the Upper Illinois was not mapped because of the limited capacity to manipulate operations at the high head dams there. The Illinois River study area defined by the 2000 LTRMP land cover extent closely matches the flood extent, with 90 percent of the land cover mapped area inundated by the 1 percent exceedence flood (Table 4). Floodplain extent was not defined so well on the Upper Mississippi River, only 72 percent of the 2000 land cover extent was inundated by the 1 percent exceedence flood (Table 4). There are many remnant glacial terraces that don't get flooded in many parts of the Mississippi River floodplain whereas many Illinois Valley terraces do get inundated. There may be slight underestimates defining the maximum flood extent at the valley margin based on the floodplain delineation used (Laustrup and Lowenburg, 1994).

Table 4. Land cover extent, flood inundation mapping extent, and extent of the 1 percent recurrence (100-yr) flood in acres and proportion for the Upper Mississippi River (UMR), Illinois River (IR), and combined Upper Mississippi River System (UMRS).

River	2000 LC Extent	Flood Mapped	Percent Mapped	100YR Extent	Percent Inundated
UMR	2,284,526	2,191,513	96%	1,567,063	72%
IR	664,372	558,041	84%	504,952	90%
UMRS	2,848,898	2,749,554	97%	1,995,622	73%

Inundation surfaces for the pool stage and 50%, 20%, 10%, 4%, 2%, 1%, 0.5%, 0.2% recurrence interval (i.e., 2-yr, 5- yr, 10- yr, 25- yr, 50- yr, 100- yr, 200- yr, and 500-

yr flood) floods were produced separately for 29 pools and 2 unimpounded reaches. Individual pools or reaches can be displayed in many ways, but the system is too large to represent in a single map image. Planners and researchers will be able to filter down through the system-wide matrix to their area of interest to understand where they are positioned in the larger ecosystem. They will be able to add their site-specific data, objectives, and design tools to optimize their research and restoration plans. Online access is achieved using a Decision Support System through USGS LTRMP servers.

Various river reach segmentation schemes (see Figure 1 and Table 2) were applied to visualize flood patterns and estimate area inundated at various scales. The navigation pool segmentation is a traditional scale considered on the UMRS. Each flood inundation layer can be plotted individually and data tallied and presented at a scale that is very familiar to most stakeholders (Figure 37). The detailed data can be plotted together to provide system-wide perspectives, and nested scales (e.g., pool reach, Floodplain Reach, District) can be layered to generalize at larger scales. Data presented at the pool scale are useful for trend detection (Figures 38 and 39). Total area inundated increased in a downstream direction as the river-floodplain gets larger. Noteworthy however at this scale, is the relatively consistent total area of the regulated pool stage regardless of the floodplain size. Mississippi River aquatic habitats south of Rock Island thus occupy a much smaller fraction of the total floodplain area than northern river reaches. The lack of separation among flood stage lines upstream from Pool 16 implies that impoundment has inundated a greater total proportion of formerly terrestrial floodplain habitat than downstream. Also, the FFS flood stage inundation estimates rapidly inundate the floodplain (Figure 39) with more than 60 percent of the maximum modeled stage (0.2 percent flood) inundated by the 50 percent recurrence interval (i.e., 2-yr) flood. The data are consistent with the estimate of bankfull stage occurring between the 1 – 2 yr recurrence interval stage (Leopold et al., 1964).

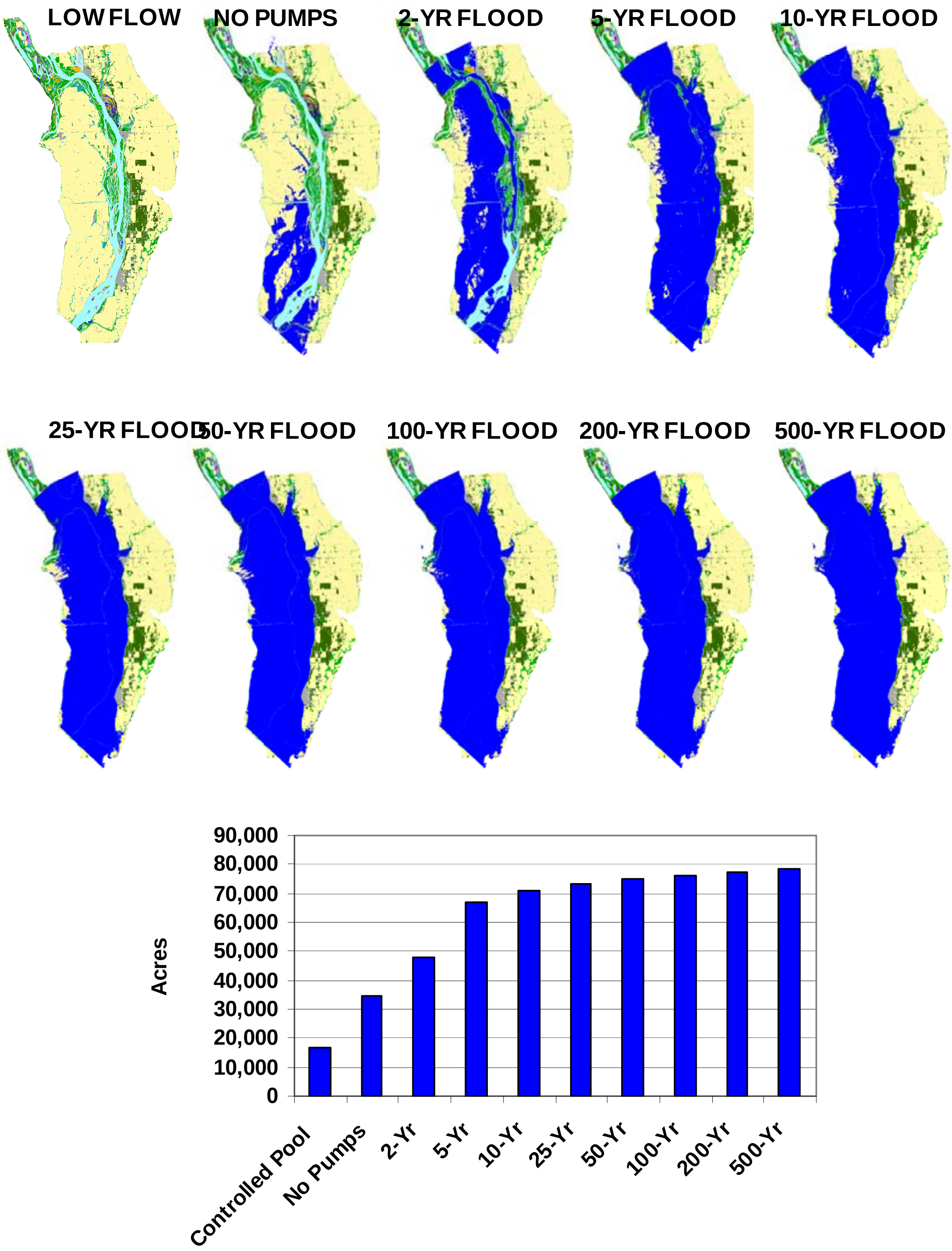


Figure 37. Examples of flood inundation surfaces for Pool 18, Upper Mississippi River System. A large proportion of the floodplain is inundated by frequent floods indicating that potential energetic and material transport could be great in the natural system and is greatly altered by dams and levees.

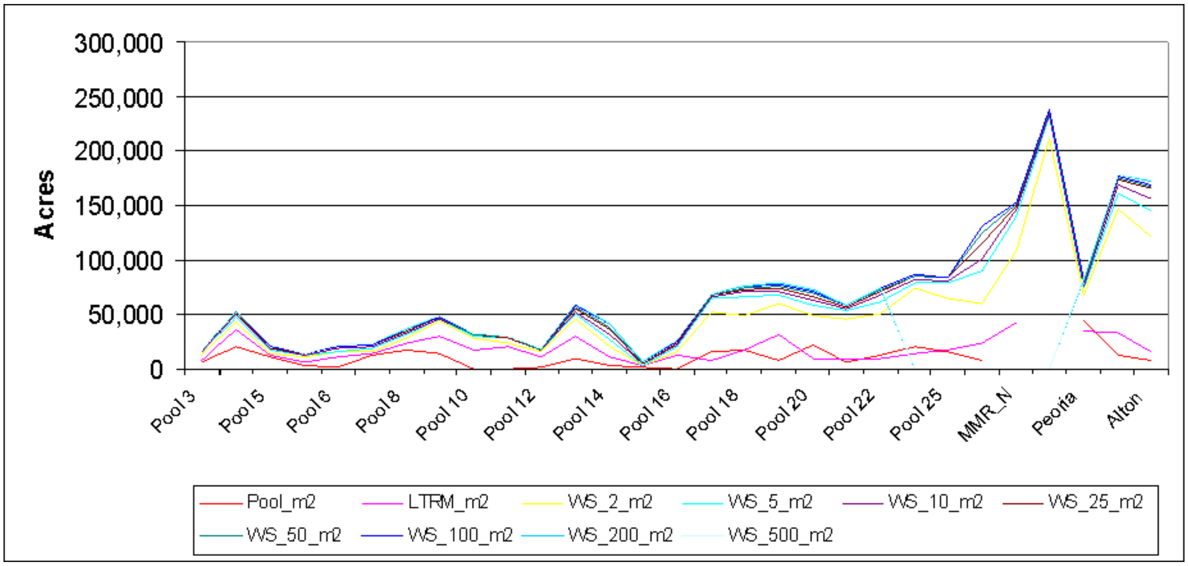


Figure 38. Area inundated by pool for each water surface assessed. Pool reaches (1 – 11) are superimposed to lump pools with similar characteristics.

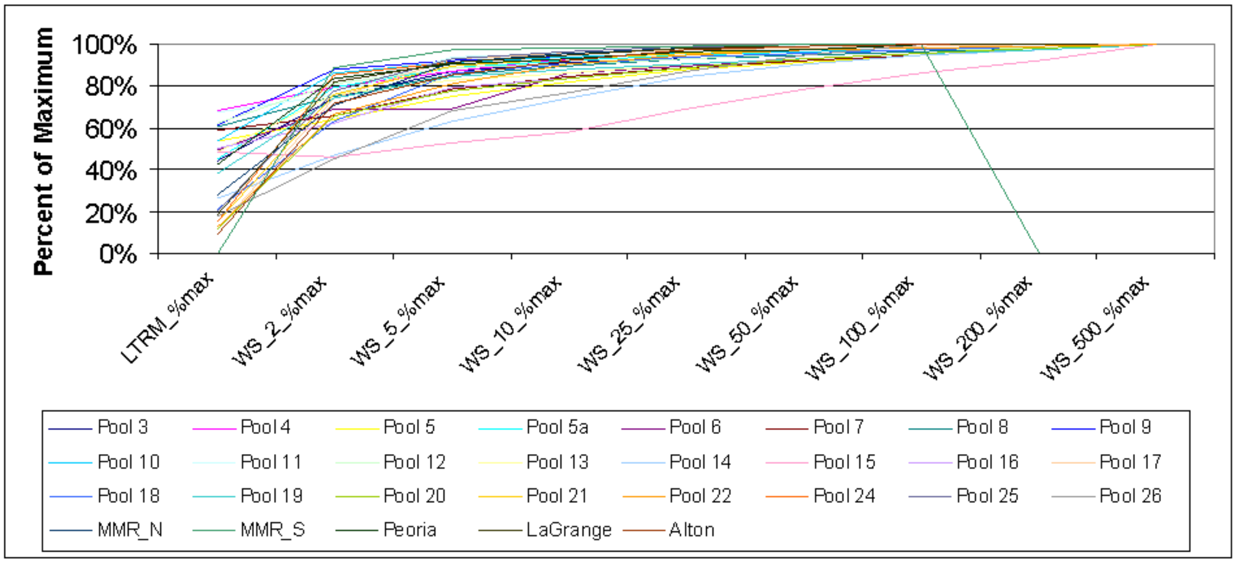


Figure 39. Percent of maximum flooded area inundated by pool for each water surface assessed reveals great similarity in the rapidity at which the floodplain was likely inundate by the frequent flood prior to development. The outliers below the group are Pools 14 and 15 in the Rock Island Gorge and Pool 26 at the mouth of the Missouri and Illinois Rivers. Estimates for WS_200 and WS_500 were not available for St. Louis District Pools 24 – 26, MMR-N, MMR-S, and Alton.

The outliers below the group are Pools 14 and 15 in the steep Rock Island Gorge and Pool 26 at the topographically diverse confluence of the Mississippi, Missouri and Illinois Rivers.

The pool scale perspective is too coarse for many applications, so a river mile segmentation was applied using a GIS overlay on the inundation maps (Figure 40). River miles follow the channel and are not uniform spatial units, but they do help refine perspective for ecological investigations. One of the most striking comparisons to the coarser resolution data above is in the River Mile 200 – 220 (Pool 26) reach at the great rivers confluence. Inundation diversity is masked in graphs above compared to readily apparent diversity in the color scheme that matches mapped colors. The geomorphic reach segmentation scheme applied here is closely aligned with geology so the range of area inundated between high and low stage is similar within each reaches. Finer scale patterns and trends can be detected by focusing on specific reaches (Theiling and Nestler, 2010). Lower Illinois Geomorphic Reaches have been lumped (Figure 40), these data can greatly support a refinement of that scheme. An upstream reach with little stage variation is apparent, and three or four reaches are apparent below river mile 150.

A regional view and stacked flood stage layers (Figure 41; Appendix C) presents a much different, larger scale perspective on hydrogeomorphic characteristics throughout the river. The image at the confluence of three great rivers, the Illinois, Mississippi, and Missouri, present a considerably different pattern and diversity of flood inundation profiles than anywhere on the river because of the huge sediment load deposited in a mound by the Missouri River (Figure 41). Plotting the proportion of the floodplain inundated system-wide (Figure 42) reveals 5 – 7 reaches that show greater diversity of flood inundation patterns than others. The diversity is coincident with tributary confluences and geologic controls (WEST Consultants, Inc 2000). Note in Figure 41

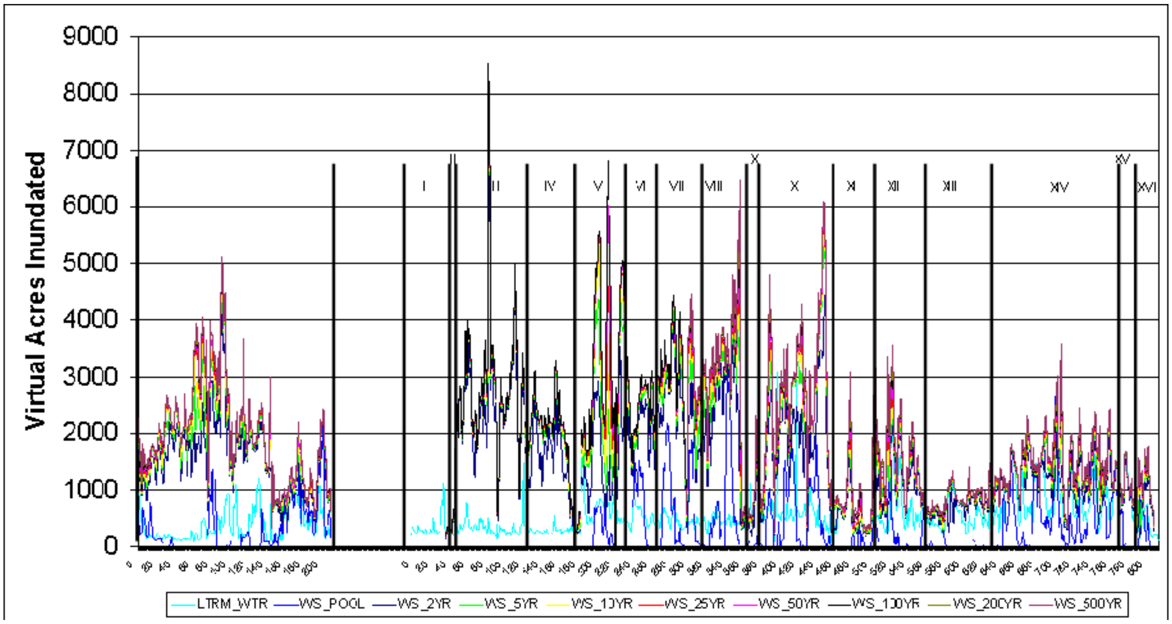


Figure 40. A river mile segmentation greatly increases the resolution of the flood inundation layers. A further refinement of Mississippi River geomorphic reaches also helps classification tasks.

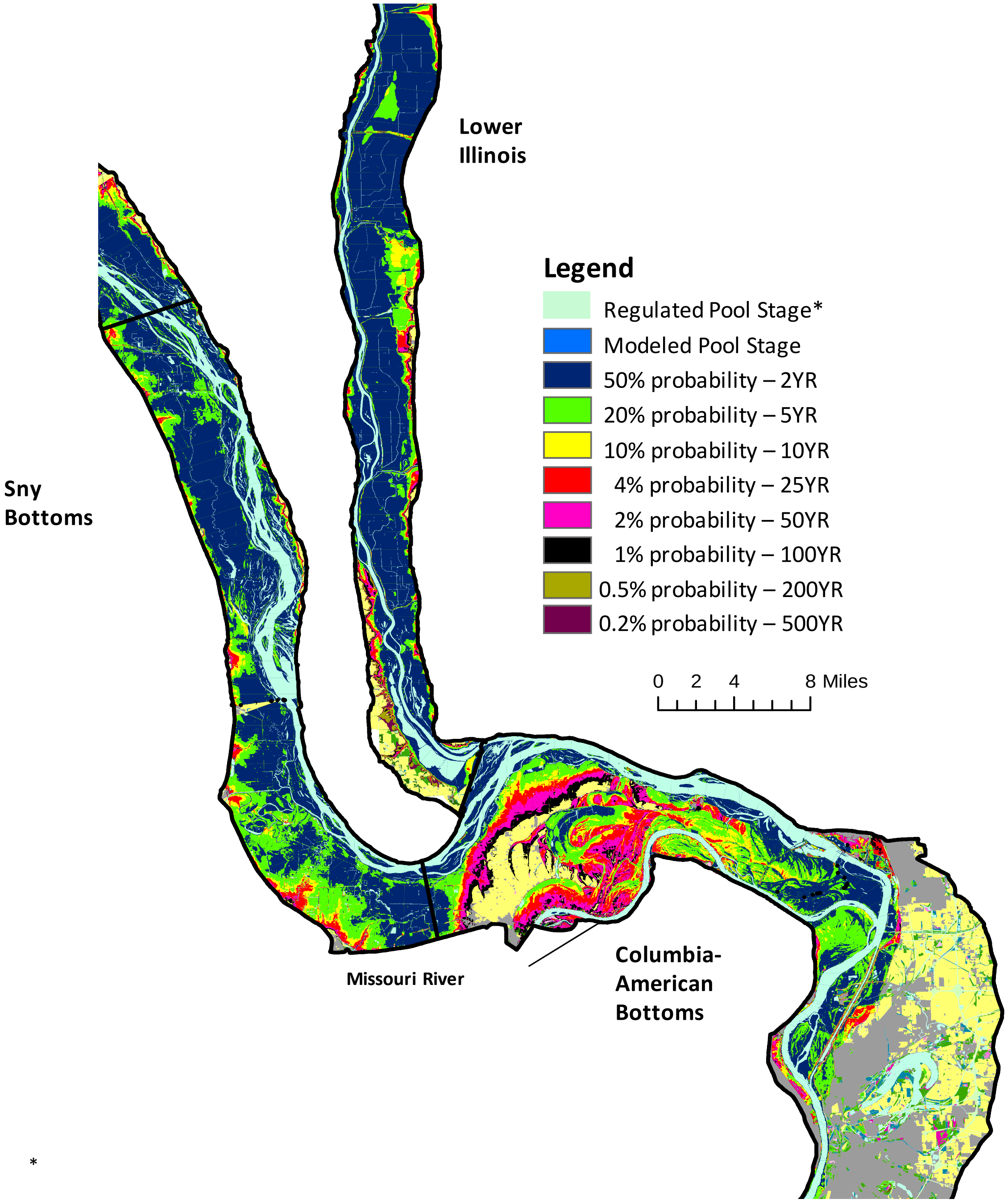


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Figure 41. A regional perspective helps visualize hydraulic associations among large geomorphic features.

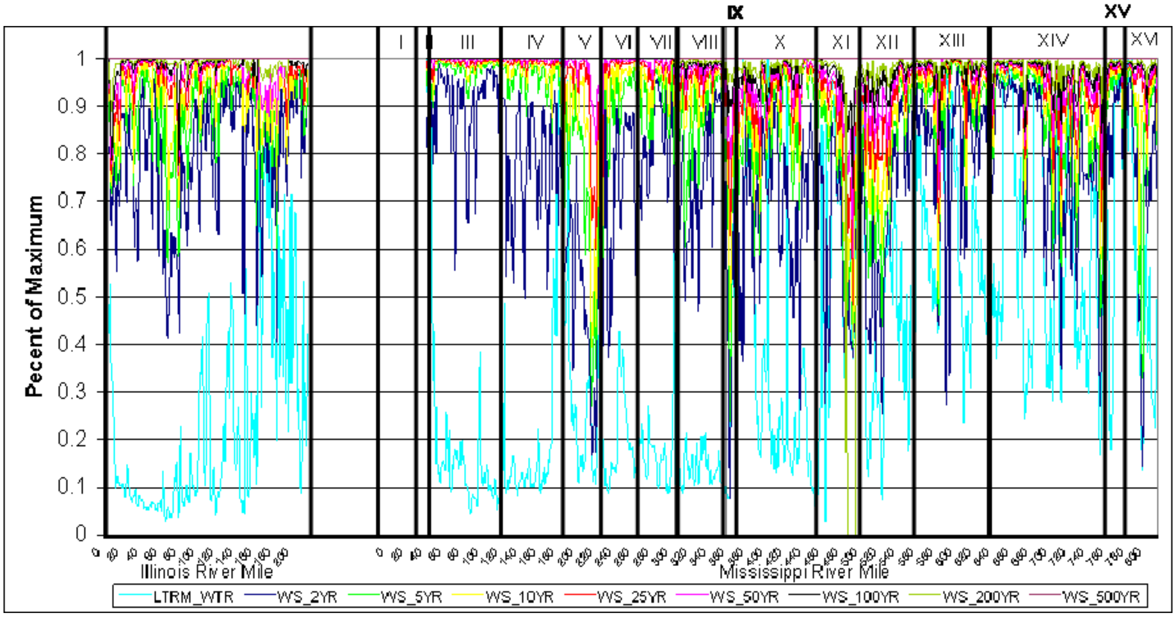


Figure 42. A system-wide view of the proportion of floodplain inundated at each flood stage reveals 5 – 7 reaches that are more diverse than others which fill 80 percent of the floodway 10 percent of the time.

how the 0.5, 0.25, and 0.10 annual recurrence probability floods completely inundate the Mississippi and Illinois floodways above the Missouri River. The impounding effect of the Missouri River alluvial fan is similar to the alluvial fan formations creating Lake Pepin and Peoria Lake (Theiling et al., 2000; WEST Consultants, Inc., 2000), but exhibited at this great river delta only at flood stage. The same flood stages inundate 70 – 90 percent of the floodplain in most reaches (Figure 41). These hydrogeomorphic characteristics have great influence on plant community development, these maps should be of great benefit evaluating land cover characteristics.

Multivariate Analysis of Floodplain Inundation Characteristics

I summarized several UMRS simulated floodplain inundation classes (i.e., 50, 20, 10, 5, and 1 percent recurrence flood) by river mile and geomorphic reach into a spreadsheet of inundation class by geomorphic reach. Inundation classes were then extracted by a mask of UMRS levees to assess changes from floodplain development. These were also summarized by geomorphic reach. The inundation classes in leveed areas were subtracted from the maximum simulated inundation surface in each geomorphic reach (i.e., 1 percent or 0.02 percent recurrence flood) and data were normalized as percent of maximum inundation area. Data were analyzed as described in Chapter 1 with Multivariate Statistical Package (MVSP, Kovach Computing, Inc., 2008) using correspondence analysis to explore geographic relationships among inundation frequency and UMRS Geomorphic Reaches. Cluster analysis was used to explore similarity among reaches.

Cluster analysis using the entire UMRS floodplain potential inundation data set created two groups and a single reach outlier, Quincy Anabranch Reach (Figure 43). The clusters represented downstream and upstream regions separated at the Rock Island

Gorge. The Quincy Anabranch and Columbia Bottoms reaches at the top of the dendrogram have diverse inundation patterns. The upstream cluster (Group C) has intermediate inundation frequency, and the downstream cluster (Group B) is potentially most frequently inundated. The correspondence analysis ordination of the simulated floodplain inundation identified three loosely related groups (Figure 44). Narrow valley reaches and low elevation reaches plot in the vicinity of the 50 percent recurrence interval area (%WS_2YR) variable on the CA biplot. The 20 percent and 10 percent recurrence interval areas influence reaches below St. Louis and in the mid valley reaches. The 2 percent and 1 percent recurrence interval inundation areas influence steep valley segments in the Rock Island Gorge and Maquoketa River Reaches, and the Columbia-American Bottoms Reach stands out as unique among all reaches because of the much larger areas inundated at higher river stages. Differences among reaches can be seen as the separation among inundation lines on Figure 42, the longer spikes represent greater relative area inundated by each river stage.

Floodplain development changes hydraulic connectivity differently throughout the UMRS. Cluster analysis of the connected floodplain area only created two clearly separated groups of leveed and unleveed geomorphic reaches (Figure 45). The geography follows the typical north-south split at Rock Island, except for Columbia-American Bottoms which has a large, unleveed high elevation area at the confluence of the Missouri River. The correspondence analysis plots very similarly to the full potential inundation area results above, except for the Jefferson Barracks Reach which moves closer to the 50 percent inundation frequency variable because part of the reach contains unleveed channel area at St. Louis (Figure 46).

Considering the same impacts from the perspective of leveed area, the cluster analysis of proportion of leveed area by geomorphic reach also yields leveed and unleveed clusters (Figure 47). The correspondence analysis draws the leveed reaches tight into the origin of the CA bi-plot in the quadrant with the 50 percent recurrence interval flood (%2YR_LEV; Figure 48). Unleveed reaches spread out along the gradient of increasing flood stage toward the bottom left of the plot. Columbia Bottoms remains an outlier as above.

The combined simulated total potential inundation area and percent connected area cluster analysis produced sets of reaches including both time periods that occurred close together on the dendrogram (Figure 49). These reaches included the narrow reaches, upstream reaches, and Columbia-American Bottoms which has a low abundance of levees. The widely separated reaches by time periods include all the wide floodplain, highly isolated, southern reaches. The correspondence analysis was color coded by Geomorphic Reach to emphasize change at each site (Figure 50). The changes were not large for most reaches except Columbia-American Bottoms (CB), Des Moines River (DM), Iowa River, Quincy Anabranch, and Jefferson Barracks (JB) Reaches. The separate simulated conditions for several reaches plotted directly on top of each other.

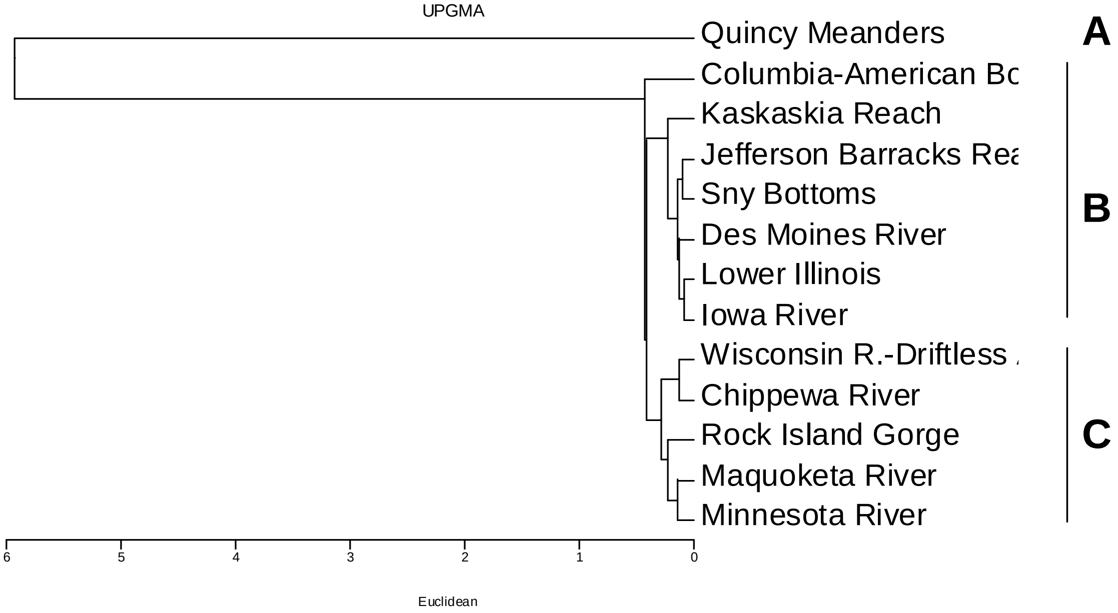


Figure 43. Cluster analysis for 50, 20, 10, 5, and 1 percent recurrence interval for the total potential floodplain inundation frequency area among UMRS geomorphic reaches.

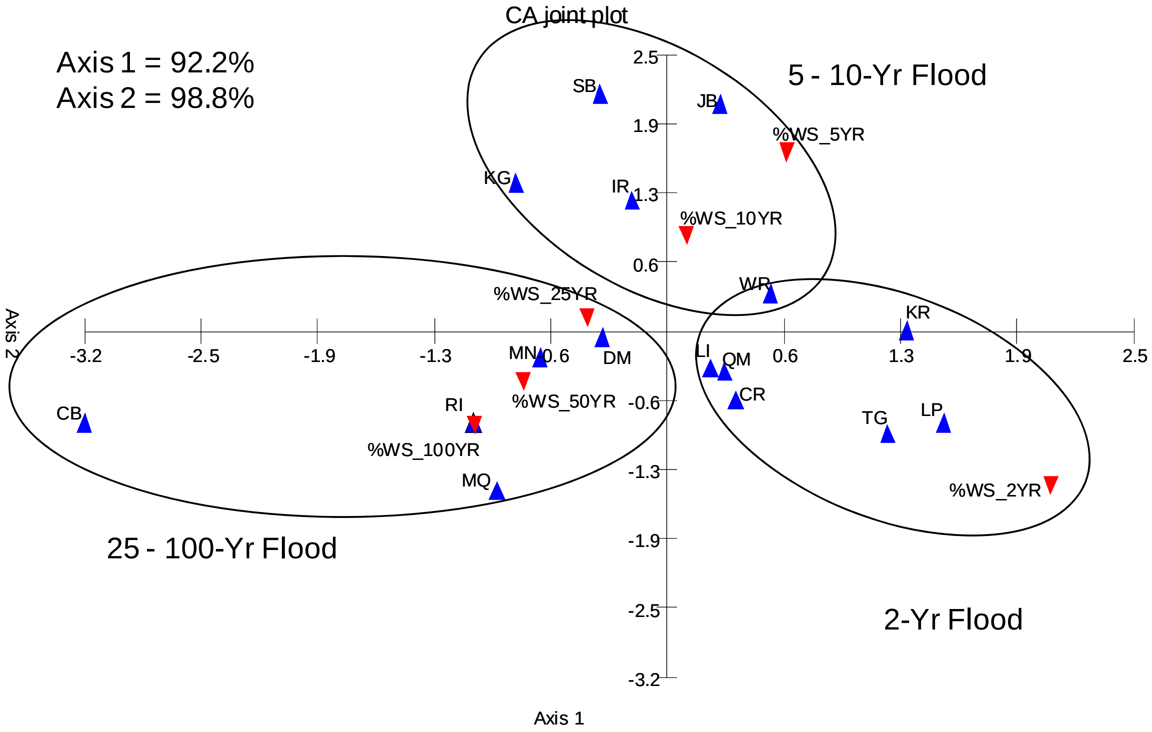


Figure 44. Correspondence analysis for 50, 20, 10, 5, and 1 percent recurrence interval for the total potential floodplain inundation frequency area among UMRS geomorphic reaches.

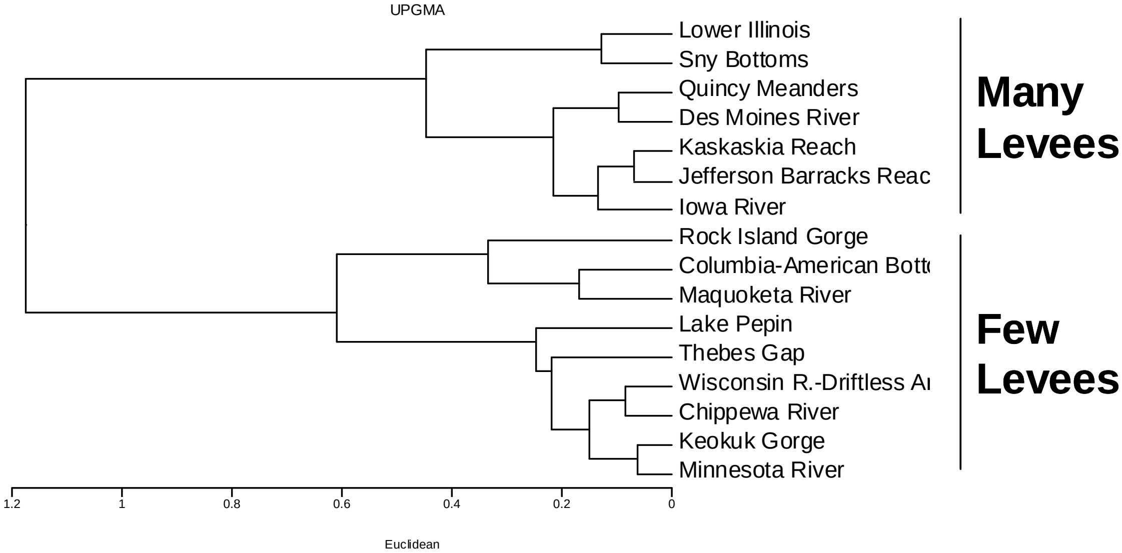


Figure 45. Cluster analysis for 50, 20, 10, 5, and 1 percent recurrence interval for the connected (i.e., unleveed) floodplain inundation frequency area among UMRS geomorphic reaches.

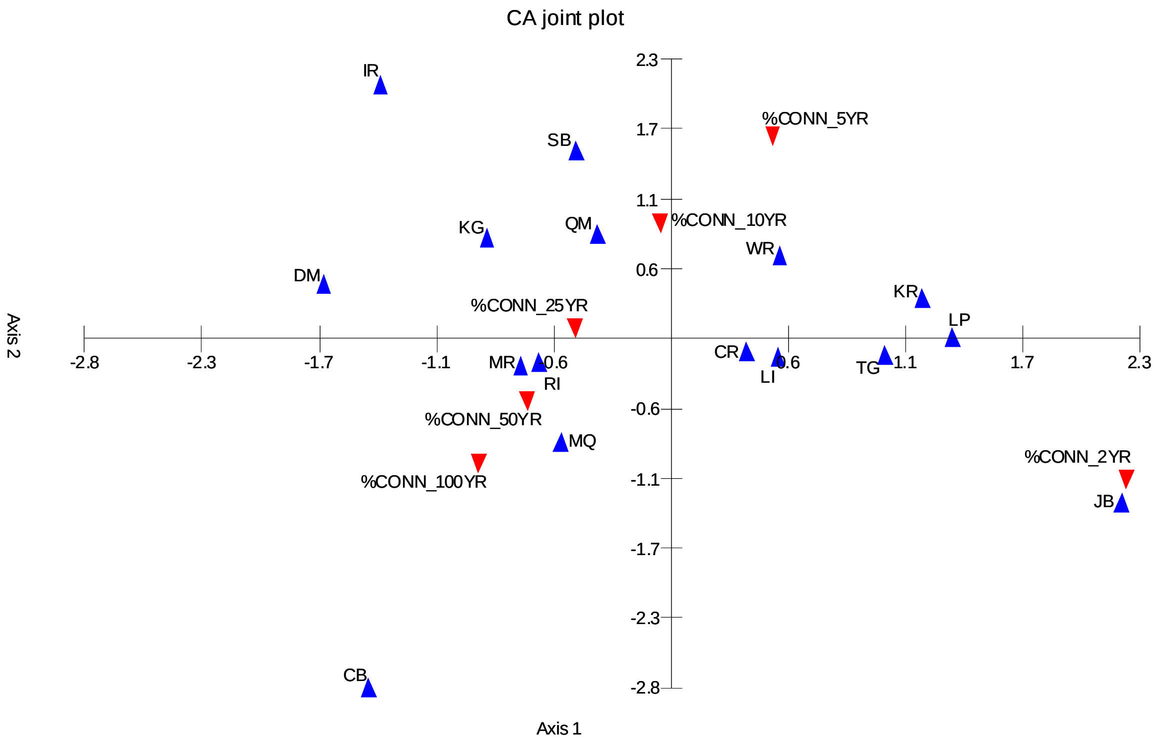


Figure 46. Correspondence analysis for 50, 20, 10, 5, and 1 percent recurrence interval for the connected (i.e., unleveed) floodplain inundation frequency area among UMRS geomorphic reaches.

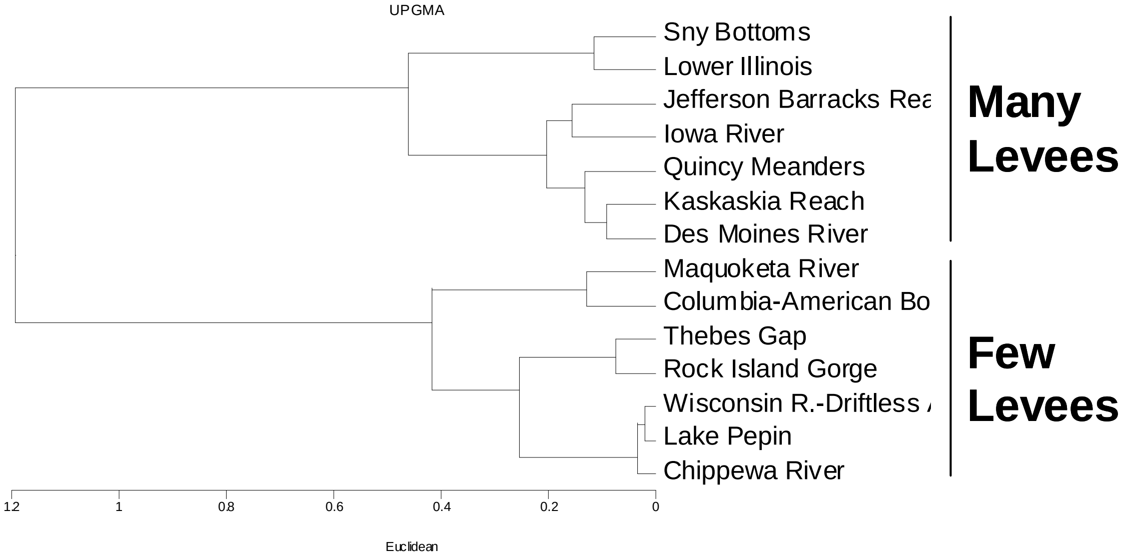


Figure 47. Cluster analysis for 50, 20, 10, 5, and 1 percent recurrence interval for the isolated floodplain (i.e., leveed) potential inundation frequency area among UMRS geomorphic reaches.

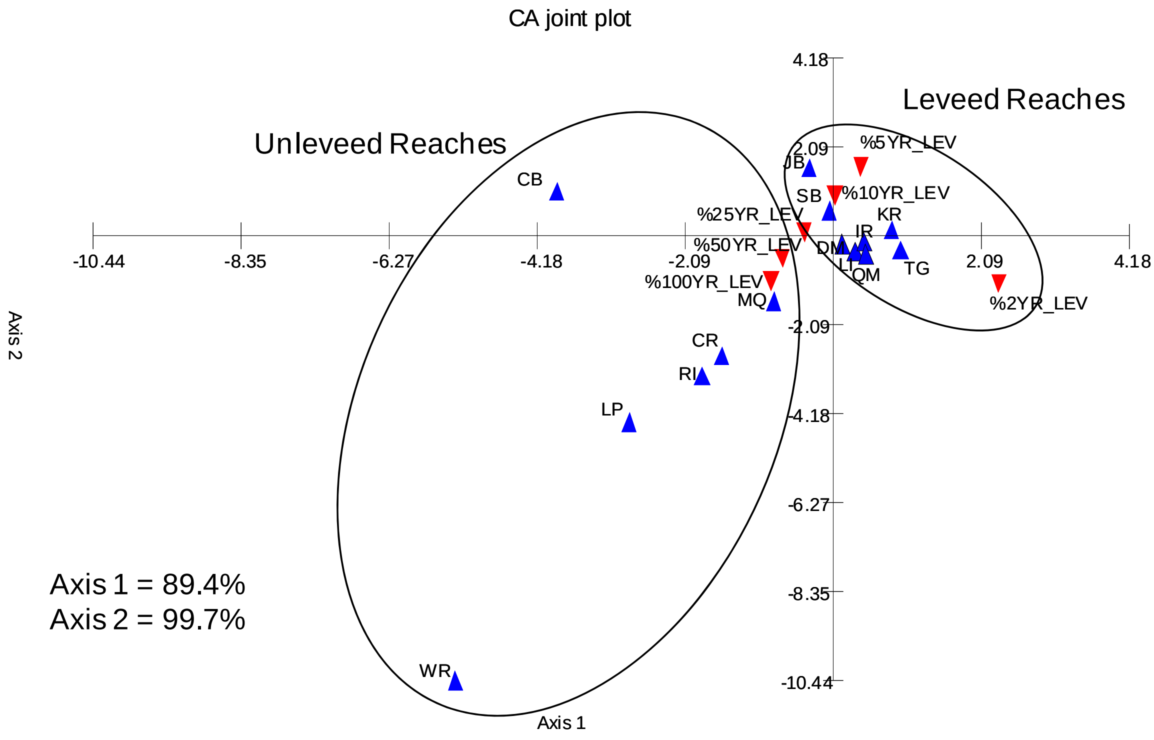


Figure 48. Correspondence analysis for 50, 20, 10, 5, and 1 percent recurrence interval for the isolated floodplain (i.e., leveed) potential inundation frequency area among UMRS geomorphic reaches.

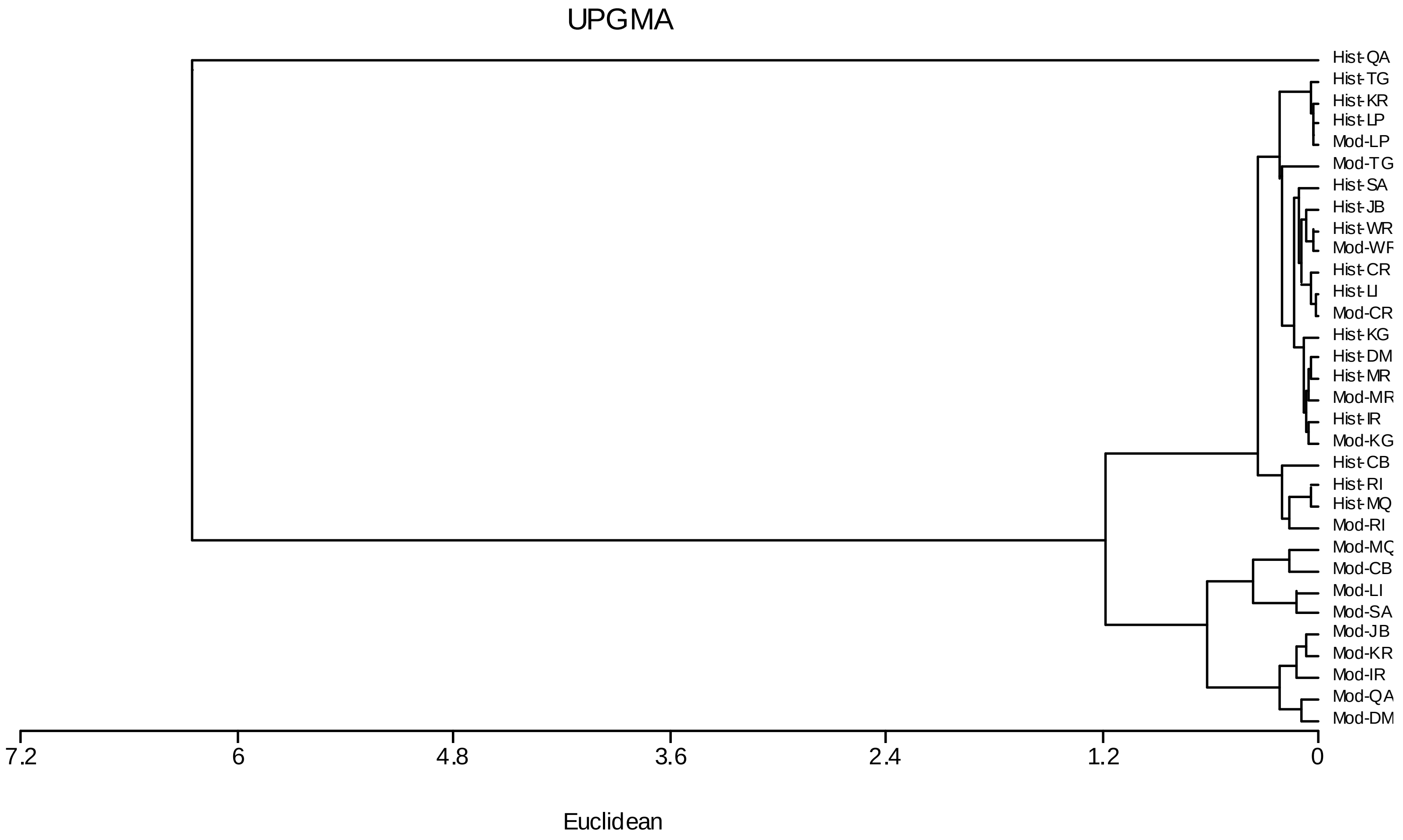


Figure 49. Cluster analysis for 50, 20, 10, 5, and 1 percent recurrence interval for the simulated unleveed potential inundation frequency and for the contemporary connected floodplain area among UMRS geomorphic reaches.

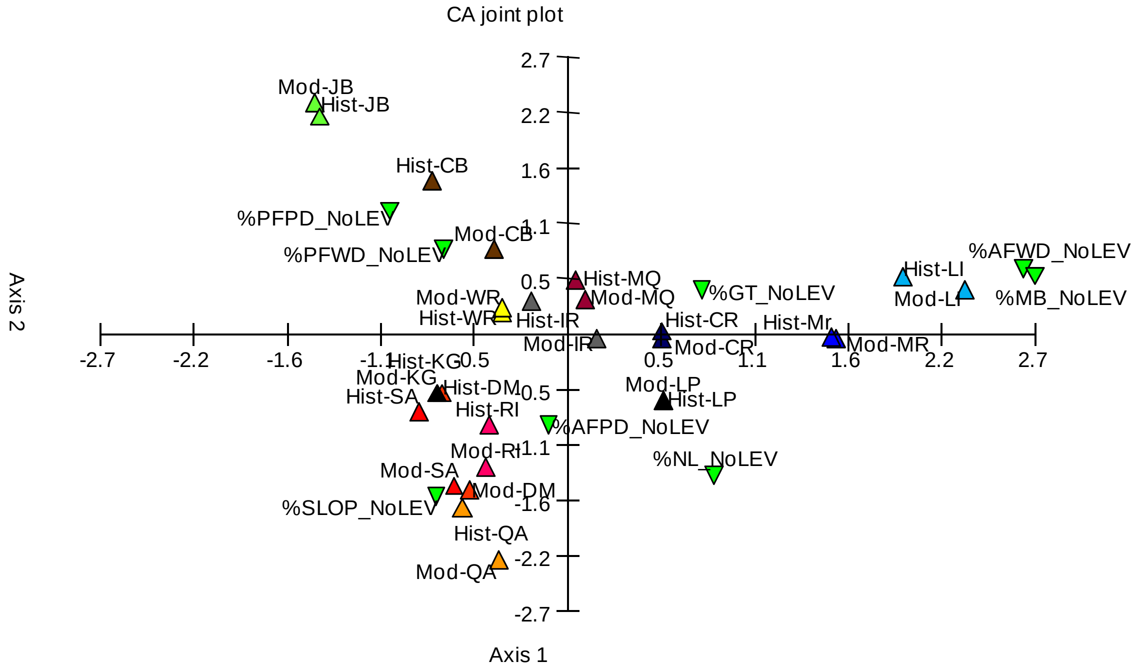


Figure 50. Correspondence analysis for 50, 20, 10, 5, and 1 percent recurrence interval for the simulated unleveed potential inundation frequency and for the contemporary connected floodplain area among UMRS geomorphic reaches.

Discussion:

Implications for Ecosystem Management

It is important to understand the drivers responsible for ecosystem condition, so that restoration and management actions can be targeted at the “most important” drivers. Hydrology is the a key driver in river systems (Welcomme, 1979; Vannote et al., 1980; Ward & Stanford, 1983; Poff et al., 1997; Sparks et al., 1998; and many others). Relating hydrologic and hydraulic changes caused by human activity at river, floodplain, and basin scales were important aspects of this chapter; levees, dams, diversions, and channelization have had profound effects on the UMRS and similar rivers world-wide. The management intent here was to synthesize river hydrology in terms of regional and local characteristics and hydrologic response to development. My analysis documents: 1) impoundment effects (i.e., less seasonal variability; see also Theiling and Nestler, 2010), 2) a post dam within-pool hydrologic gradient that creates repeating patterns of riverine, backwater, and impounded aquatic habitat conditions among the pooled reaches (see also Theiling and Nestler 2010), and 3) potential floodplain inundation patterns. The synthesis demonstrated that hydrologic conditions and alterations were expressed differently in general on the landscape in at least four distinct river reaches (Lubinski, 1999; WEST Consultants, Inc., 2000) and in detail in 18 river reaches. These differences have implications for the type of responses to development that have occurred and the types and likely success of management actions among river reaches.

Hydrologic alteration is responsible for much of the ecological change in the UMRS, including obvious direct effects of impounded surface waters, restricted flood flows, regulated flow patterns in channels, and altered hydraulic residence time in backwaters. More subtle indirect effects like altered water quality (Houser and Richardson, 2010), vegetation distribution (Moore et al., 2010), forest community structure (Romano, 2010), and invertebrate and fish community distribution (Garvey et al., 2010) are harder to document.

Ecological conditions can be managed by adjusting key drivers, and hydrology and hydraulic drivers are highly responsive to management actions that can be achieved at reasonable cost. On the UMRS for example, islands are constructed at a local scale to break up wind and currents in open water impounded areas subject to wind-generated waves that resuspend fine sediment (Langrehr et al., 2007). Water level drawdowns at the dams or in managed backwaters are used to promote emergent and submersed aquatic vegetation in shallow floodplain aquatic areas at a larger scale. Innovation and refinement of restoration techniques in the field for more than 20 years has set the foundation for a more active adaptive environmental assessment and management framework for the UMRS. The multivariate analysis described here can help target restoration actions to the most appropriate hydrologic condition .

The juxtaposition of navigation, flood protection, ecosystem management, and other social issues on the UMRS creates a complex hydrodynamic environment that is largely controlled by human processes. Frequent floods inundate a disproportionately large part of the floodplain as occurs on most rivers (Leopold et al., 1964). The overlap in space between the ecological benefits provided by the movement of the 2-yr flood across a connected floodplain (i.e., Aquatic Terrestrial Transition Zone, *sensu* Junk et al., 1989) versus the immense agricultural production behind a levee is a perfect example of the management issues that must be faced. It may rarely make sense to remove a L&DD completely, but there are some that will make sense to remove and they should be pursued ambitiously to relieve pressure on remaining levees (USACE, 2006). There are others that may be economical for agriculture, but may harbor exceptional restoration opportunities that warrant conversion also. Wetland management opportunities within levee districts must also be pursued. Recent floodplain restoration has shown great success converting entire L&DDs to ecosystem restoration purposes (The Nature

Conservancy, 2007; Wetlands Initiative, Inc., 2008), it may be possible to manage wetland and agriculture cooperatively in others. The flood inundation layers I present here provide important information for large scale UMRS floodplain ecosystem restoration planning.

CHAPTER 4: CAN LAND COVER PATTERNS AND THEIR CAUSES BE IDENTIFIED IN THE UPPER MISSISSIPPI RIVER LANDSCAPE?

Introduction

The Upper Mississippi River System (UMRS; see Figure 1) is an excellent ecosystem to consider many landscape ecology topics because, like all river ecosystems it is influenced by physical and biological factors at many scales (Malanson, 1993; Turner et al., 2001; Naiman et al., 2005). The physical landscape structure is of glacial origin and Holocene evolution (Fremling, 2005; Bettis et al., 2008), with large differences in the age and magnitude of events defining homogenous reaches. Distinct reach-scale hydrogeomorphic differences help understand ecosystem response to the development (Clarke et al., 2003; Stallins, 2006) because plant community structure is a result of biological processes and functions regulating their distribution and abundance (Naiman et al., 2005). Benda et al. (2004) and Thorp et al. (2008) both predict that physical structure of the system strongly influences plant community composition and distribution. My analysis uses well documented presettlement and contemporary vegetation communities to test hypotheses regarding plant community and hydrogemorphic relationships for the Upper Mississippi River System

In northern latitudes seasonal cycles present regular spring floods which river ecosystems are adapted to (Sparks et al., 1998; Wlosinski, 1999; Theiling and Nestler, 2010). Seasonal flooding in rivers contributes to high ecological productivity through material transport (Bayley, 1991, 1995), nutrient conversion (Spink et al., 1998), and physical habitat transformation (Leopold et al., 1964). Seasonal growth, reproduction, senescence, etc. are frequently linked to seasonal hydrology (Bunn and Arthington, 2002). Several characteristics of seasonal hydrology: timing, frequency, magnitude, duration, and rate of change, generally occur within a “normal” range of variation, but deviations can occur in any or all characteristics (Poff and Ward, 1989; Poff et al., 1997). Seasonal and inter-annual variation drives high productivity through a predictable (Junk et al., 1989) pattern of “intermediate disturbance” (Grime, 1973; Resh et al., 1988; Ward, 1998), extreme events can reset systems or move then to a new stable state (Sparks et al., 1990). Contemporary rivers are also faced with a variety of human disturbances that have altered physical structure, processes, and communities (Theiling et al., 2000; WEST Consultants, Inc., 2000).

My research presents generalized land cover characteristics for predevelopment and contemporary periods to document ecological patterns and changes in the river-floodplain ecosystem. My intent is to provide river managers consistent landscape scale data system-wide to support large-scale ecosystem restoration implementation in an effective and efficient manner. I use landscape scale information independently and coupled with geomorphic (see Chapter 2) and hydraulic data (see Chapter 3) in a multiple reference condition analysis (Nestler et al., 2010; Theiling and Nestler, 2010) that quantifies differences among historic, contemporary, and modeled ecosystem conditions to document needs, significance, and benefits of ecosystem restoration actions (USACE, 2000). Changes in the landscape will be examined with respect to the effects of navigation and flood protection systems at large scales. Existing infrastructure and operations will be reviewed with regard to their flexibility to achieve multiple objectives. Prior experience with Environmental Management Program island, backwater, side channel, and wetland restoration (USACE, 2006b) and recent pilot studies in floodplain restoration (The Nature Conservancy, 2007; The Wetlands Initiative, Inc., 2008) and pool scale water level management (Kenow et al., 2007) show great success from the restoration tools available, this large scale landscape information should help planners set and quantify objectives for the system.

The scientific intent of my research is to test the hypotheses established in Chapter 1, the term land cover can easily be inserted into the language of several hypotheses. Both Benda et al. (2004) and Thorp et al. (2008) predict ecological zonation along the river continuum and higher ecological productivity at tributary confluences and below constricted valleys. I believe the land cover data integrated with the hydrogeomorphic relationships presented in Chapters 2 and 3 offer opportunities to test hypotheses and explain the plant community drivers that can be used to predict plant community response under various land cover reference conditions. Land cover is a significant response variable in ecosystem restoration science because it integrates many ecosystem components and thus is a reliable indicator of many processes. The strength of conclusions from my broad system-scale statistical analysis establishes important ecological relationships and adds credibility to predictive models that may be derived for site specific analyses.

Methods

Presettlement Land Cover

Land cover databases are the foundation of our vision of UMRS landscapes and habitats over multiple reference conditions. Early explorers described interesting new landscapes, vast abundances of strange new animals, and drew crude maps as they moved through North America. As settlers followed explorers, the Public Land Survey (PLS) mapped and characterized the mostly unsettled Louisiana Territories to sell land to the westward-expanding population of the United States (Sickley and Mladenoff, 2007). Initial pilot studies reconstructing PLS surveys in the UMRS (Nelson et al., 1996) proved to be very valuable and popular, so The Nature Conservancy contracted the University of Wisconsin Forest Ecology Lab to complete a comprehensive interpretation in a GIS for the entire UMRS (Sickley and Mladenoff, 2007). PLS data extend beyond the bluff into upland habitats, but the data were clipped to the extent of the 2000 dataset for this initial analysis. The Nature Conservancy dataset, and recently available statewide PLS plat map GIS coverages, provide a snapshot to speculate on ecological processes in the undeveloped landscape.

The PLS methods first divided the region into 36 square mile townships and then subdivided each one into 36 one mile square sections. Along the township and section lines, the surveyors set posts every half mile at locations called ½ section corners (where section lines intersected) and quarter section corners (midway between the section corners). Between two and four bearing trees were marked near each post and recorded in their notebooks by species, diameter, and compass bearing and distance from the post. The surveyors recorded other features that they encountered along the survey lines in the notebooks as well, including water features, individual trees located between the survey posts, boundaries between the ecosystems through which they were traveling, boundaries of natural and anthropogenic disturbances, and cultural features such as houses, cultivated fields, roads, and towns. PLS surveyors used a variety of terms to describe the ecosystems through which they were traveling. The long list was aggregated to a shorter list of related ecosystems (Table 5) when mapping and summarizing ecosystems over the reaches and pools.

A spatially-referenced GIS database of vegetative information from the surveyors' notebooks was created as point features based on their location along a given section line. They were classified as one of five distinct data types:

1. section and quarter section corners, with information about the associated bearing trees
2. meander corners, with information about the associated bearing trees
3. line trees
4. ecosystem boundaries

5. disturbance boundaries.

Every record in the database contains a code indicating in what type of ecosystem the feature occurred. This information may have come from the presence of an ecosystem boundary along that section line or a neighboring section line, or it may have come from the description of the entire section line where the surveyors characterized the land surface, soil, timber, and understory species.

Tree species were entered into the database with the common name recorded by the surveyor in the notebooks and scientific names associated with common names used. In some cases, a single common name was assigned to multiple scientific names, depending on where those trees occurred in the study area. Local experts and range maps were consulted to assist in making these assignations. All analyses herein are based on ecosystem classifications, trees will be considered in another analysis.

Scale and resolution are important issues to consider when using PLS data. The quarter section and ½ section corners are a half mile apart and are generally marked by two to four trees each. A single section is commonly bounded by eight corners, which means that a square mile in the data would contain information about only16 to 32 trees. This is too sparse to be used at a stand or site level in anything other than the most qualitative sense. It is recommended to use the data at broad spatial extents (tens to thousands of square miles) and at resolutions of no less than a square mile (Schulte and Mladenoff, 2001).

Contemporary Land Cover

The Long Term Resource Monitoring Program (LTRMP) has compiled several system-wide land cover data sets (http://www.umesc.usgs.gov/data_library/land_cover_use/land_cover_use_data.html).

The 2000 land cover dataset was used here because it represents the most complete spatial coverage among other data sets. The 2000 land cover data extent was used to define the floodplain area for other GIS coverages. LTRMP land cover data were interpreted from 1:15,000 scale infra-red aerial photography with a minimum map unit of one acre. Several land cover classifications schemes have been used, but National spatial data standards have helped optimize and standardize the scheme. The current classification scheme includes 31 classes that are ecologically or socially relevant. The scheme can be lumped or split as necessary to match other data sets. The HNA-18 land cover classification was reclassified to the general ecosystem classes (Table 5).

Land Cover Classes

Land cover data from historic and contemporary periods were generalized to a common 12 class scheme (Table 5). The classification scheme combined several forest classes from the contemporary classification and two from the historic. The savanna class combined 11 classes from the PLS surveys, but none from the modern surveys. A “bottom” class was evident in the historic data but not clear in the contemporary data which were lumped as “forest.” Similar to forests, the historic data allowed separation of several prairie classes: prairie, bottom prairie, and wet prairie which were not separable in the modern data. The historic classification identified forested wetlands as swamps, but that distinction is not made in the contemporary data where forested wetlands were not identified. Shrubs were represented in both data sets. Water was classified as several aquatic area types in the historic data, but in the modern data distinctions among classes depended on the presence of vegetation. Agriculture and developed classes are not common in the historic data, but they are very important in the modern data. PLS data have been criticized for inaccurate and inconsistent identifications and naming conventions and just plain sloppiness. Their use at the general landscape level here is to provide a broad view of the system without consideration of species and precise locational information.

Data Analysis

I overlayed the river reach segmentation schemes on land cover layers to provided acreage estimates for each land cover class summarized by the river mile segmentation to show plant community composition change along the river. Tim Fox (USGS, La Crosse, Wisconsin) constructed a GIS extension to complete point counts for each land cover class at each river mile. The point count tool is adaptable to any polygonal segmentation scheme and was used at the river mile scale and summed up to other scales as necessary. I also completed point counts by geomorphic class and hydraulic inundation frequency. I normalized the data as proportion of total points within each segment (i.e., river mile, pool, reach, etc.) to assess the relative importance of each class in each area. The normalized data were plotted and used in subsequent statistical analyses also (see Chapter 1).

I summarized land cover and aquatic area data in a contingency table with area class type (i.e., forest, prairie, etc. or backwater, channel, etc.) as columns and scale (i.e.,

Table 5. Land cover class crosswalk between the general Ecosystem classes, the PLS Surveyor Description, and the 2000 LCU data.

Ecosystem	Surveyor description	LTRMP HNA-18
Forest	Grove	Populus Community
	Forest/timber	Wet Floodplain Forest
		Mesic Bottomland Hardwood Forest
Savanna	Scattered timber	
	Sparse timber	
	Thinly timbered	
	Open woods	
	Open Plains	
	Opening	
	Oak opening	
	Scattered oak	
	Oak Barren	
	Brushy barrens	
	Barren	
Bottom	Bottom	
	Wet Bottom	
Bottom prairie	Prairie bottom, Bottom prairie	
Prairie	Prairie	Grassland
	Meadow/not-man-made field	
Wet prairie	Wet prairie	Wet Meadow
Wetland	low land, low wet area	Semi-permanently Flooded Emergent Annual
	Marsh	Semi-permanently Flooded Emergent Perennial
		Seasonally Flooded Emergent Annual
		Seasonally Flooded Emergent Perennial
Forested wetland	Swamp, Timber swamp	
Shrub	Brush	Salix Community
	Rough	Scrub/Shrub
	Shrub/shrubby	
	Thicket	
Water	Creek	Open Water
	Lake, pond	Submersed Aquatic Bed
	River	Floating-Leaved Aquatic Bed
	Slough, Slew, Sloo	Sand/Mud
	Beach	
	Bayou	
		Agriculture
		Developed

mile, pool, reach) as rows. The contingency table was used as input for cluster analysis (Kovach Computing Service, 2008) and correspondence analysis (CA) (Kovach Computing Service, 2008; Greenacre, 1993; see Chapter 1). Cluster analysis was used to depict similarity of land cover classes with the idea that reference periods and geomorphic reaches would be sorted by their land cover characteristics. Reaches could mix or separate in time and space depending on land cover characteristics at various scales. Cluster analysis became harder to interpret as resolution got finer, so it was dropped for pool scale analyses because of the large number of units. Finer-scale hydrogeomorphically defined classifications could refine ecological relationship and be analyzed using more rigorous statistics.

Results

Presettlement Land Cover

The Nature Conservancy, Madison, Wisconsin and University of Wisconsin Forest ecology Lab digitized presettlement land cover data for the entire Upper Mississippi River and the Illinois River upstream to river mile 215 through the Lower Illinois Reach (Appendix D). The large scale landscape data showed a downstream longitudinal pattern of forest mixed with mostly wetlands and savannas in the north (higher river miles), to prairie and wetlands in the mid-valley, and bottomland forest south of the Missouri River (<river mile 200; Figure 51). Although the water class is not well represented in the PLS data, the abundance of water on the landscape south of the Missouri River is interesting because it compares historically in proportion with the upper reach which is very different than now. Large oxbow lakes were once prominent on the Middle Mississippi River landscape (Heitmeyer, 2008). The Illinois River had a similar forest component throughout the river valley with a diverse upstream reach (higher river

miles) transitioning downstream through wetlands, mixed wetland and prairie, and prairie and forest at the lowest reach (Figure 51).

The river mile segmentation provides a quite detailed perspective of the landscape composition that can be considered as a reference for restoration alternatives and also in relation to physical and hydrologic factors. The point coverages derived from the PLS provide an intermediate resolution between a map that may prescribe a restoration solution versus the pixilated view which provides a more abstract image for restoration planning (Appendix D).

Contemporary Land Cover

The contemporary UMRS can be roughly separated into two reaches, one dominated by water in the north and another dominated by agriculture in the south (Figure 51). A forest corridor is evident throughout the river and wetlands occur in low abundance system-wide also (Appendix D). Developed area occurs more evenly at low proportions in the north and as spikes near river miles 450 (Quad Cities) and 200 (St. Louis). Dams impounded water in upper reaches to create large Water area, levees reduce risks from flooding which supports large scale Agriculture in the lower one-half of the valley. A repeating water-wetland-forest sequence is evident in the Chippewa River Reach (river miles 650 – 800) where navigation dams have the most effect on surface water distribution in the lower one-half of each pool.

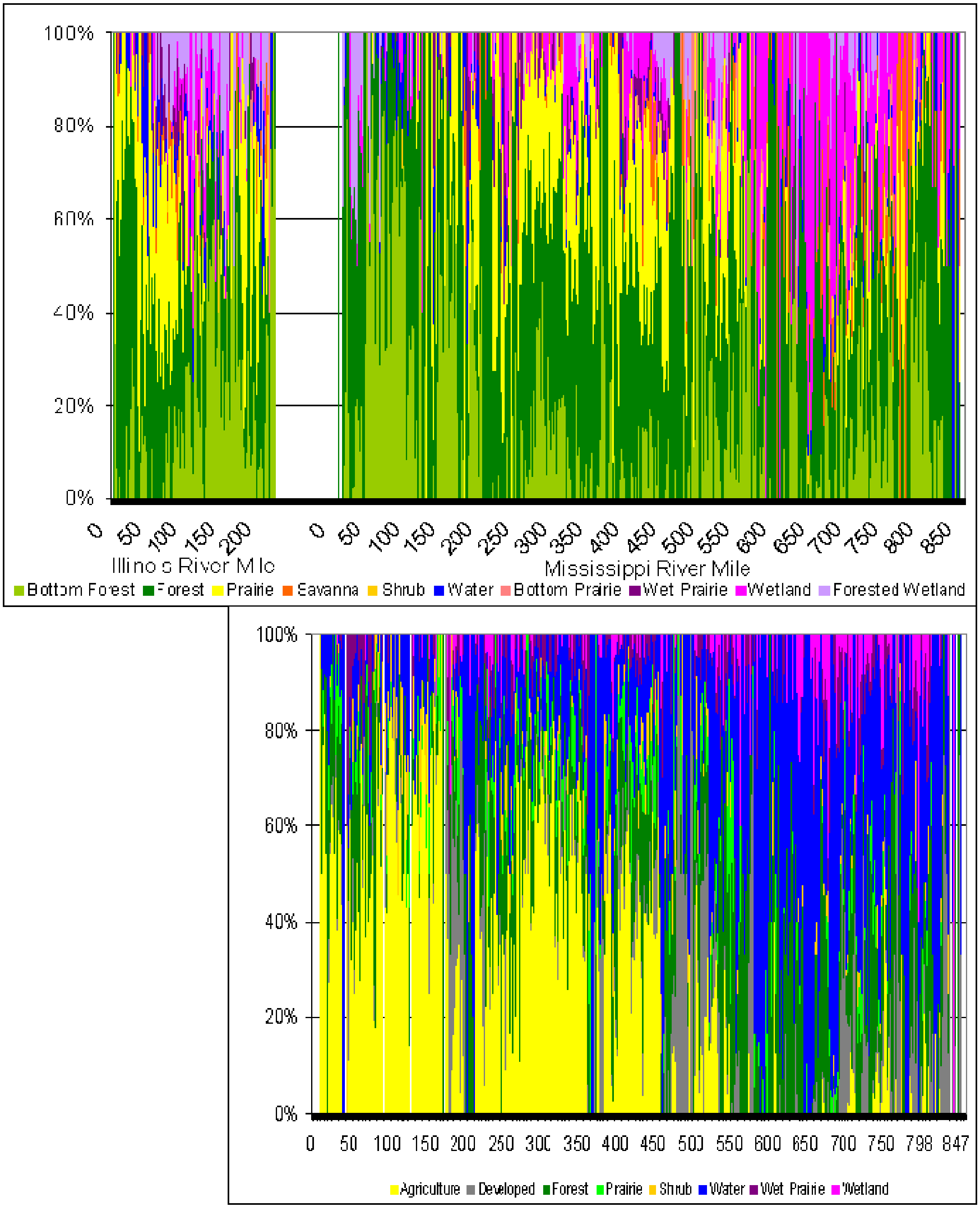


Figure 51. Historic Public Land Survey (<1850, top) and contemporary (2000, bottom) Upper Mississippi River System land cover relative abundance by river mile.

Land Cover Spatial Ordination

Floodplain Reach

The simplest, most comprehensive conclusion of this analysis is in the NMS ordination of the 1850 and 2000 land cover classes at the Floodplain Reach scales (Figure 52). The Floodplain Reach scale ordination is presented first examined using cluster analysis and correspondence analysis. The large scale view is followed by each of the progressively finer spatial scales. At the pool scale the “wing effect” in correspondence analysis becomes apparent and nonmetric multi-dimensional scaling is used to corroborate results. Cluster analysis of floodplain reaches sorted them by time periods, except the modern Upper Impounded Reach was loosely grouped with the presettlement period (Figure 52).

Correspondence analysis results lumped the three downstream Floodplain Reach modern landscapes based on the proportion of agriculture (Figure 52). The modern Upper Impounded Reach separated from the other modern period data along Axis 2 based on the proportion of Agriculture and Developed area. The modern Upper Impounded Reach separated from a historic group along axis 2 based on Bottom, Forested Wetland, Savanna, and Bottom Prairie. The modern Upper Impounded Reach separated from the others along Axis 2 based on Water and Wetland.

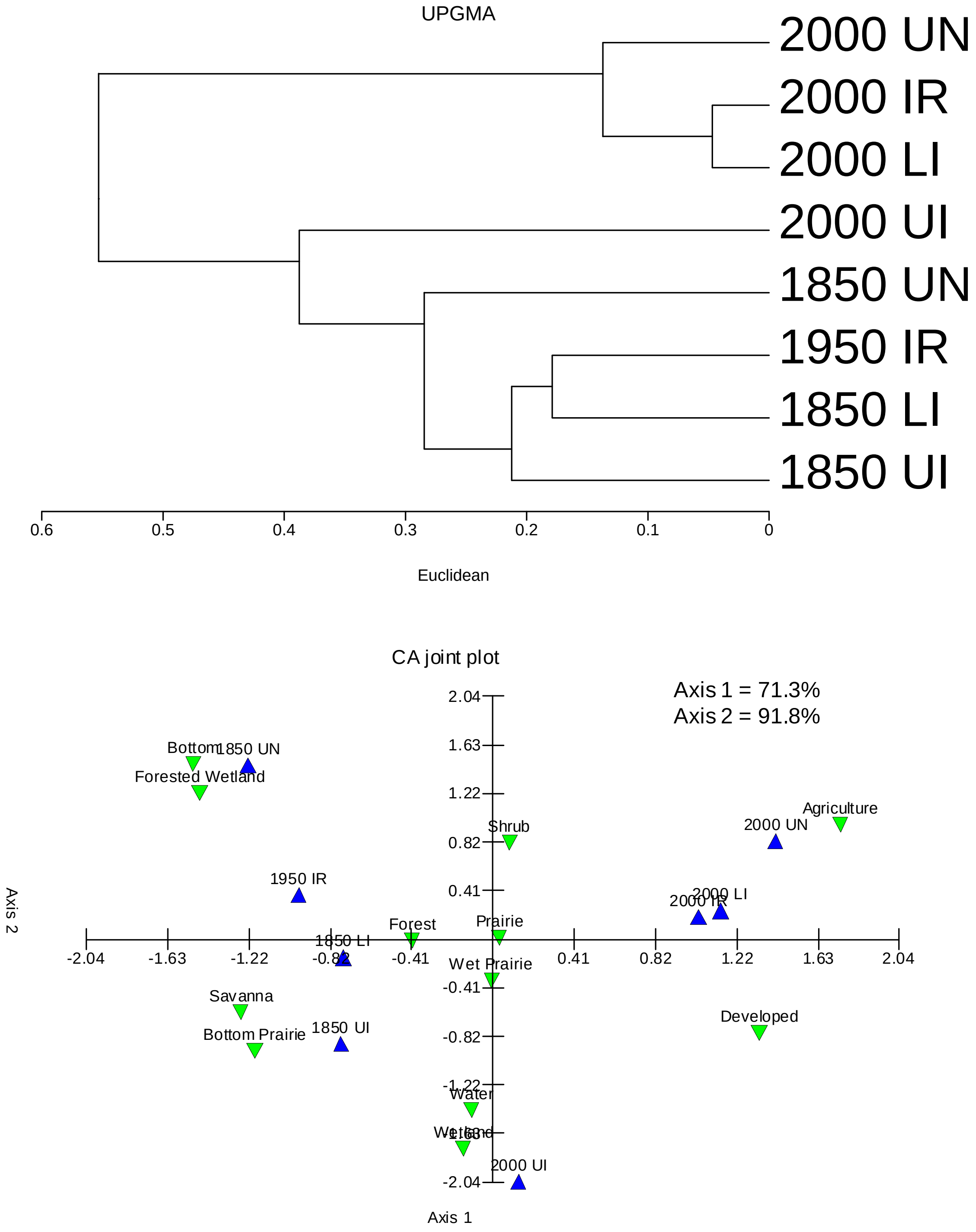


Figure 52. Cluster analysis and correspondence analysis of land cover classes scaled at the Floodplain Reach scale during presettlement (1850) and contemporary (2000) periods. IR = Illinois River Reach, LI = Lower Impounded Reach, UI = Upper Impounded Reach, and UN = Unimpounded Reach.

Pool Reach

The Pool Reach scale was devised by Knox and Schuum (in WEST Consultants, Inc., 2000) to reflect the large scale geomorphology of the river using the navigation pools to define the breakpoints. The method masks the fine scale geomorphology defining reaches but incorporates the artificial partitioning caused by navigation dams that create the navigation pools which were the prior common reference scale. Ten Pool Reaches on the Mississippi and the Lower Illinois River Reach were considered in the analyses.

Cluster analysis clearly separates the presettlement and modern land cover at the Pool Reach scale (Figure 53). The cluster groupings are consistent in both time periods with the northern and southern reaches separated at the Rock Island Gorge. CA ordination separates three groups: presettlement, modern upstream, and modern downstream (Figure 53). The modern upstream reaches are separated by the high proportion of water and developed area. The modern downstream reaches are separated by the high proportion of agriculture area.

Each time period was considered separately using CA. Historic land cover defined upstream, mid-valley, and downstream reaches separated at Pool Reach 5 (RM 500, Rock Island) and Pool Reach 8 (RM 200, Missouri River; Figure 54). The mid-valley included Pool Reaches 6, 7, and 8 defined by Prairie and Wet Prairie and Reaches 5 and 12 having slightly more forest. The upper valley, Pool Reaches 2 and 3, had high proportion of savanna and wetland and reaches 4 and 1 had more water placing them lower on Axis 1. The lower reaches separated on Bottom and Forested Wetland classes. Forest plotted in the center of the ordination reflecting its even distribution.

The ordination of contemporary land cover by Pool Reaches creates a southern group of agriculture dominated reaches separated along the CA Axis 2 from the northern reaches characterized by water and wetlands (Figure 55). Pool Reach 5 separates along Axis 1, Developed. Prairie and Forest occur near the origin of the axes.

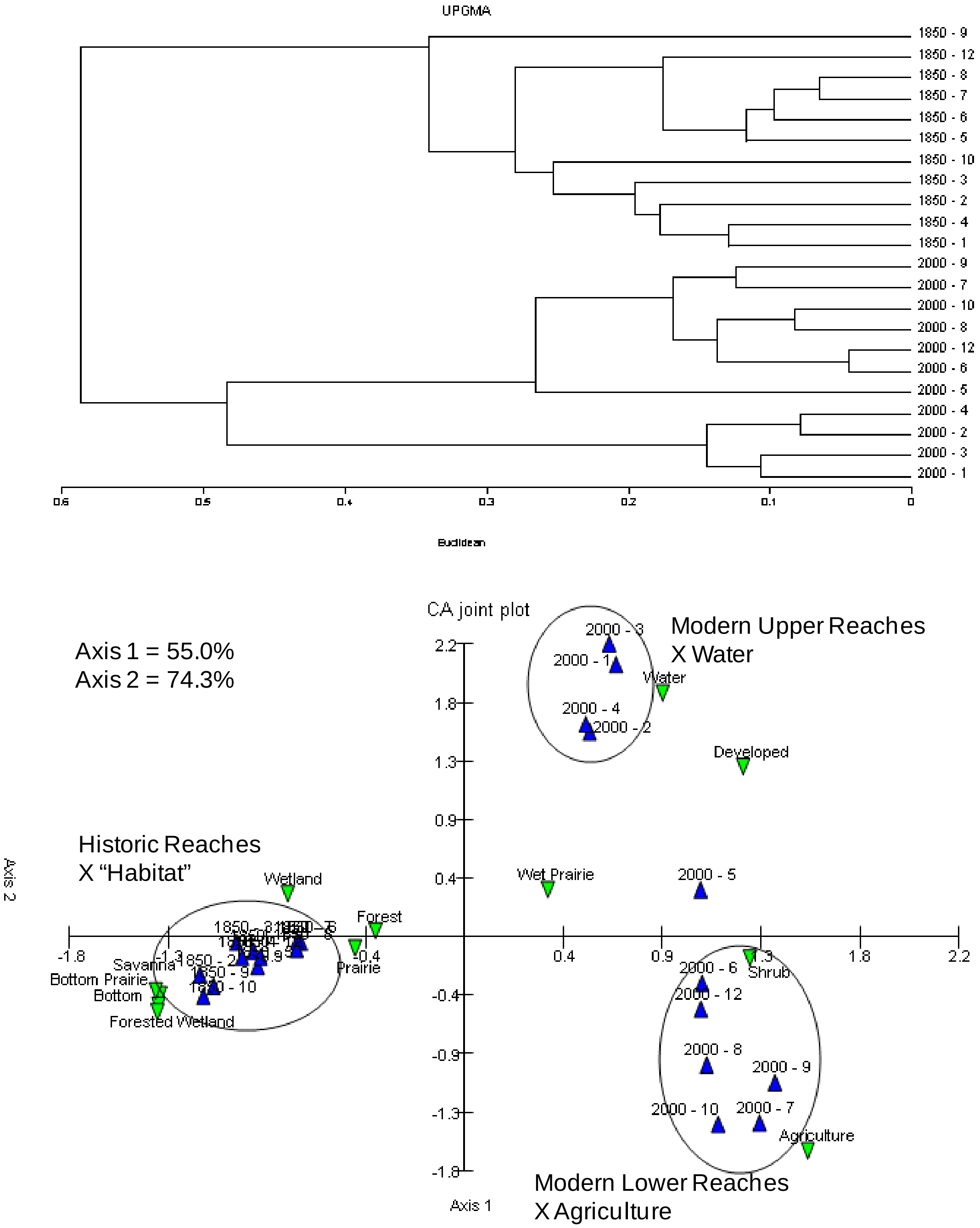


Figure 53. Cluster analysis and Correspondence analysis of land cover classes scaled at the Pool Reach during the presettlement (1850) period. Reach labels per table 2.

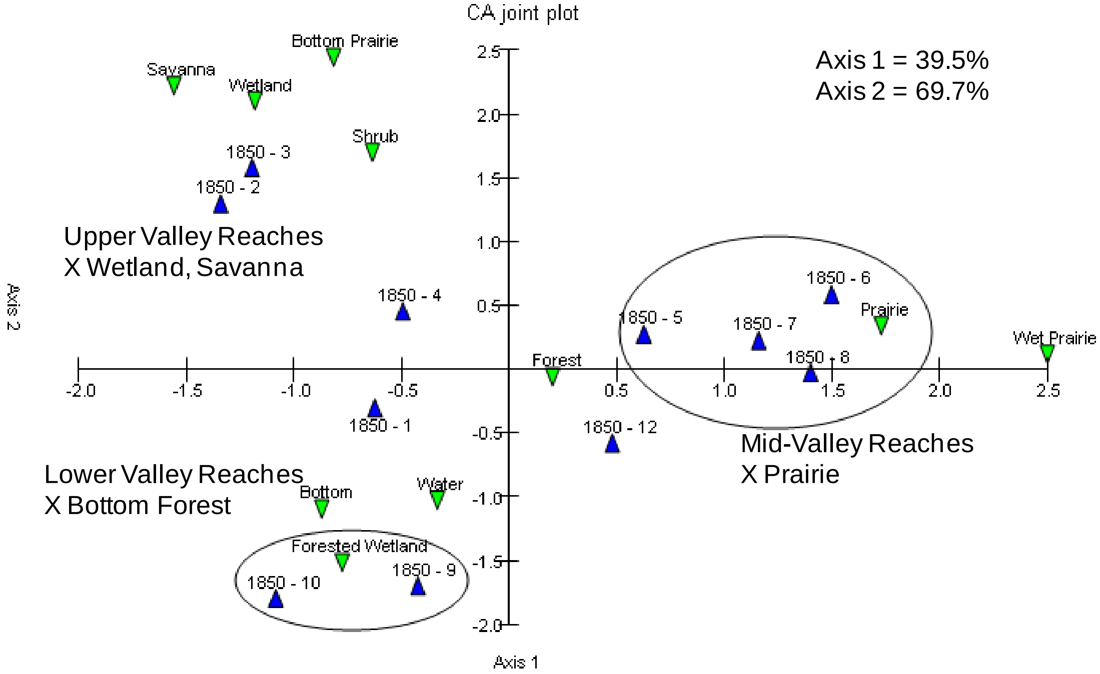


Figure 54. Correspondence analysis of land cover classes scaled at the Pool Reach during the presettlement (1850) period. Reach labels per table 1.

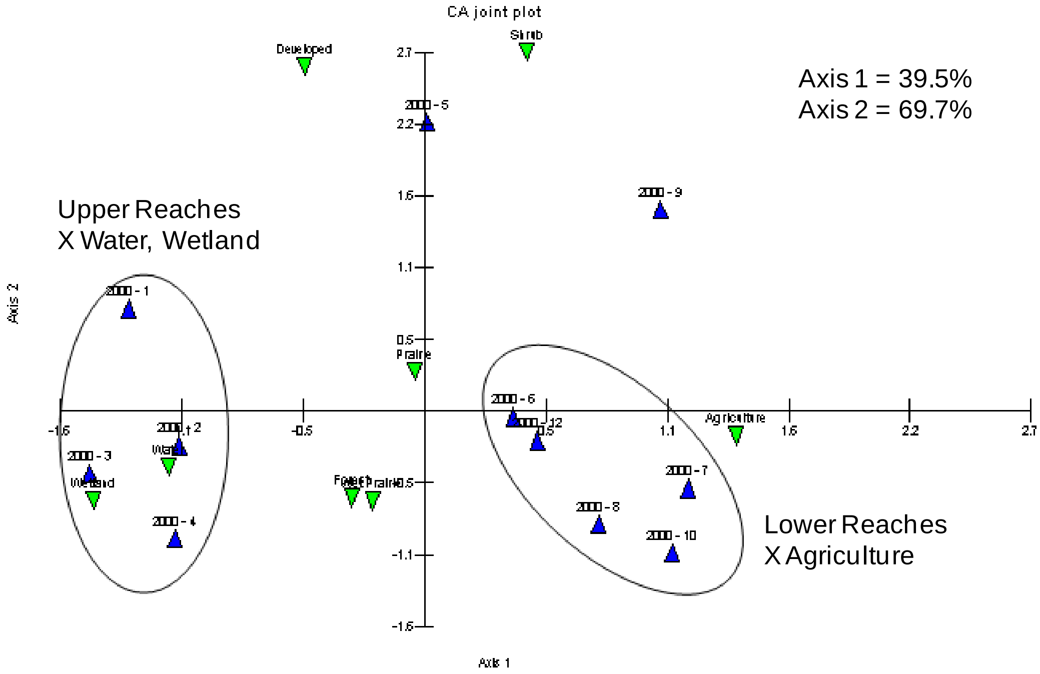


Figure 55. Correspondence analysis of land cover classes scaled at the Pool Reach during the contemporary (2000) period. Reach labels per table 1.

Geomorphic Reach

Cluster analysis at the Geomorphic Reach scale clearly separated PLS data and the modern land cover (Figure 56). There were 18 Geomorphic Reaches and the cluster dendrogram was becoming highly branched and difficult to interpret. The CA produced five clusters that clearly separated the PLS and modern land cover among time periods (Figure 57). The modern land cover separated into a northern group with Water and Developed area and a southern group with agriculture (Figure 57). Several reaches, two valley constricted and two broad valley segments, did not fit in clusters. The historic landscape in the constrained reaches: Upper Illinois, Thebes Gap, Keokuk Gorge sort with the Kaskaskia and Jefferson Barracks Reaches along Axis 2 because of the high proportion of Bottom. The other historic Geomorphic Reach landscapes bunched together around Forested Wetland, Savanna, and Bottom Prairie. Forest, Prairie, and Wetland occurred closest to the origin of the axes where mid-valley reaches group on Prairie and Wetland (Figure 57).

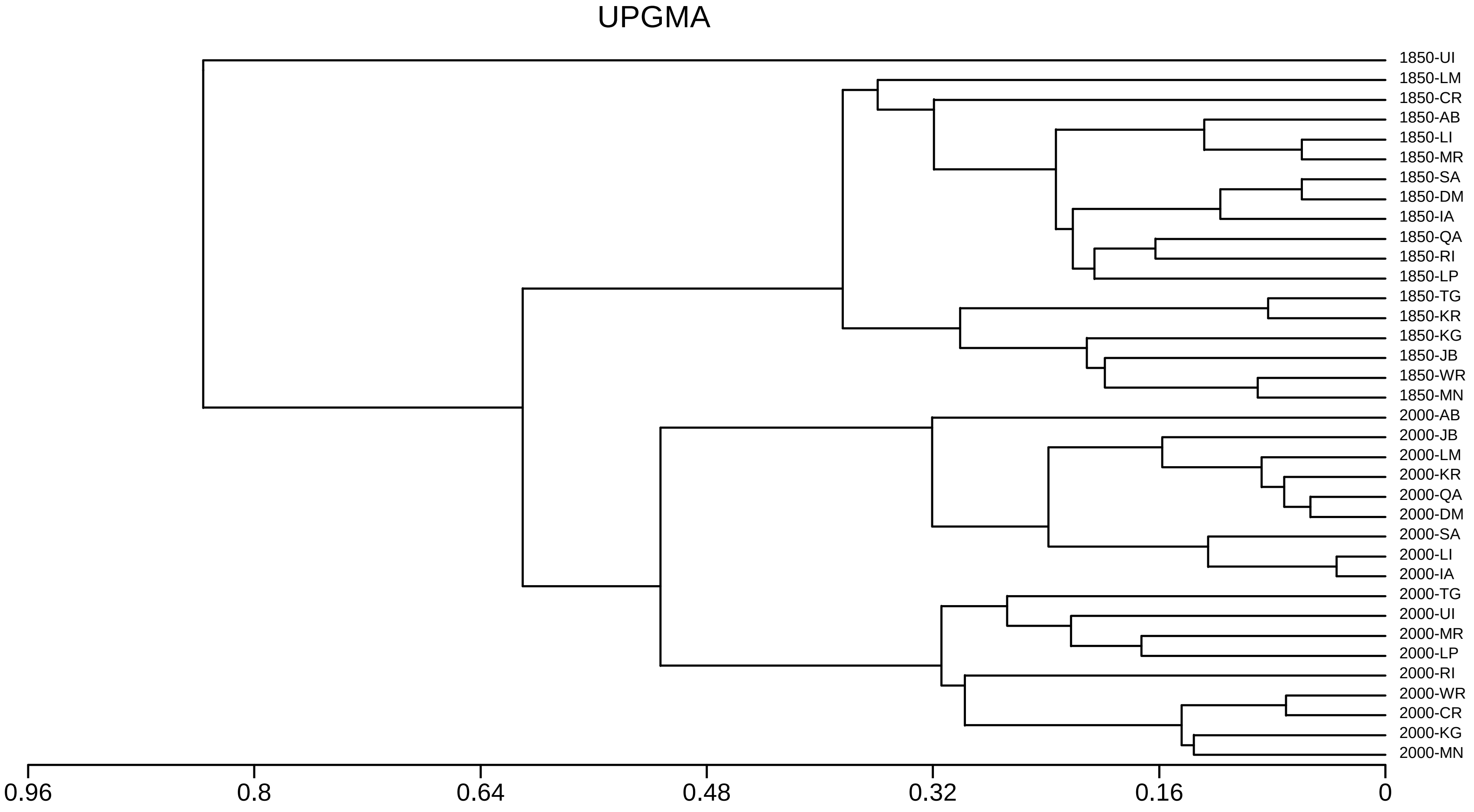


Figure 56. Cluster analysis of land cover classes scaled at the Geomorphic Reach scale during presettlement (1850) and contemporary (2000) periods. Reach labels per table 1.

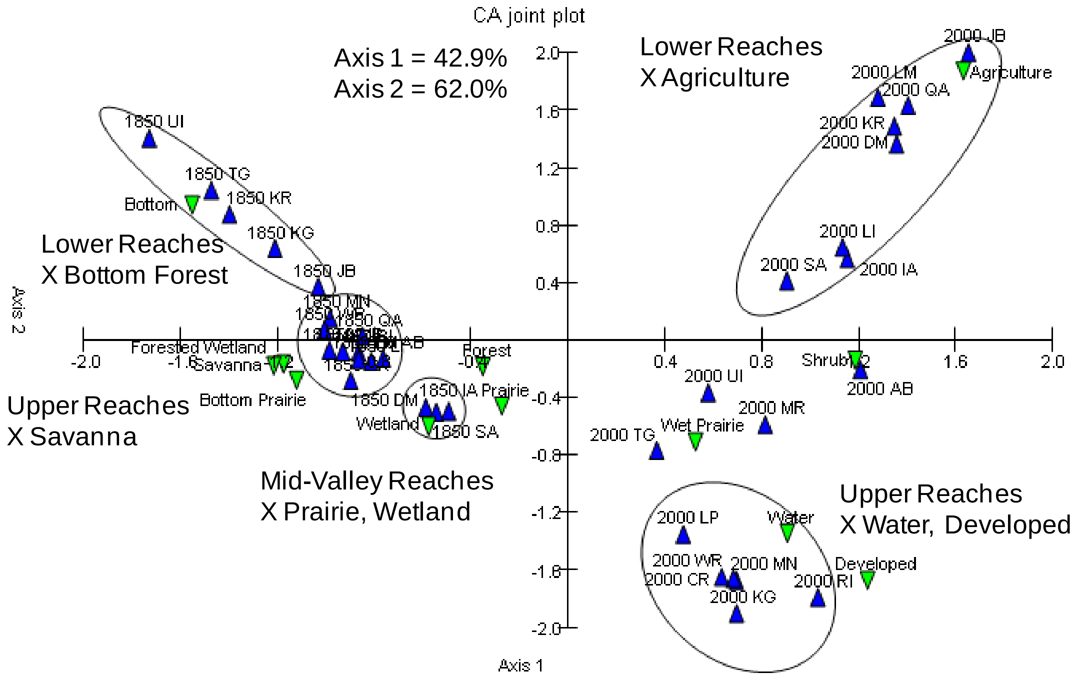


Figure 57. Correspondence analysis of land cover classes scaled at the Geomorphic Reach scale during presettlement (1850) and contemporary (2000) periods. Reach labels per table 1.

The first CA at the Floodplain Reach and this one with 36 total cases showed indications of the “arch effect” which is what prompted addition of the NMS analysis. Similar groupings can be detected in the NMS ordination (Figure 58) which strengthens the conclusions with multiple lines of evidence. Similar groupings can be detected by both ordination methods in each time period. Geomorphic reaches in the historic period separate on Bottom and Prairie and Wet Prairie along Axis 2 of the CA plot (Figure 59). The Kaskaskia River and the narrow gorges group on Bottom and the mid-valley reaches separate on Prairie and Wet Prairie. The upper Geomorphic Reaches cluster in the quadrant toward Wetland and Savanna. Groupings are less clear in this CA but they follow the trend seen at the other scales. The modern land cover classes separate into three groups with the Rock Island Gorge as an outlier using each ordination technique (Figure 60). An upstream group clustered near Water and a downstream group clustered near Agriculture on CA Axis 2. A central group is harder to discern, but the Maquoketa River Reach and Columbia-American Bottom Reach are beginning to separate from other groups at the more resolved scale. The same groupings are supported by the NMS for the contemporary data (Figure 60).

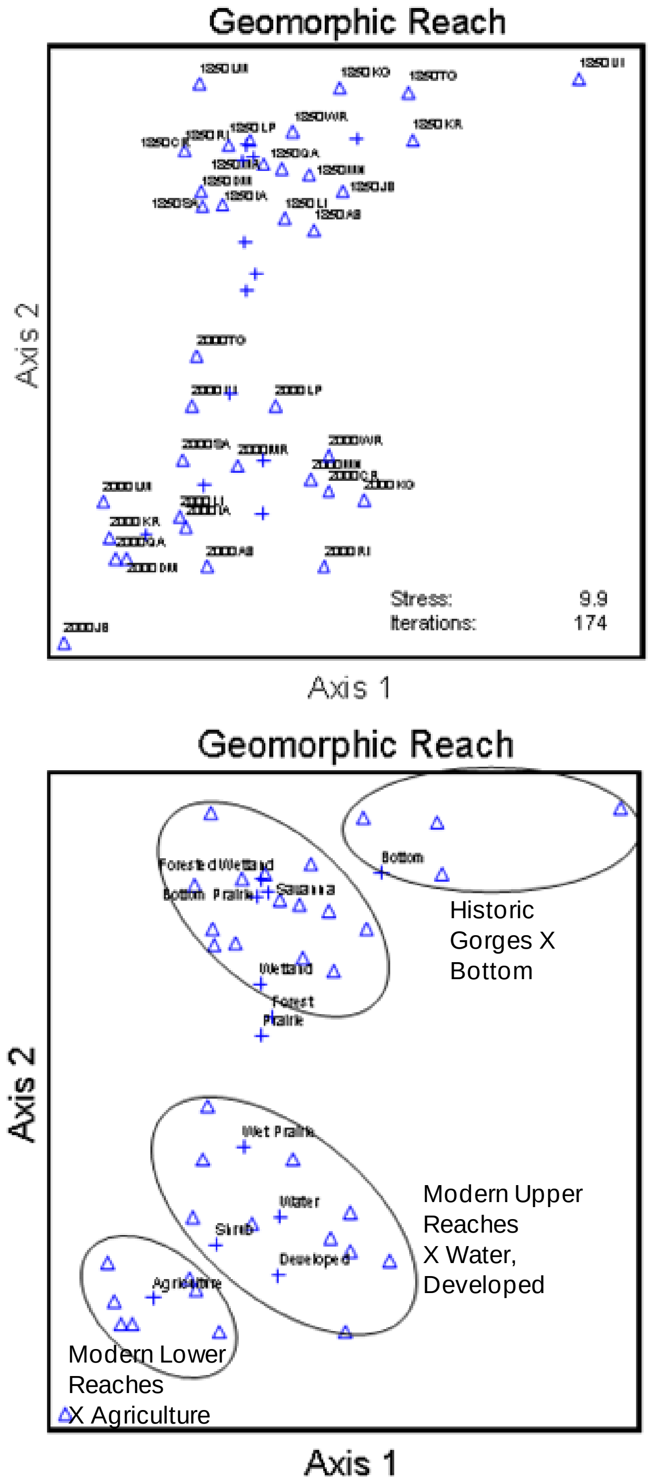


Figure 58. Nonmetric multidimensional scaling analysis of land cover classes scaled at the Geomorphic Reach scale during presettlement (1850) and contemporary (2000) periods. Reach labels per table 1.

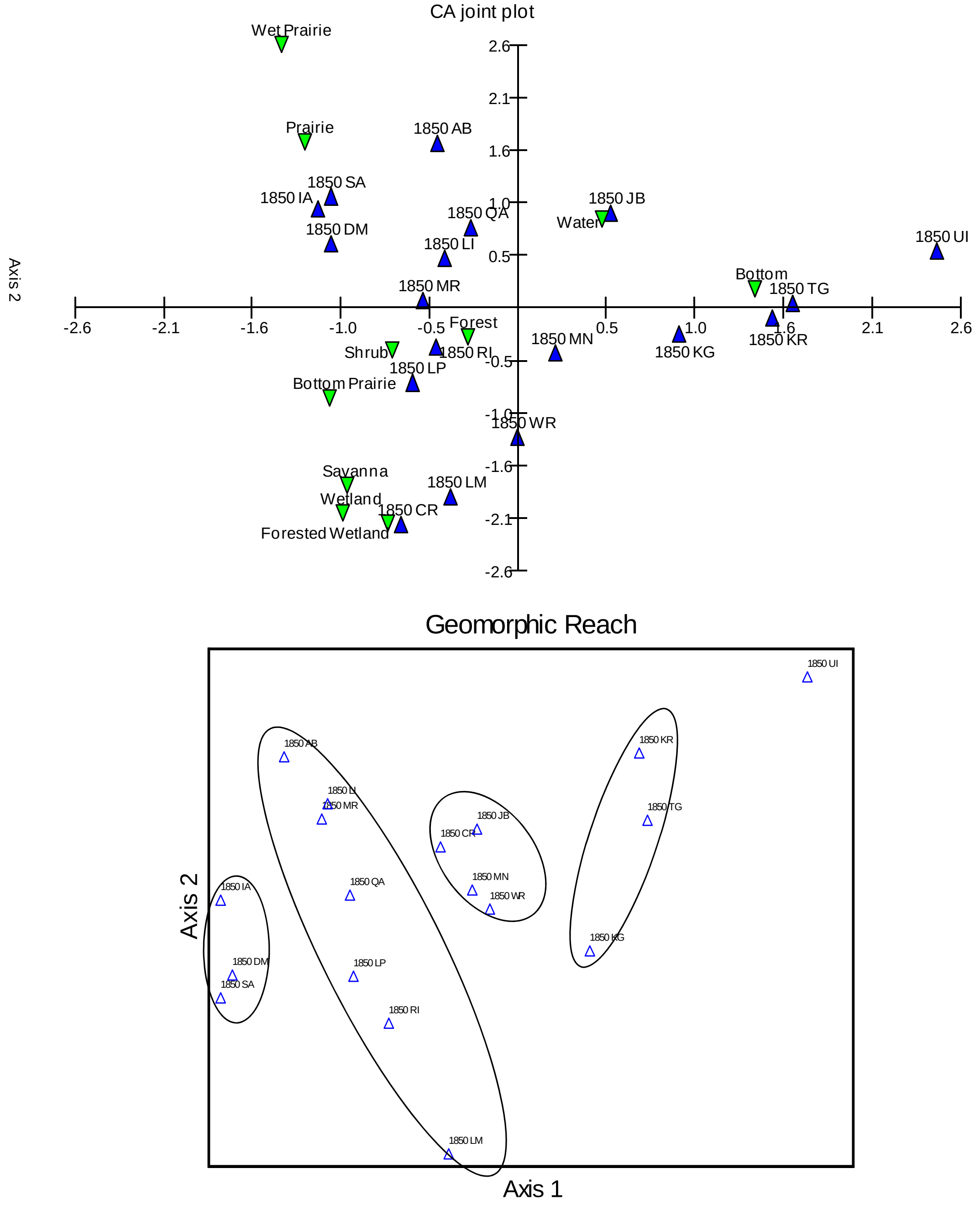


Figure 59. Correspondence analysis and nonmetric multidimensional scaling analysis of land cover classes scaled at the Geomorphic Reach during the presettlement (1850) period.

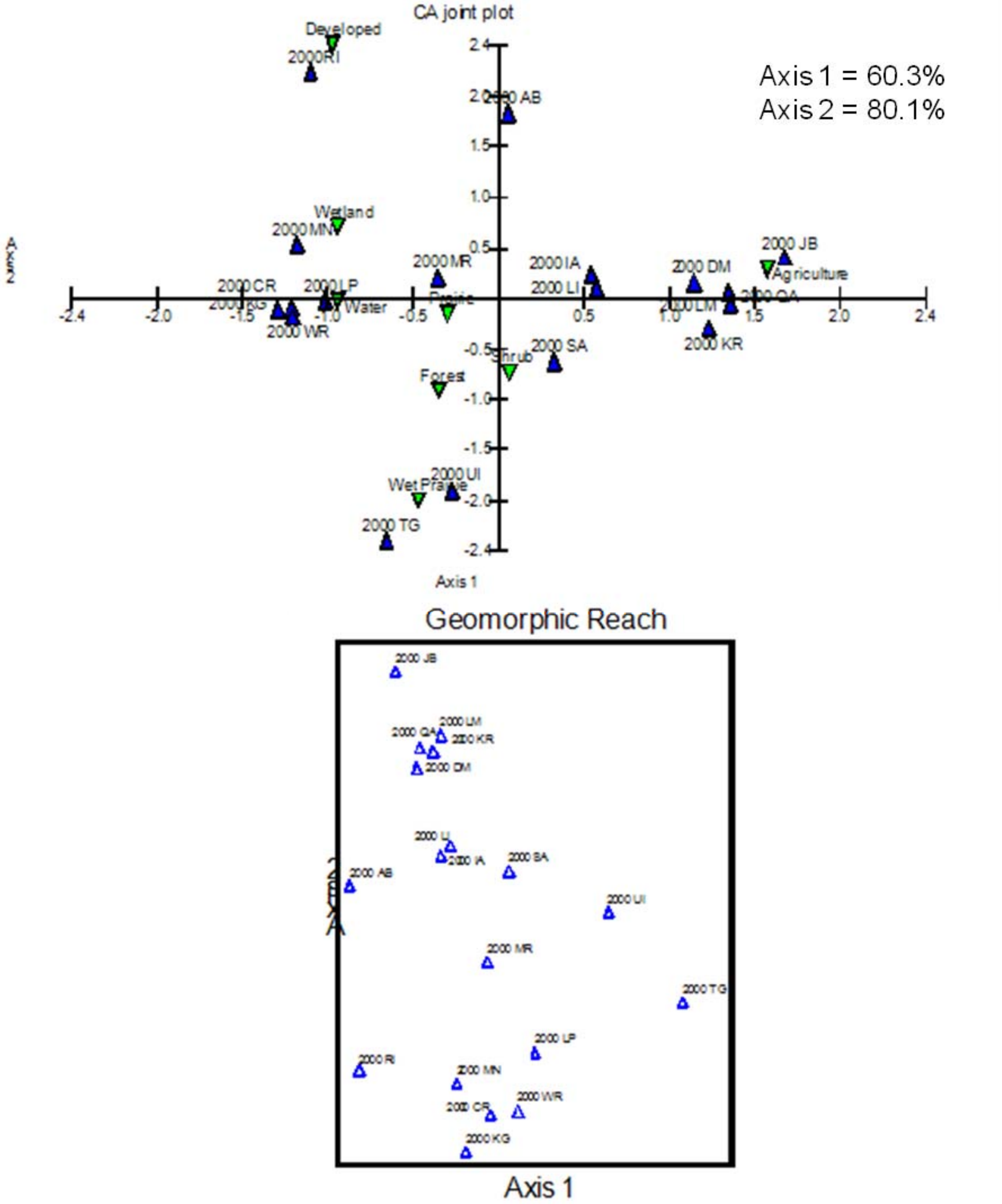


Figure 60. Correspondence analysis and nonmetric multidimensional scaling analysis of land cover classes scaled at the Geomorphic Reach during the contemporary (2000) period.

Pool Scale

Cluster analysis was dropped at the Pool Scale because it was too highly branched with more than 60 cases (i.e., pool by time period combinations), but time periods did separate entirely in exploratory analysis. The CA results have three distinct groups centered on Water and Developed area (2000 LCU upper Pools), Agriculture (2000 LCU upper Pools), and Wetland, Prairie, Forest, etc. all the 1850 pools (Figure 61). Each of the pools falls within the expected range considering results at coarser scales. The NMS results show a similar pattern with three detectable groups (Figure 62).

Focusing on individual time periods, the 1850 PLS data at the Pool scale create two groups separated along CA Axis 2 by Wetland-Savanna and Prairie-Wet Prairie (Figure 63). Pools in the Chippewa River Reach form the Wetland-Savanna Reach and Pools in the Iowa, Des Moines, Quincy, Sny, and Columbia Bottoms make up the Prairie reach. Other pools occur in a geographical mix in the quadrant with the Bottom and Forested Wetland classes which indicates a forest influence. Nearly identical groups are detected in the NMS ordination (Figure 63).

The 2000 LCU separated Pools by the same Agriculture, Water-Wetland, and Developed classes seen at the Geomorphic Reach scale (Figure 64). Pools separate from their prior groups in several cases, but there is generally strong affiliation with the prior groupings in most cases. Pools 1, 2, 14, 16 all show more influence from Development than at prior scales. Peoria Pool moves to the upper pool group based on its high proportion of water. The NMS ordination creates similar groups (Figure 64).

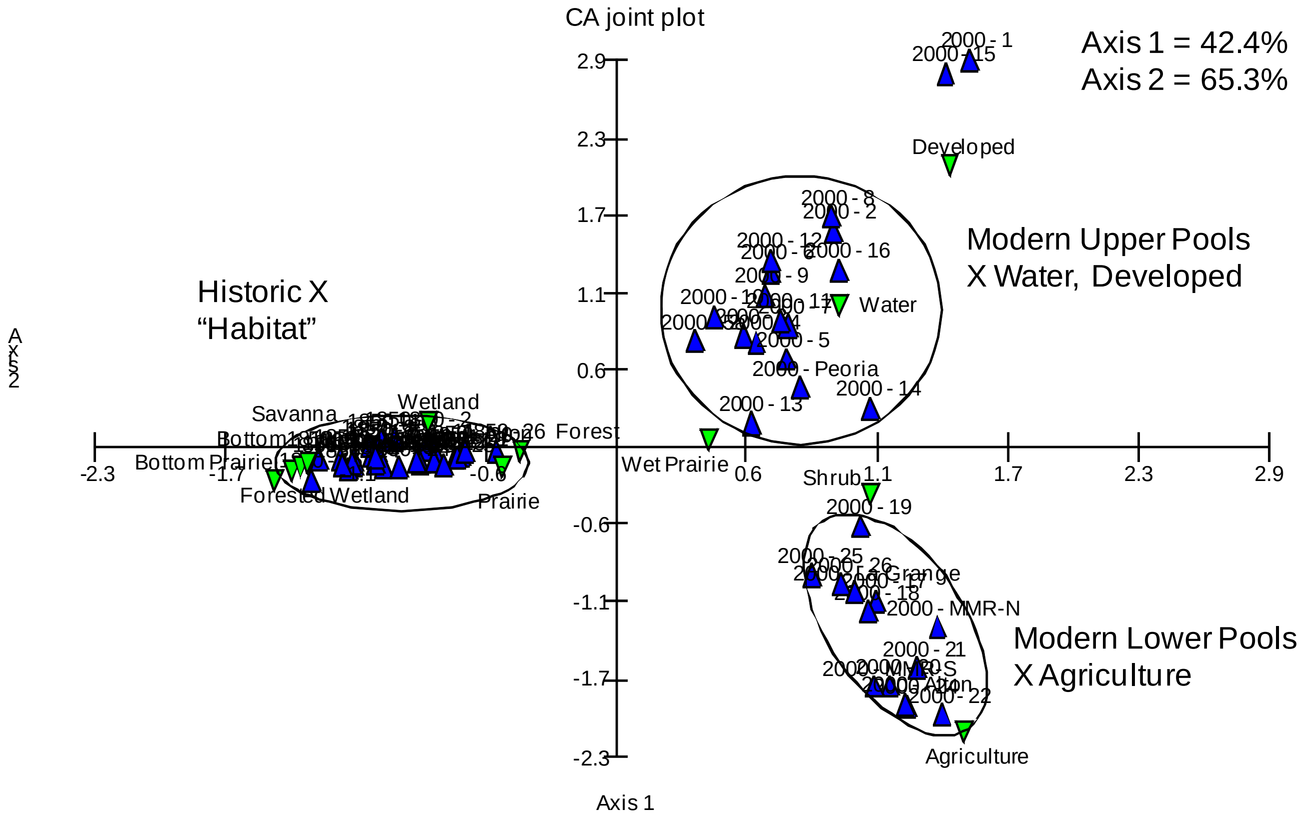


Figure 61. Correspondence analysis of land cover classes scaled at the Pool scale during presettlement (1850) and contemporary (2000) periods.

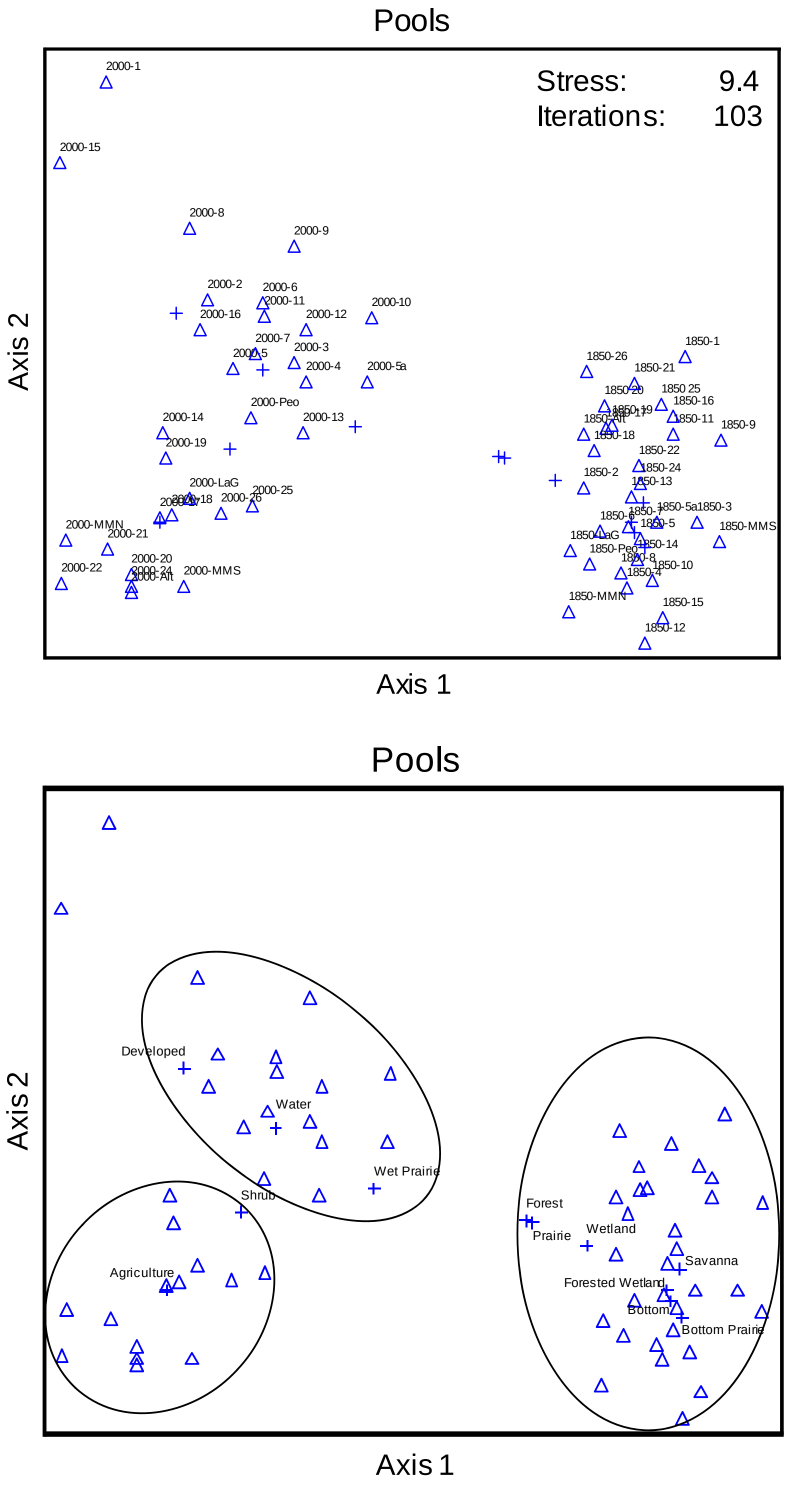


Figure 62. Nonmetric multidimensional scaling analysis of land cover classes scaled at the Pool scale during presettlement (1850) and contemporary (2000) periods. Reach labels per table 1.

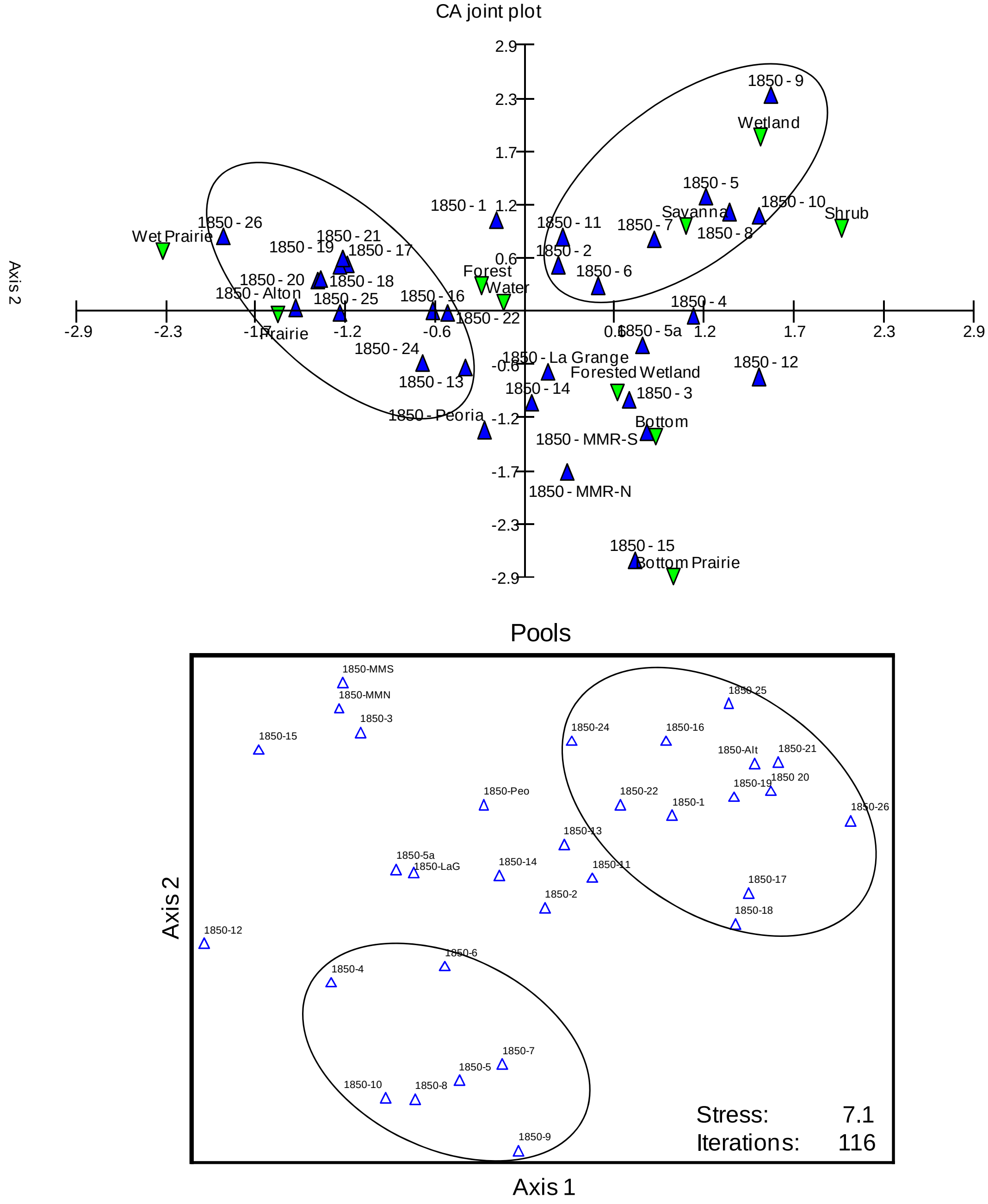


Figure 63. Correspondence analysis and nonmetric multidimensional scaling analysis of land cover classes scaled at the Pool scale during the presettlement (1850) period. Reach labels per table 1.

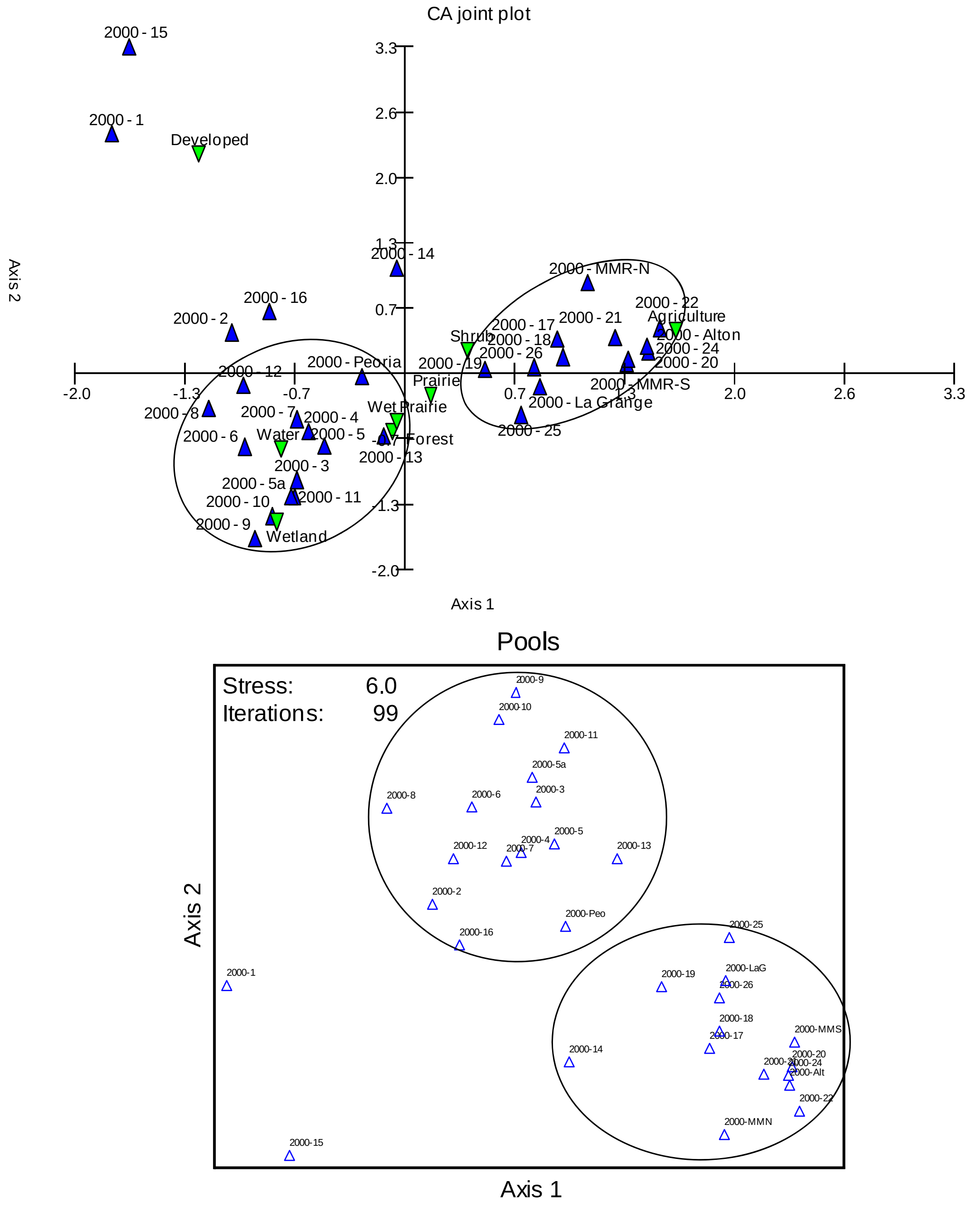


Figure 64. Correspondence analysis and nonmetric multidimensional scaling analysis of land cover classes scaled at the Pool scale during the contemporary (2000) period.

Land Cover Geomorphic Ordination

I evaluated the distribution of historic land cover classes among the geomorphic classes using correspondence analysis (Figure 65). The ordination followed a moisture gradient with the wetter conditions on the left along axis 1 and dryer conditions to the right on axis 1. Forest and wetlands occurred in areas converted to modern channel, Active Floodplain Poorly Drained, Natural Levees, and Paleo-Floodplain Well Drained. The latter classes would likely be drier and there may be a forest species gradient that I did not assess. Bottom Forest occurred in this region of the biplot also, but it was located up axis 2 toward Modern Backwaters which occur lateral to historic main channel areas. These areas also include the large impounded areas apparent in some pools. Shrub, Bottom Prairie, and Wet Prairie are intermediate in the distribution, skewed upward along axis 2. The driest land cover classes, Savanna and Prairie, are most closely associated with Glacial Terraces and Colluvial Slopes.

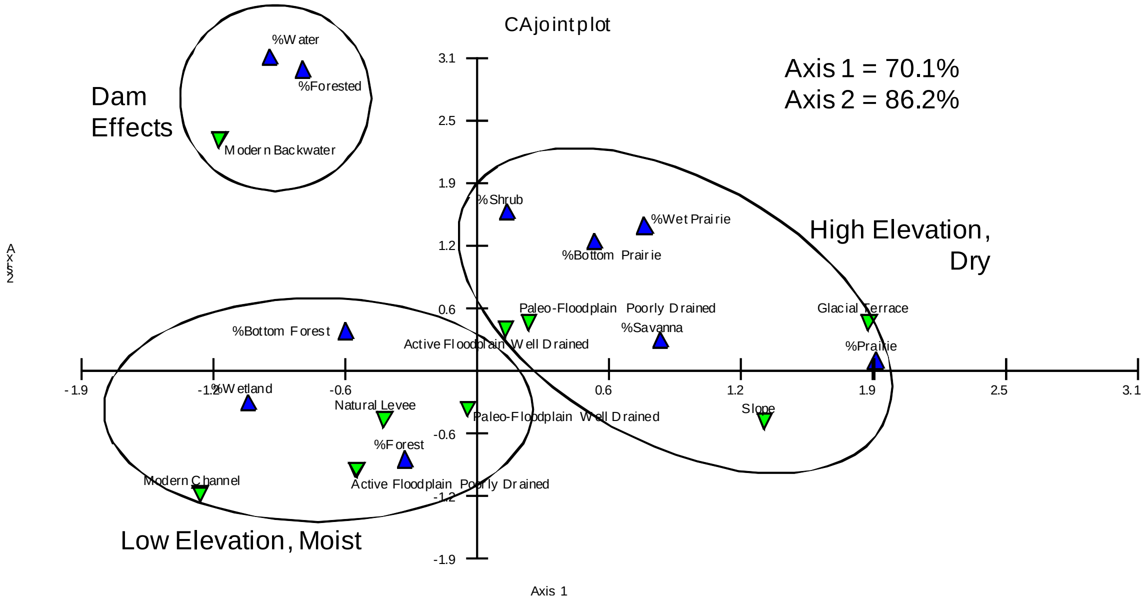


Figure 65. Correspondence analysis examining geomorphic factors associated with presettlement land cover classes.

Land Cover Flood Inundation Ordination

I evaluated the distribution of historic land cover classes among the inundation frequency classes graphically and with correspondence analysis. Land cover data were separated within each flood inundation interval which appear as adjacent bands across the floodplain toward the bluff. The 1 percent recurrence interval flood (i.e., 100-yr Flood) was the maximum stage considered and land cover class points within each lower flood stage were subtracted from the maximum occurring within the 100-yr flood band. Thus, the 50 percent recurrence interval flood had the most points because it covers a large area. All inundation class results were normalized as percent of maximum points within the 1 percent flood.

My graphical analysis illustrates the weighted distribution of land cover classes into the 2-yr flood inundation area (Figure 66). Land cover classes occurring at higher elevations, prairie classes and savanna, have greater relative abundance in the less frequent flood zones. Despite the skewed distribution of points in the 2-yr flood zone, the correspondence analysis did separate classes along a moisture tolerance gradient (Figure 67). Water, Forest, Wetland, Forested Wetland, Bottom Forest, and Wet Prairie are all closely associated with the 2-yr flood. The less flood tolerant land cover classes, Savanna, Prairie, and Bottom Prairie were distributed to the right along axis 1 toward the less frequent flood zones.

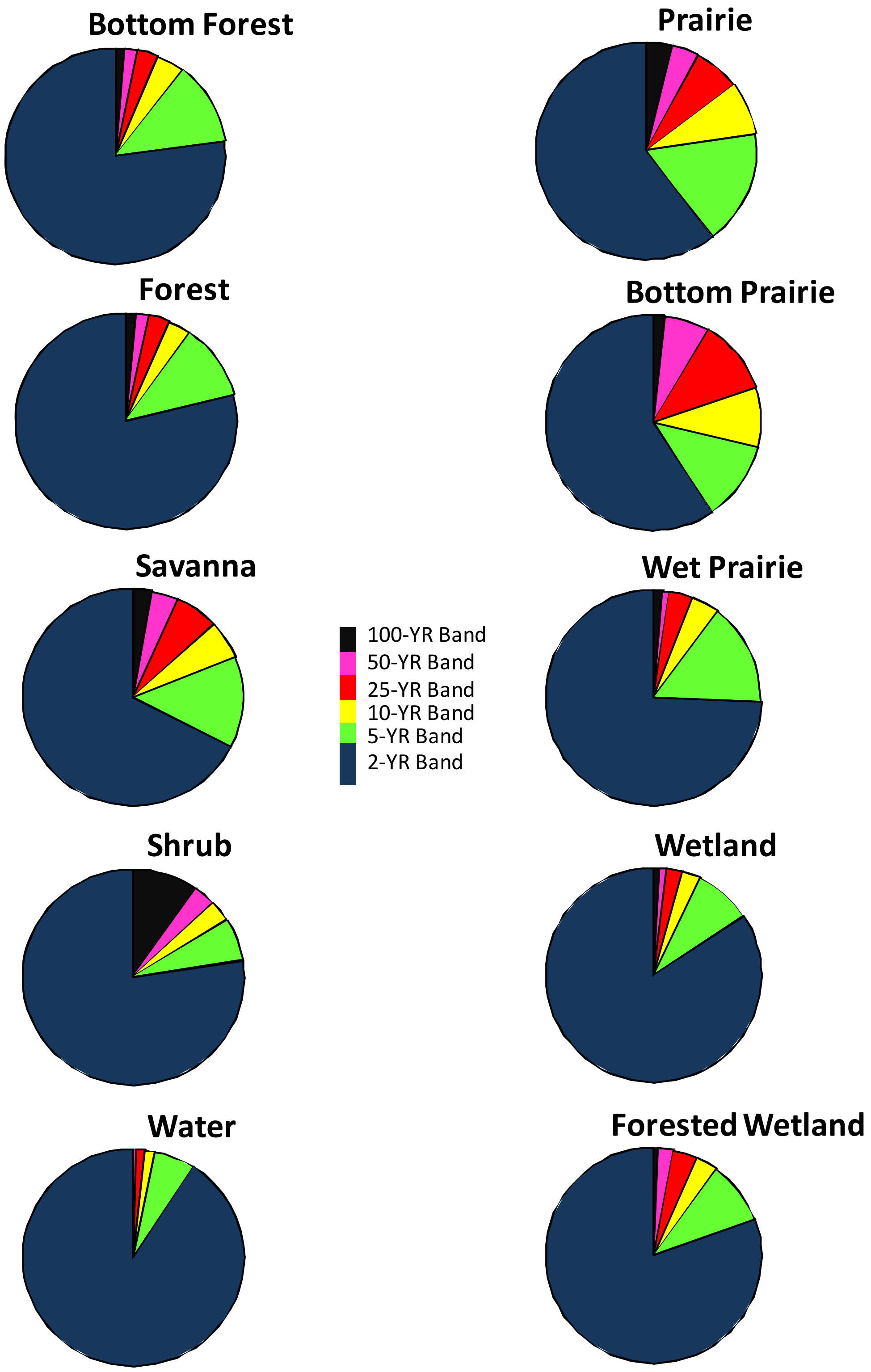


Figure 66. Presettlement (<1850) land cover distribution among the 50 percent recurrence interval (2-year) to 1 percent recurrence interval (100-year) flood extent in the Upper Mississippi River System.

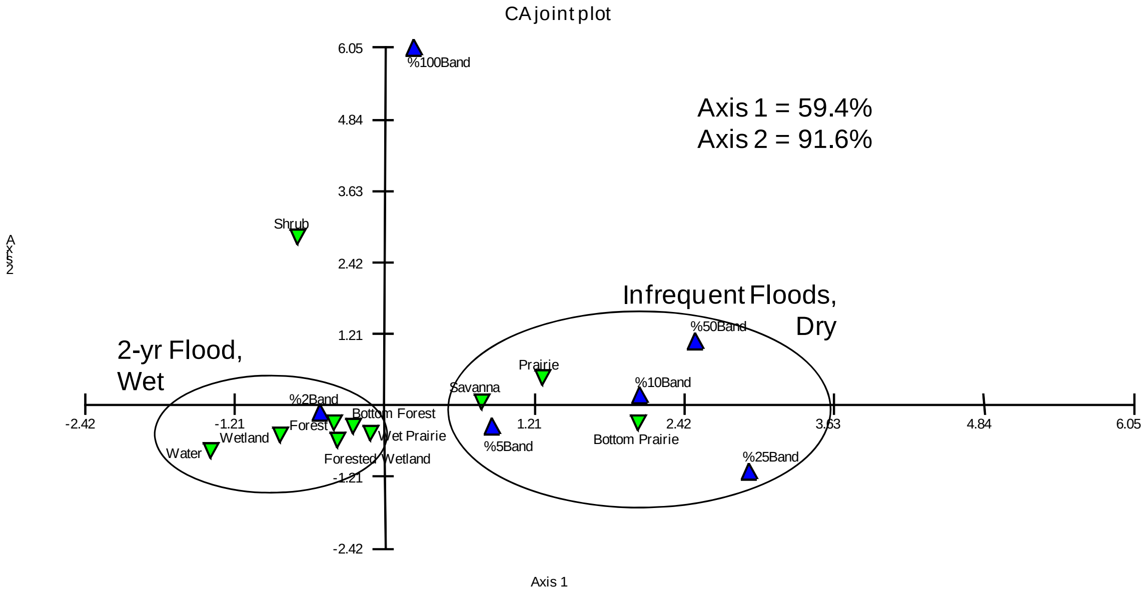


Figure 67. Correspondence analysis examining simulated floodplain inundation extent associated with presettlement land cover classes.

Pre-Development and Post Development Connected Floodplain Land Cover Ordination

I evaluated the distribution of historic land cover classes among connected floodplain areas during pre-levee and post-levee (contemporary) condition using correspondence analysis (Figure 68). Pre-Development (i.e., pre-levee) connected floodplain was represented by the PLS <1850 land cover within the 1 percent recurrence flood interval area (i.e., 100-yr flood). Post development connected floodplain conditions were represented by the 2000 land cover in the unleveed floodplain. The upper 2 and lowermost Mississippi River reaches, and in one case the Illinois River were excluded from analyses because of incomplete data for each reach.

Time periods were clearly separated in the biplot (Figure 68). The historic land cover was distributed along axis 2 on the left side along axis 1. The reaches distributed along a gradient with forests important in the south and wetlands and savanna being important in the northern reaches. All of the modern reaches, except for Floodplain Reach 9, were distributed near contemporary water, agriculture, and developed area.

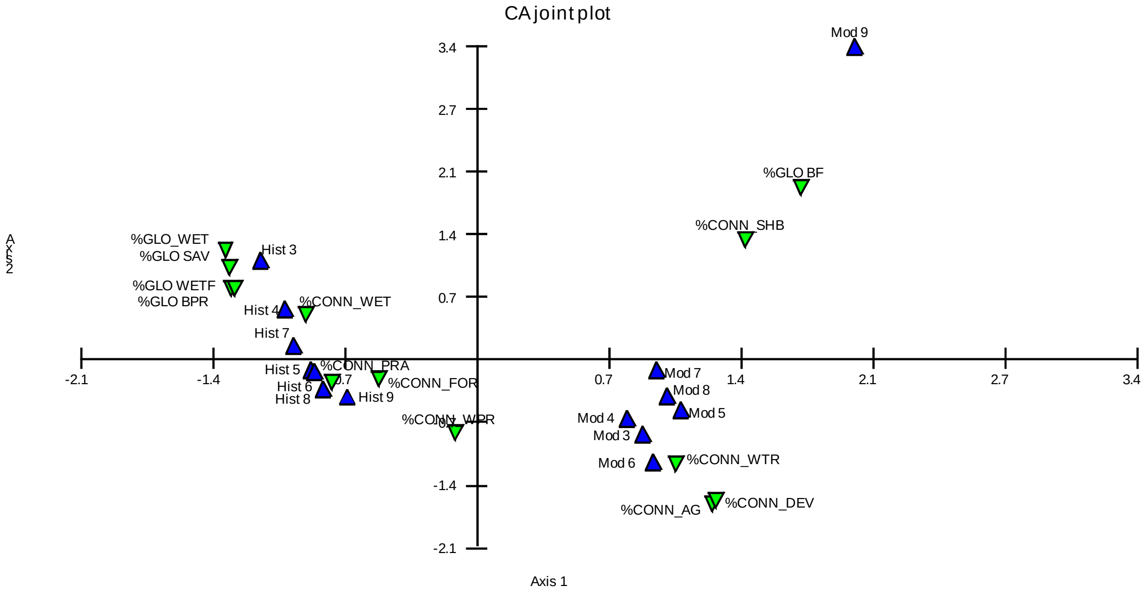


Figure 68. Correspondence analysis examining simulated floodplain inundation extent associated with presettlement and contemporary connected floodplain land cover classes.

Discussion

Spatial and temporal differences in Upper Mississippi River land cover are quite evident using the general classification schemes for land cover and aquatic areas. The PLS methodology and generalization of land cover classes may be criticized by some working at fine scales, but the data are excellent for large scale environmental restoration planning on the UMRS for which there is no contemporary physical reference (Nestler et al., 2010). Historic land cover condition also helps elucidate of the ecological drivers creating and maintaining these landscapes. Chapter 2 summarized the floodplain geomorphology (Appendix A) to characterize river reaches and Chapter 3 summarized floodplain inundation characteristics (Appendix C) to describe river reaches. The physical landscape parameter correlations with presettlement land cover help explain plant community drivers and provide the empirical evidence required to build and validate predictive models. They, therefore, can help estimate the expected benefits of ecosystem restoration actions applicable for the set of physical conditions at project sites. It is important to refine investigations to appropriate scales and extrapolate to this large ecosystem scale as applicable.

Implications for Ecosystem Management

My multivariate analyses support a consistent segregation of time periods and reaches at the Floodplain, Geomorphic Reach, and Pool scales based the relative abundance of Agriculture-Developed-Water classes in the contemporary period and Savanna-Wetland-Forested Wetland classes in the historic reference. Forest and Prairie were relatively neutral in the ordinations because of their even distribution, especially forest. Patterns of development are clear in the mapped data (Appendix D) and also in the simple ordination at the floodplain reach scale (see Figure 52). The consistency of results among the larger scales will support ecosystem restoration planning by helping target problems, opportunities, and tools for large scale ecosystem restoration.

The Upper Impounded Reach retains characteristics most similar to the historic reference condition. The cluster analysis linked the Upper Impounded Reach with the historic land cover from all the reaches (see Figure 52). The CA Separates the reaches midway along Axis 2, between the historic land cover and modern land cover in the other reaches (see Figure 52). The Upper Impounded Reach and subdivisions within it consistently separate out on Water-Wetland land cover classes while the historic data separate on Savanna-Bottom-Forested Wetland-Bottom Prairie classes and the modern land cover separates on Agriculture-Developed area.

These ordinations fit the contemporary pattern of habitat quality seen on the UMRS. Quality is difficult to quantify without multiple physical, biological, and chemical parameters, but there have been significant investments monitoring river ecosystem quality (USGS, 1999; Johnson and Hagerty, 2008). The general impression of UMRS habitat quality is of a healthy functioning ecosystem that is attractive and fun for recreation in the Upper Impounded Reach, and more degraded and commercially developed agricultural and urban systems in the other reaches. The lower river reach typically support a narrow riparian corridor of “habitat” between leveed agriculture and urban areas, which both have significant direct effects changing land cover. The conversion from forested wetlands, wetlands, and braided channels to lakes, marshes, and open impounded areas in the Upper Impounded Reach was indeed a massive direct effect conversion from ephemeral floodplain-aquatic habitat to a permanent aquatic habitat (Green, 1960). The conversion to the shallow aquatic littoral habitat, however, had a high initial natural production capacity, the “new reservoir effect” (Fremling et al., 1989; Bayley, 1991). High productivity in the deep marsh and shallow littoral areas was maintained in the Upper Impounded Reach until the 1970s. Since then, the effects of "pool aging" have been exhibited by plant die-offs during periods of environmental stress (Lubinski, 1999; Rogers and Theiling, 1999), but the Upper Impounded Reach has demonstrated the capacity to rebound (Lubinski and Theiling, 1999). In other cases, like where sedimentation has eliminated submersed aquatic vegetation in backwater lakes in the Lower Impounded and Illinois River Reaches, ecosystem processes associated with low river stages are not allowed to support the ecosystem which cannot recover from continuous cumulative impacts (Sparks et al., 1990; WEST Consultants, Inc., 2000).

The modern land cover is a response variable to the human development actions in the river-floodplain and watershed. The physical and hydrodynamic changes imposed by levees, dams, channel structures, and sedimentation all act to help explain the existing landscape condition. Understanding the physical operational constraints of engineered structures will allow "management at the margins" where pool scale drawdowns, for example, are conducted to promote emergent aquatic vegetation during simulated summer low flow river stage without impeding navigation or recreation (Landwehr et al., 2004). Floodplain wetland management within large levee districts is a viable alternative to manage for isolated wetlands and lakes also (Havera, 1999). In some cases there will be no "margin" to share and alternative uses will persist independently. The primary large scale alternative uses for the Upper Mississippi and Illinois Rivers exist in the form of a safe and efficient 9-ft. navigation channel, reliable and productive crop land, and healthy and sustainable ecosystems and communities. There are potential trade-offs between environmental quality and flood protection that have not been fully explored, but can be now using information in these databases and results. Integrated floodplain management, like ecosystem and navigation system management, should consider the best available information for benefits evaluation of a variety of ecosystem services.

CHAPTER 5: CAN HYDROGEOMORPHIC AND LAND COVER ATTRIBUTES SUPPORT LARGE RIVER SCIENCE AND MANAGEMENT?

I have presented hydrogeomorphic and land cover data that I believe support large river science and management very well. Upper Mississippi River ecosystem restoration practitioners are fortunate to have a wealth of information available, I was able to enhance existing data sets collected for flood control and archeological investigations into valuable ecological data. The data are available at relatively fine scale for nearly 3 million acres of floodplain habitat. The GIS layers can be manipulated and used for many scientific investigations, I use them here to answer the hypotheses put forward at the beginning of this dissertation. I demonstrate recent large-scale ecosystem restoration planning results using these data in the following section.

Large River Ecology Hypotheses

I have liberally adopted several of the Riverine Ecosystem Synthesis tenets (Thorp et al., 2008) and Network dynamics Hypotheses testable predictions (Benda et al., 2004) as hypotheses to test on the large scale of the Upper Mississippi River System. I discuss below how each data set can help test most of the hypotheses.

River Ecosystem Synthesis Hypotheses

Distribution of Species/Physical Characteristics:

H_0: Can ecological/hydrodynamic/geomorphic patches be defined on the scale of the UMRS?

Hydrogeomorphic and land cover classes can be defined for the entire UMRS. The work of prior investigators helped establish the base geomorphology, hydrology, and land cover layers used to define spatial distribution of geomorphic class, flood stage class, and land cover class patches. Each of the layers was analyzed and their distribution could be explained by geographic, development, or hydrogeomorphic factors.

H_0: Can ecological/hydrodynamic/geomorphic functional process zones be defined for the UMRS?

The geomorphic reaches defined in by Knox and Schuum (WEST Consultants, Inc., 2000) and refined herein can be considered functional process zones (FPZ). Several FPZs are large and may have several reaches (per Thorp et al., 2008) within them. There is longitudinal zonation in some reaches, several reaches have higher slope at their upper end which flattens near downstream controls as described by Benda et al. (2004). Higher geomorphic diversity is evident directly below constricted reaches as occurs at Muscatine, Iowa (WEST Consultants, Inc., 2000) and Keokuk, Iowa.

H_0: Does development change functional process zones?

Yes, development clearly changes the relationship among geographic and environmental factors when the influence of levees or impoundment are considered. The effect is apparent in my geomorphic, floodplain inundation, and land cover analysis.

H_0: Is ecological/hydrodynamic/geomorphic diversity greatest at nodes?

I am unable to determine whether environmental diversity, expressed here as geomorphic, inundation, and land cover diversity, is greatest at nodes because I did not conduct the spatial analyses to adequately test the hypothesis. My floodplain inundation area as proportion of floodplain by river mile plot visually demonstrates inundation diversity at nodes quite clearly, and land cover maps and charts seem to have more wetlands near tributary confluence areas. Potential flood inundation diversity is greatest at the large Des Moines and Missouri Rivers confluences, but small tributary fans from the Missouri bluff, for example, also provide inundation diversity.

H_0: Does ecological/hydrodynamic/geomorphic complexity increase with increased hydraulic retention?

I am unable to determine whether complexity increases with hydraulic retention because I did not conduct the hydraulic analyses to adequately test the hypothesis. The initial UMRS geomorphic reach classification was based on changes in riverbed slope, with leveling at tributaries being an important characteristic. As channel slope decreases, there should be decreases in river current velocity and increases in aquatic area distribution and abundance. Land cover maps seem to have more wetlands near tributary confluence areas. None of these parameters were tested relative to their spatial proximity to tributaries, however. Available data would support aquatic area and land cover spatial statistics. Hydraulic modeling could provide crude estimates of current velocity, but not with the precision of contemporary models.

One interesting impact of the navigation system is the increase in repeating river, wetland, pool sequences because of the effects of the navigation dams. Where the undeveloped river had 8 – 10 such reaches between Minneapolis, Minnesota and St.

Louis, Missouri, navigation dams create 26 similar repeating sequences. The relevance of these hydrodynamic effects on land cover could be studied many ways. It appears there is potential to support more wetland habitat in floodplain areas than existed in the mid 1800s if L&DD pumps were used to support wetland management and hydrodynamic variability was maintained to support a high functioning Aquatic Terrestrial Transition Zone (*sensu* Junk et al., 1989).

Community Regulation:

None of the RES community regulation hypotheses can be tested.

Ecosystem and Riverine Landscape Processes:

H_0: Does primary production vary with hydraulic residence time?

I'm not able to conclude with certainty that primary production varies with residence time. There are several lines of evidence that support the conclusion, but I did not specifically test them: 1. I make the assumption that wetlands indicate the highest potential primary production followed by forests and grasslands. 2. Hydraulic residence time increases in low velocity environments and where there is abundant groundwater. 3. Riverbed slope and current velocity decrease at tributary confluences. 4. Wetlands are abundant at tributary mouths. 5. Wetlands are abundant in the Chippewa River Reach and other northern reaches where there is an abundance of clear groundwater influence. 6. Forests dominate the riparian corridor and the entire floodplain south of St. Louis, Missouri where extended flooding supports hydric floodplain forests in the backswamps on the floodplain and riverfront forest on banklines. Items 4, 5, and 6 are evidence for higher ecological productivity where water is more abundant on the floodplain.

H_0: Does dynamic hydrology support diverse habitat?

Yes, dynamic hydrology does support diverse habitat. My land cover and inundation zone analysis indicates that a more even abundance of land cover classes is found at less frequently flooded areas as opposed to frequently flooded areas that were dominated by forests. I also believe that greater land cover diversity is also associated with tributaries which are more hydrologically dynamic because of the effects of tributaries backing up the mainstem or, more commonly, the mainstem backing up the tributary during floods. This tributary influence is detected in the geomorphology and hydrology also. My tests for land cover and hydrologic associations could be stronger with simple diversity analyses, but I have so few land cover classes the results may not be informative. Conversely, the tree data available with this land cover data set would be ideal for such work in the future.

H_0: Do UMRS landscape classes demonstrate flood-linked evolution?

UMRS landscape s demonstrate flood-linked evolution, but that is not the primary or only driver affecting landscape condition. The Pleistocene geology and abundant groundwater may be the foremost drivers supporting abundant wetlands in the Upper Impounded Reach. Glacial processes established the valley morphology and Holocene evolution created the large-scale geomorphic template that contemporary floods occasionally inundate in the Lower Impounded Reach where there is a pronounced abundance of flood-tolerant forest and wetland communities in the 2-yr flood zone and flood intolerant communities in the less frequently flooded areas. Extended flooding in the Middle Mississippi River and the Lower Illinois River supports forests on most of the floodplain.

H_0: Does biocomplexity peak at intermediate levels of connectivity?

I cannot determine with confidence whether biocomplexity peaks at intermediate levels of connectivity. The highest historic wetland abundance, inferring high biodiversity, was in the Upper Impounded Reach, which was likely related to the stability of groundwater inputs. The most frequently flooded areas were dominated by forests, which in a historically dynamic hydrologic environment supported greater species diversity. Historic evidence shows that areas with diverse flood patterns seem to support more community types.

In the modern era increased connectivity related to impoundment inundated many forests and altered groundwater hydrology such that low diversity flood tolerant communities dominate throughout the river system. High stable water in impounded areas initially supported high diversity throughout the river system, but post dam conditions in southern reaches is degraded by too much connectivity and a lack of exposing backwater sediment during low flow. In northern reaches the impoundment effects are still positive in most years, but some large open water areas are degraded and do not support plant communities. Upper pool areas that respond to natural hydrology have greater forest species diversity and wetlands developing on exposed mudflats at the river margin.

It appears my data support the hypothesis that biodiversity is high at intermediate levels of connectivity. It also appears that biodiversity is high where structural complexity is high. I propose simple ecological rules apply, areas with high edge and variable river stage support high biodiversity and ecological productivity. These hypotheses can be investigated with different spatial assessments of these data.

H_0: Do landscape patterns characterize UMRS functional process zones?

UMRS geomorphic, inundation, and land cover landscape patterns all help characterize floodplain reach functional process zones. Land cover similarities sometimes extend beyond one or two geomorphic reaches, but differences in geomorphic or hydrologic attributes also help define reaches. Greater species level analysis would help define patterns in the forest communities.

Land cover landscape patterns are evident among functional process zones, but geomorphic and hydrologic landscapes can be analyzed also. My analysis shows how geomorphic classes are distributed, which helps understand their origin and composition. My analysis also shows that flooding is distributed differently in areas with large tributary alluvial fans and valley wall anomalies that create high topographic and flood inundation.diversity

Network Dynamics Hypothesis

Benda et al. (2004) integrated principles of fluvial geomorphology and riverine ecology in an analysis of watershed stream networks and also suggested several testable predictions. Their work was more related to watershed characteristics, but their presentation of tributary effects and several conclusions related to tributaries as “biological hotspots” are relevant on the UMRS river-floodplain ecosystem. Several of their predictions related to watershed disturbances can be adapted to the UMRS:

H_0: Do glacial influences (i.e., higher punctuated sediment supply and transport) cause greater confluence effects?

The original hypothesis regarded contemporary sediment delivery, but I believe the effects on the Mississippi River are more related to glacial and early Holocene evolution. The presence of mainstem lakes like Lake Pepin in the North or Peoria Lake on the Illinois River are because of the impounding effect of glacial sediment dams. The entire Chippewa and Wisconsin Rivers reaches were likely formed by a stream running at the base of the glacier. Occasional zones of erosive bluffline create larger floodplain areas within the Upper Impounded Reach. Each large tributary in Iowa has its own glacial history that is responsible for large floodplain features like the Des Moines alluvial fan. The Missouri River is a huge water and sediment transport influence above and below St. Louis, Missouri that created the unique sediment hump at the confluence and the historic strong meandering pattern downstream. The Middle Mississippi River meander pattern decreased in amplitude as Missouri River flows decreased through the Holocene. It has run in a relatively straight course in the contemporary climate and with the significant channel armoring. The Lower Illinois River is also influenced by relatively recent glacial events, but the Illinois Valley climate stabilized earlier and the valley has been vertically acreating for thousands of years.

> H_0: Do channelized disturbances (i.e., gorges in the natural system, or river engineering in the modern system) lead to greater hydro-geomorphic heterogeneity?

Natural channelization in constrained valleys and through tributaries increases hydrogeomorphic diversity above and below the feature. A constricted valley can impound water upstream to alter sediment patterns, and the splay of sediment at the downstream end also creates diversity. Tributaries can be broadly viewed as channelized disturbances, and the alluvial fan or prograding river deltas are evidence of the greater hydrogeomorphic heterogeneity. The intefingering of active floodplain over older geomorphic surfaces is another mechanism creating geomorphic diversity.

Channelization, conversely, has greatly simplified aquatic habitat structure by closing secondary channels and inducing sedimentation between wing dams. The effects are most pronounced below the Missouri River where thousands of wing dams are in place to move sediment in the channel and induce sediment deposition between wing dams.

H_0: Is the age distribution of landforms skewed toward older features in the upstream portions of the valley and younger features in downstream portions of the valley?

Ancient Pleistocene features are characteristic of the narrow valley Upper Impounded Reach. Glacial till, loess, and sand influences the Lower Impounded Reach which is characterized by ancient Holocene channels in the floodplain. Sediment in the Middle Mississippi Reach is sequentially aged with decreasing amplitude of meander scrolls, though there may be a lot of historic mixing. The Middle Mississippi River carries a huge sediment load.

H_0: Is physical heterogeneity concentrated in certain parts of the river valley?

UMRS physical heterogeneity is concentrated above, within, and below irregular valley segments and at tributaries.

Potential Habitat Mapping

Potential habitat mapping can be achieved using a relatively simple rules-based approach or through highly detailed simulation modeling. The rules based approach applies quite well to the level of detail available over large geographic regions (Heitmeyer, 2008; Klimas et al., 2009). The hydrogeomorphic methodology developed in southern bottomland hardwoods and adapted first to a single UMRS refuge site and then to the Middle Mississippi River (Heitmeyer, 2008) gained widespread approval from natural resource managers who could visualize their sites on the maps. The process has moved outward to other refuge sites and northern river reaches, and there is an objective to complete the whole river. The data provided herein have been used in the earlier assessments, and the higher level of quantification possible using these results could lead to greater statistical rigor, probabilistic modeling, and quantitative objectives.

A simple demonstration of the potential vegetation mapping is presented below, there are many specific alternative river-floodplain management scenarios that could be modeled. The predictive capability of the potential vegetation mapping can be very beneficial for project alternative environmental benefits analysis which is a cornerstone of environmental restoration decision making and mitigation risk assessment for large Federal projects.

The distribution of several plant community classes was simulated by spatially combining the geomorphic surfaces with the flood inundation surfaces using simple rules regarding the potential for plants to occur on specific flood and geomorphic combinations (Figure 69). The individual maps could be validated using overlays from the presettlement vegetation data, or they could be made more statistically rigorous using relationships derived from those data. The individual layers can then be overlayed on each other and addition rules included for overlap and community maps can be derived (Figure 70). This analysis was limited in scope because such exercises require an open modeling exercise that incorporates input from managers and scientists working collaboratively as codified with the Hydrogeomorphic Methodology (Klimas et al., 2009). The ultimate objective for Upper Mississippi River ecosystem restoration planning is to develop and aquatic HGM that can predict habitat potential in aquatic habitats also (Figure 70).

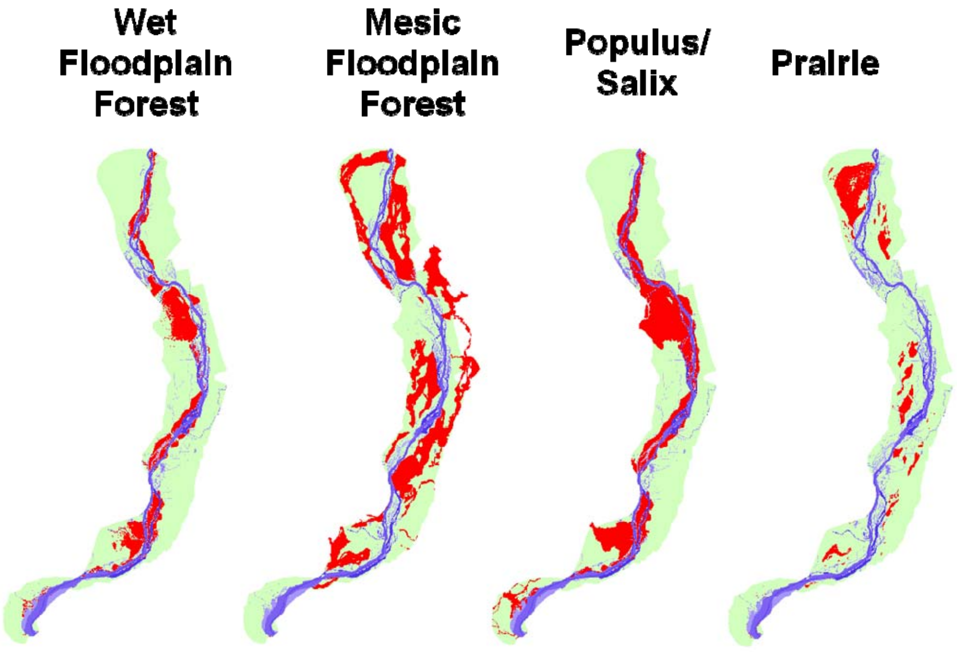


Figure 69. Potential vegetation mapping incorporates simple rules regarding suitability of large geomorphic features and flood hydrology to estimate the potential distribution of individual plant communities.

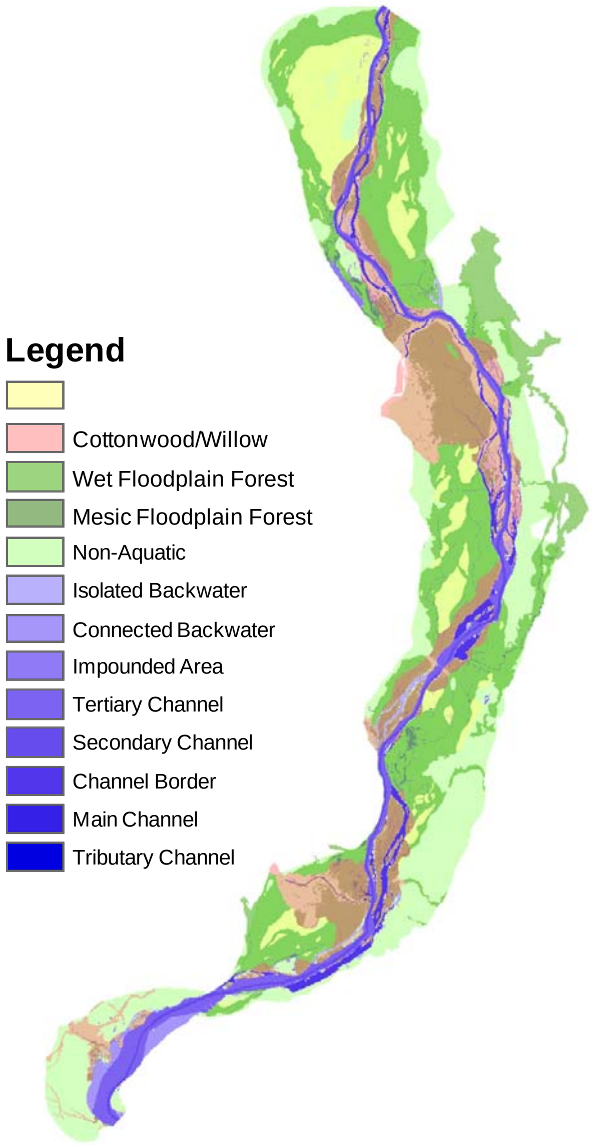


Figure 70. Potential plant communities can be overlayed with aquatic habitat features to develop a seamless aquatic-terrestrial predictive habitat capability.

Large River Management

The UMRS river manager's collective ecosystem restoration objectives were summarized using the conceptual model to illustrate components of each EEC (Figure 71). The objectives were classified as Process and Function Objectives among EECs that affect Composition and Structure Objective outcomes. Processes and functions associated with some EECs are more easily monitored and modeled than others. Examples of ecosystem restoration criteria for several spatial scales are presented in Table 6.

One common approach used to incorporate ecological process and function is into ecosystem restoration planning is to imply ecosystem function and animal habitat suitability from the dominant land cover classes, plan for target habitat benefits, and compare alternative project designs based on potential benefits provided. Seasonal habitat attributes like flooding were implied rather than modeled in most cases because the tools to conduct such evaluations were not common. The approach was reinforced by Federal planning guidance that promoted "habitat units" as ecosystem benefits (i.e., HEP and other suitability models) for restoration project alternatives evaluation (USACE, 2000; Thorp et al., 2010). Late summer land cover became a planning "currency" on the UMRS. As planners gained experience, the "everything" project (many alternative measures affecting many habitat types) fared well in benefits evaluation and competition for funding. Large projects with many constructed features affecting many habitat classes were common.

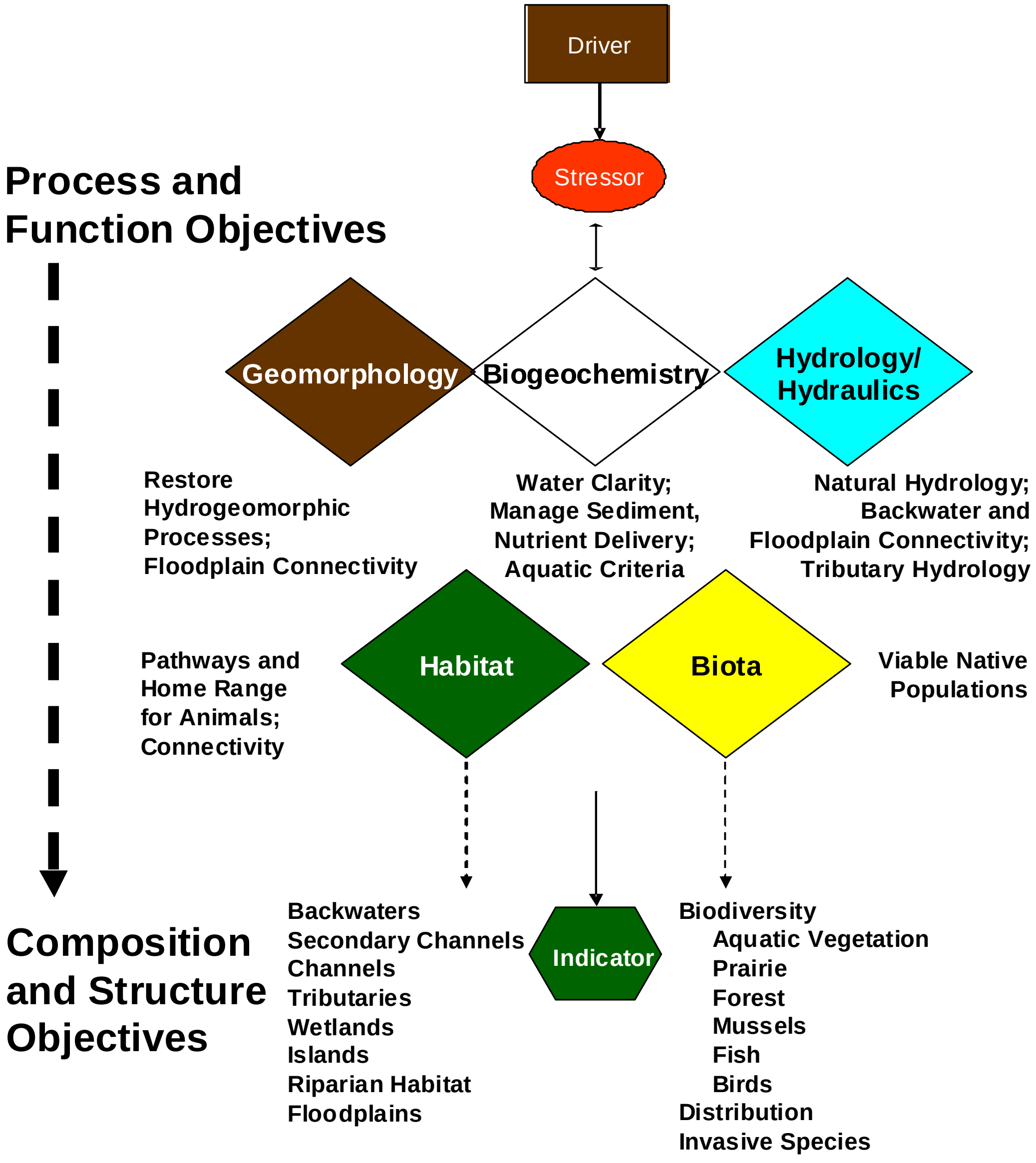


Figure 71. System-wide ecosystem restoration objectives compiled from separate planning team for four Upper Mississippi River System Floodplain Reaches.

Table 6. Ecological indicators applicable at several spatial scales for Upper Mississippi River System essential ecosystem characteristics.

	Boundary Condition	Reach Scale	Local Scale
Geomorphology	• Glacial Geology	• Land Sediment Assemblages; • Impoundment effects • Levee effects • WEST aquatic area geomorphic change • HNA geomorphic change	• Elevation • Soil • HNA Geomorphic change
Hydrology & Hydraulics	• Climate/Discharge – magnitude, frequency, timing, duration, rate of change	• Water Surface Elevation - magnitude, frequency, timing, duration, rate of change • Inundation - magnitude, frequency, timing, duration, rate of change	• Flow distribution, direction, velocity, depth • Inundation - magnitude, frequency, timing, duration, rate of change • Pool scale hydrologic gradient • Floodplain lakes • Deep holes
Biogeochemistry	• Basin geology • Basin land cover • Non-point pollution	• Major watershed – geology, – land cover, – non-point pollution	• Nutrient abundance • Water clarity • Dissolved oxygen • Sediment Quality • Point source pollution • non-point pollution
Landscape	• Climate • Biodiversity • Geomorphology • Hydrology	• Regional Climate • Ecoregions • Land use • Ecosystem/community type • Disturbance	• Land cover • Ecosystem/community type • Geomorphology • Hydrology
Biota	• Biodiversity • Long distance migrants	• Populations • Communities	• Species • Composition
Biotic Processes	• Biochemistry	• Climate • Genetics	• Production • Growth

Contemporary restoration theory emphasizes the point that restoration activities must be process based to achieve system-wide sustainability (SER, 2004; Thorp et al., 2010). Understanding and restoring important ecosystem process and functions will make the UMRS ecosystem more resilient to human and natural disturbances. Conveying ecosystem process and function in a conceptual model or textbook is a complex task, however, because ecosystem functions range from cellular processes like photosynthesis to large scale fluvial processes like sediment transport. Quantifying processes in the field with statistical rigor is challenging also. Thus, advanced ecological simulation models of the UMRS are rare despite the fact that the UMRS is a data rich environment with vast amounts of system-wide data for river levels and discharge, land cover, topography, soils, and sediments and nutrients.

Process based hydrodynamic simulation models which can be the fundamental base to other riverine ecological models have become commonly applied ecosystem restoration design tools that allow alternative benefits evaluation and design optimization for most projects. They are being incorporated into ecological models also (Zigler et al., 2008). My analyses presented here will provide large-scale estimates for geomorphology and flood inundation drivers to help define ecosystem restoration project significance and benefits.

Quantifying Upper Mississippi River System Ecosystem Restoration Objectives

Reach scale ecosystem objectives were compiled for the four Floodplain Reaches and compared system-wide (USACE, 2010). The objectives operate at different scales, including many objectives that can only be achieved from outside the floodplain (i.e., tributary sediment and nutrients; Table 7). System level plans were already prepared for fish passage (Wilcox et al., 2004), water level management (Landwehr et al., 2004), forests, the entire Illinois River Watershed (USACE, 2007), system-wide flood protection (USACE, 2006), and navigation (USACE, 2004). Many process and function objectives operate on a small scale that is difficult to evaluate at the reach scale (e.g., bathymetric diversity, sediment transport, local water quality, local habitat; see Table 6). These smaller scale physical characteristics and process such as depth and current velocity can be generalized for aquatic classes or land cover classes at the reach scale, as they have been in the past, but site specific processes affecting local habitat and subareas must be considered at smaller scales.

The following discussion demonstrates how multiple reference condition analysis can be used to evaluate restoration potential by measuring former ecosystem condition, contemporary ecological response to systemwide hydrologic management, and alternative hydrologic management strategies at the reach scale.

Table 7. Upper Mississippi River System system-wide ecosystem restoration objectives sorted by their appropriate planning scale.

Reach Plan	**Site Specific, Not Evaluated**	**Beyond UMRS, System Plan**
A more natural stage hydrograph	Reduced sediment loading and sediment resuspension in backwaters	Reduced nutrient loading from tributaries to rivers
Restored hydraulic connectivity	Restored lateral hydraulic connectivity	Reduced contaminants loading and remobilization of in-place pollutants
Increase storage and conveyance of flood water on the floodplain	Water quality conditions sufficient to support native aquatic biota and designated uses	Restored floodplain topographic diversity
Restored backwaters	Restore rapids	Forest Plan, Floodplain Landscape
Restored secondary channels and islands	Restored bathymetric diversity, and flow variability in secondary channels, islands, sand bars, shoals and mudflats	
Restore a sediment transport regime so that transport, deposition, and erosion rates and geomorphic patterns are within acceptable limits		
Improved water clarity		
Naturalize the hydrologic regime of tributaries		
Restored lower tributary valleys		

Quantifying System-Wide Ecosystem Restoration Benefits

A More Natural Stage Hydrograph

Important ecological characteristics of the stage hydrograph include the timing, frequency, magnitude, duration, and rate of change of hydrologic events (Poff et al., 1997; Richter et al. 1997). In large floodplain rivers the distribution of floodwater is also an important consideration (Junk et al., 1989). These have all been altered to some degree in the impounded reaches of the UMRS and by diversions and channelization in others (see Chapter 3). Evaluating change in the natural hydrograph (see Theiling and Nestler et al., 2010) is important, but mapping surface water distribution is also important to classify, quantify, and visualize surface water on a large scale. Pre-dam and contemporary maps have been used to infer impacts to the dynamic stage hydrograph for a limited set of conditions (see Figure 25). My research expands the aquatic area classification systems on pre-dam maps and also simulates floodwater distribution. It provides a tool to visualize alternative dam operations and alternative levee and drainage district management opportunities.

Significant increases in surface water distribution are concentrated in the Mississippi River Upper Impounded Reach, Reaches 1, 3, and 4, and Upper Illinois River, Reach 11 (Figure 72). However, the loss of low flow physical functions like sediment compaction and oxidation during degrades backwaters throughout the system. From a spatial perspective the greatest potential to affect change in the altered hydrology is in the Upper Impounded Reach. The Floodplain Reach can be subdivided to subareas to more closely examine the potential benefits. Subareas closer to dams stand out with large areas of potential benefits (Figure 73). Some areas with large potential benefits are clustered in lower pool 8 and Pool 9. A no-dam scenario (Figure 74) has been simulated, but environmental drawdowns of less than 2-feet are a more likely scenario. For all practical purposes, a return to moderate flow drawdowns, similar to the St. Paul District pre-1973 water regulation operating manual, would be desirable to promote sediment quality and aquatic plant productivity. Restoring stage variation keyed to natural discharge variability, as is the run-of-the-river hinge point operating rules, should benefit shallow littoral and wetland habitats. Navigation channel dimensions should be maintained deeper to accommodate drawdowns in the UIR. Environmental benefits of drawdowns may not be large in reaches less impacted by impoundment.

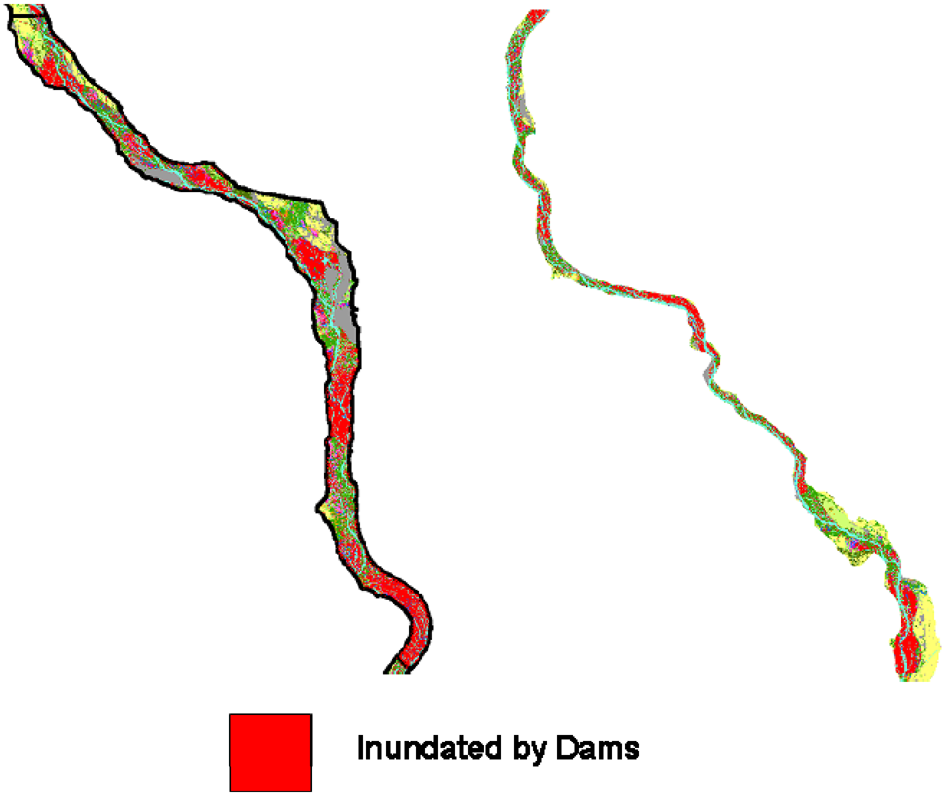


Figure 72. Changes in surface water distribution from impoundment are most pronounced in the Upper Mississippi River System, Upper Impounded Reach.

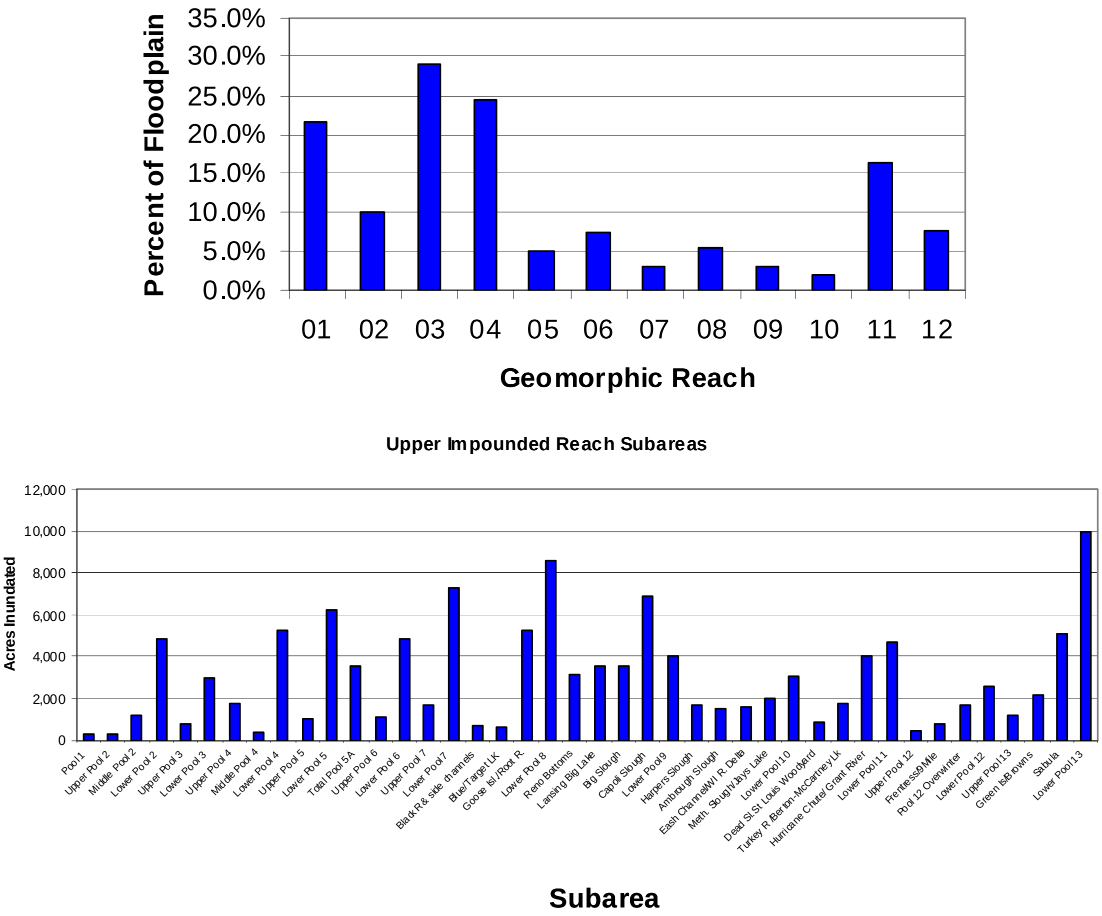


Figure 73. Impoundment effects as percent of floodplain area are most pronounced in Upper Mississippi River System Geomorphic Reaches 1, 3, and 4, (Upper Impounded Reach; Top). The effects can be subdivided within the UIR to identify subareas and sets of subareas that may benefit from pool-scale water level management.

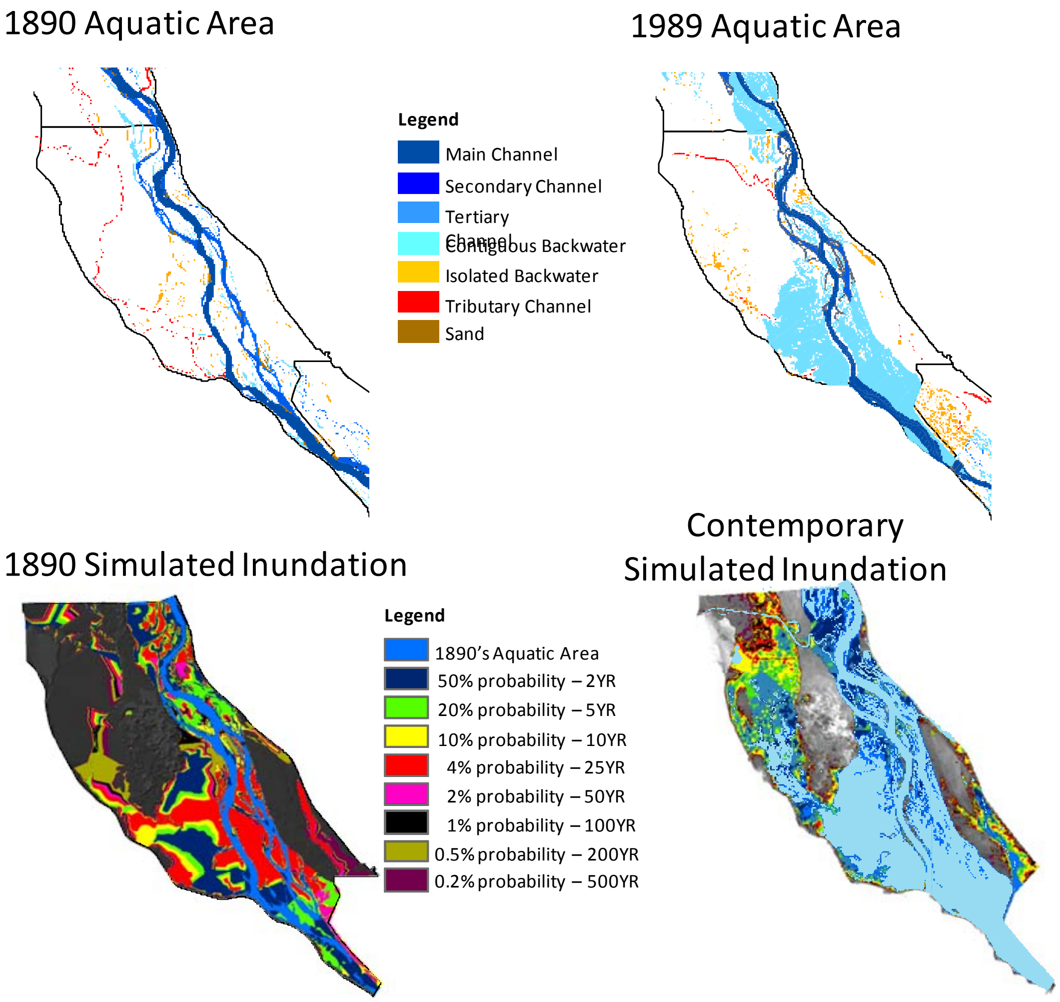


Figure 74. A larger-scale perspective on site specific change can help understand ecosystem stressors like flooding and impoundment effects using historic (top left), contemporary (top right), and simulated alternative conditions (bottom pannels) can help bound the expectations for restoration.

Increased Floodplain Connectivity

Increased floodplain connectivity implies levee removal, but there are actually many intermediate comprehensive floodplain management alternatives that can increase habitat benefits, reduce crop production costs, balance flood protection between agricultural and mixed uses, and increase recreation opportunities. There are indeed individual LD&Ds at tributary confluences, for example, that offer high hydro-geomorphic diversity which would support high biodiversity and water quality objectives. Conversely, there are other L&DDs in the LIR that would simply become large open lakes if they were managed for aquatic resources (Figure 75). These conditions are familiar in places like Lake Chautauqua which was a failed L&DD nearly from inception, Lake Odessa in Iowa, and Swan Lake at the Illinois and Mississippi River confluence which was recently rehabilitated with a management levee and pump system. Much of the floodplain in the Reaches 7 and 8 would be flooded comparable to the open water impoundment effects exhibited in the Upper Impounded Reach if L&DDs were not pumping groundwater against the head of the navigation pools (Figure 75). Large scale backwater, moist soil management opportunities have demonstrated long-standing success for wetland management, especially when they are compartmentalized as discrete wetland units. But large open aquatic areas are not necessarily the desired objective and such areas may be better allocated to other uses.

A mixed use floodplain management plan can achieve multiple benefits within the existing infrastructure (Figure 76). Complete year-round aquatic river-floodplain habitat connectivity is unlikely without significant modification of L&DD infrastructure, but there may be larval fish export to the river from floodplain wetlands that can be managed with L&DD water management infrastructure. There will definitely be an energetic input to the river from the managed wetlands. Wetland dependent fauna (i.e., mammals, birds,

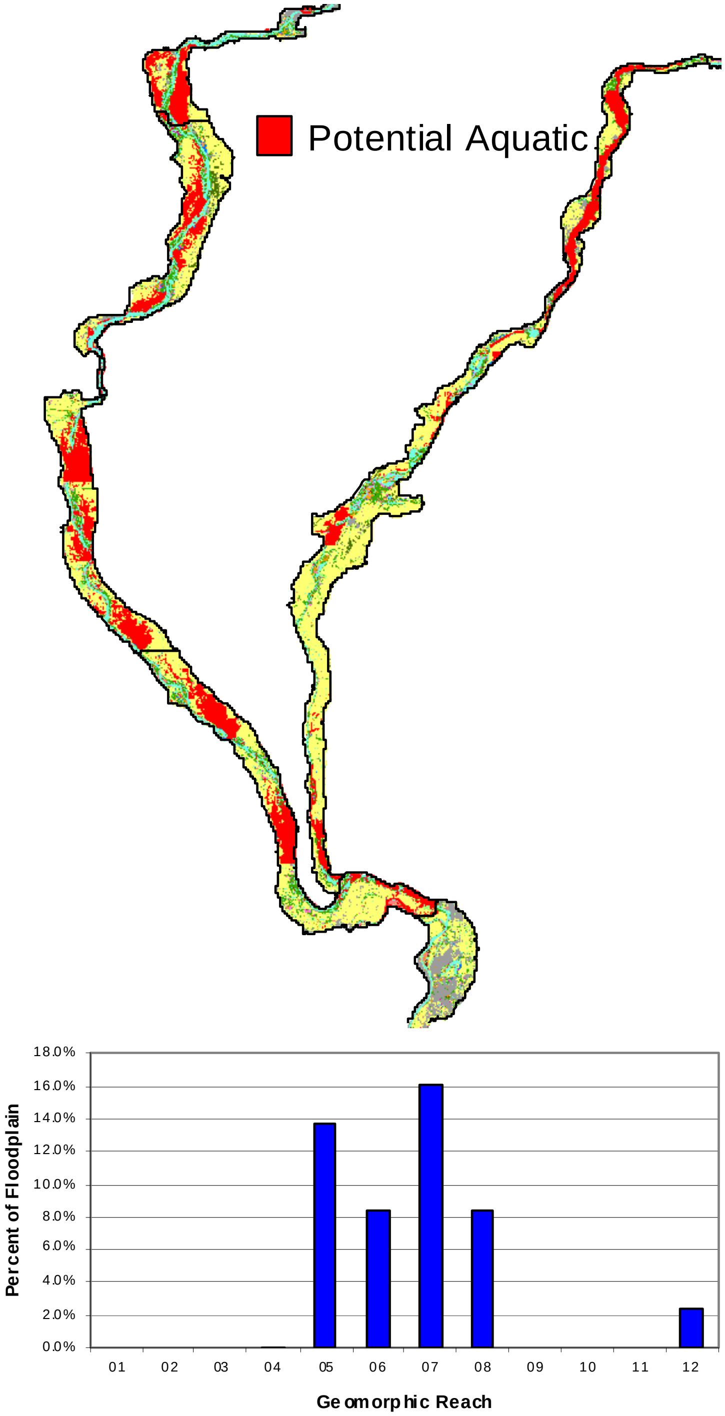
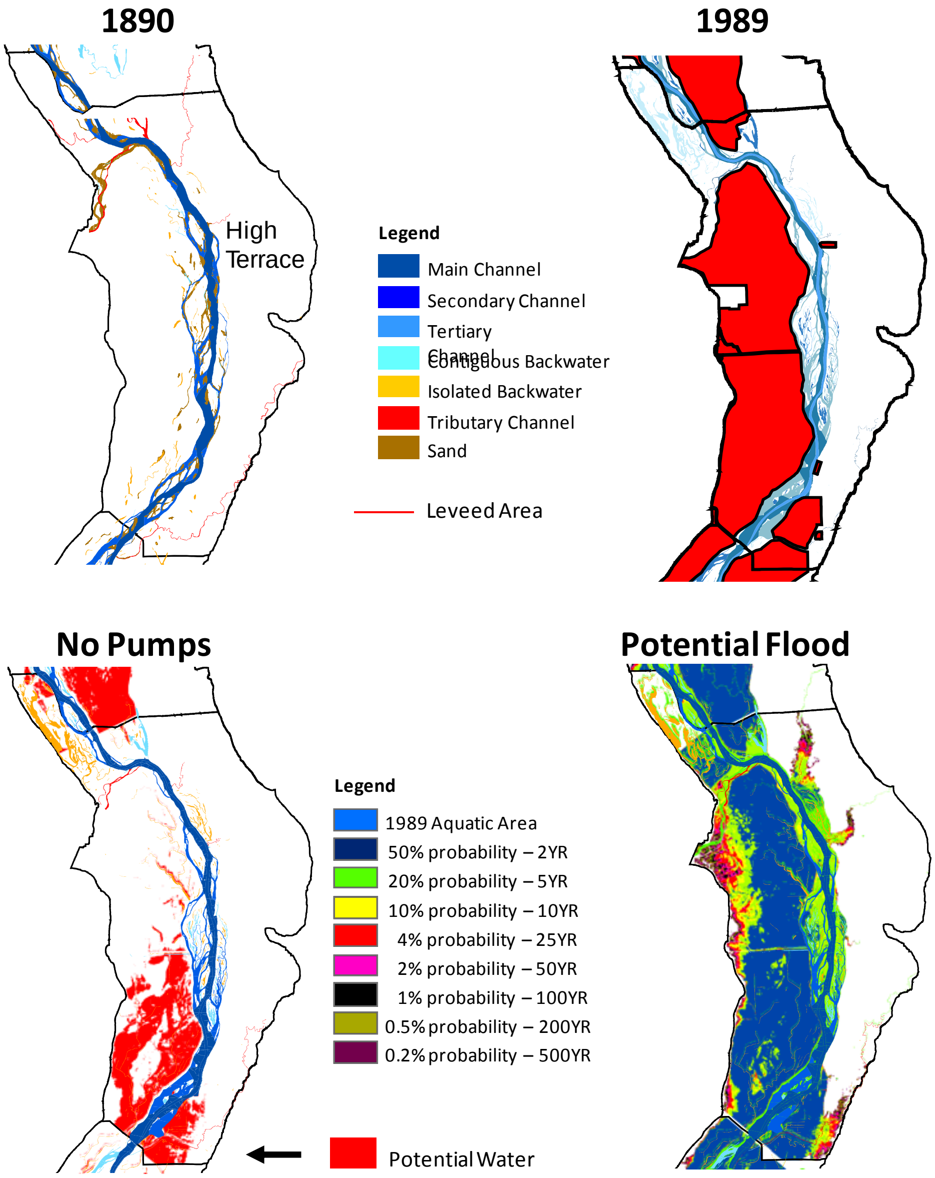


Figure 75. Potential floodplain aquatic area is much greater than existing conditions in the Upper Mississippi River System, Lower Impounded Reach because L&DDs pump significant amounts of groundwater compared to other river reaches.

reptiles, and amphibians) thrive in such conditions. Conservation easements could be structured so seasonal wetlands can be hayed for feed or fuel to minimize financial impact to landowners. Livestock could also be seasonally rotated into floodplain grasslands.

A large scale floodplain management strategy to manage flood risk entails flood protection for crops at a high enough level to support economic opportunity, but low enough to discourage structures in the floodplain (Brent Hoerr, Palmyra, Missouri, personal communication). Crop insurance and flood easements could be structured to pay for crop losses when floods occur. This option is suboptimal for habitat management, but in the sense of a multiple use resource it provides moderate crop protection in some areas that will allow for more flood security and restoration opportunities in other areas. L&DD lands managed for aquatic habitat might be purchased outright, but they may also be accessed through a variety of flood and conservation easements. L&DD wetland management benefits are concentrated in the Lower Impounded Reach (Figure 77) and some places in the Lower Illinois Reach, but the habitat benefits can be achieved in most agricultural environments. Large amounts of urban development around St. Louis and extremely large levee management areas in the Middle Mississippi River limit large scale floodplain restoration opportunities. MMR locations suitable for increased hydraulic connectivity are identified as high priority objectives.



1890

1989

No Pumps

Potential Flood

Figure 76. Historic, contemporary, and modeled alternative future (virtual) reference conditions help visualize and quantify alternative floodplain management scenarios in Upper Mississippi River System. (Pool 18 - 1890 aquatic areas, 1989 aquatic areas and levees, No Pumps hypothetical inundation to pool stage, Potential Flood maps spatial distribution of Flow Frequency stages regardless of existing levees).

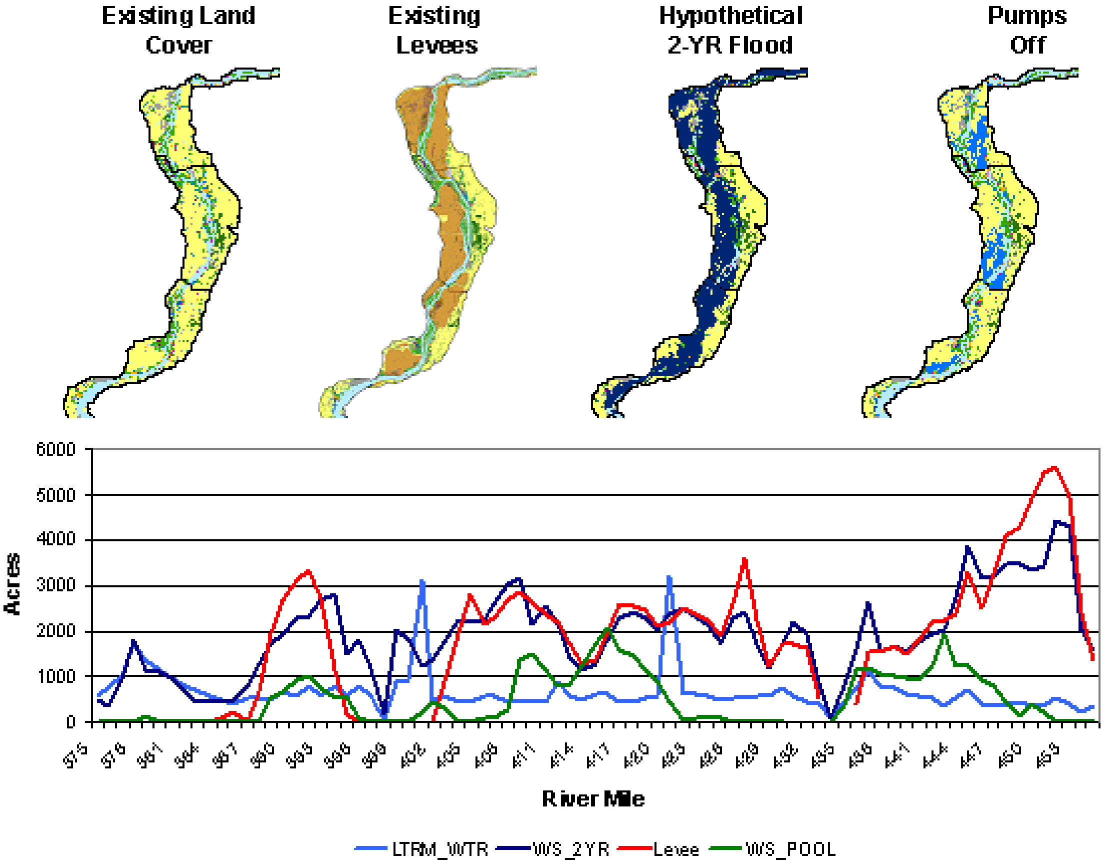


Figure 77. Ecosystem restoration benefits were calculated for the Iowa River Geomorphic Reach by comparing the area inundated by different river stage profiles and area protected by L&DDs. Leveed area and the potential 50 percent recurrence flood area (WS_2YR) track very closely indicating their intent to protect from frequent floods. Low flow river stage (LTRM_WTR) is the existing aquatic area, and the potential new floodplain aquatic area (WS_POOL) is the area under the green line.

Backwater Restoration

Off-channel habitats are highly degraded in southern river reaches (Bhowmik et al. 1986; Bhowmik and DeMisse, 1989; Figure 78). Water level management is effective, but expensive and subject to damage in floods (e.g. Chautauqua, Odessa, Swan Lake, etc.) using common low levee and pumping practices. Restoring low flow stage variability in backwaters is the objective, it should be pursued with minimal infrastructure. Pool scale drawdowns aren't predictable because they rely on discrete discharge ranges that occur on the ascending or descending flood hydrograph, backwater scale water level management during extended low flow periods could be more predictable. An alternative to permanent levees for water level management would be to close-off narrow openings in backwater lakes with material dredged from sump bays for dewatering pumps, and then operate the pump through the summer growing season to simulate summer low flow river stages. In the fall, pick up the pump and put the equipment on high ground. The sump may remain as deepwater habitat and the lives of backwaters would be extended by keeping them open to the river. Pumps and equipment on reserve for flood fighting could be shared for natural resource management as has been proposed by the U.S. Fish and Wildlife Service and U.S. Corps of Engineers Emergency Management (Robert Clevenstine, USFWS, Rock Island, Illinois and Rodney Delp, USACE, Rock Island, Illinois personal communication). Equipment and crews would likely be very cost effective. It's possible to imagine a scenario where several backwaters per reach are managed each year such that most backwaters are drawndown every decade or so. Lakes with large openings can be partitioned with peninsulas and islands that can be easily closed-off to allow temporary water level management. Peoria Lake, for example, might be surrounded by low islands that could be variously connected to create management units. Pumping would be energy intensive, but perhaps siphon technology or renewable energy could be used.

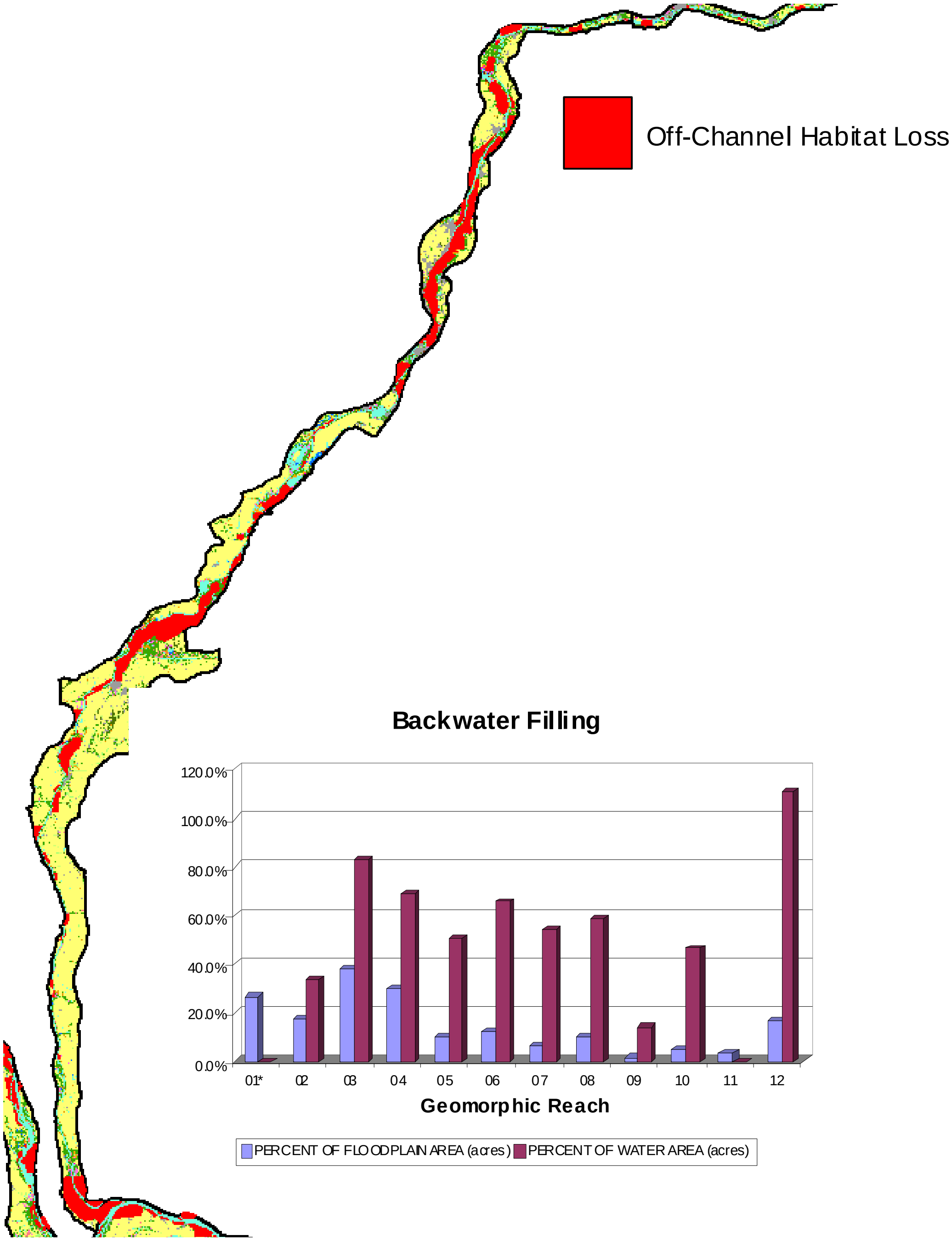


Figure 78. Backwater habitat loss as designated by natural resource managers.

Conclusion

I demonstrated the ecosystem restoration planning utility of using multiple reference condition data sources including historic, contemporary, and modeled alternative geomorphic, hydrodynamic, and land cover data. I was also able to test many current hypotheses in Large River Ecology. I showed how the data can support hydrogeomorphic methodology assessments, but further model development must be completed by interdisciplinary teams. I achieved my primary objective to support large scale ecosystem management for the Upper Mississippi River System.

My analysis demonstrates the importance of having scale-appropriate data because I was able to test larger geomorphic and land cover landscape hypotheses but not finer-scale biotic community regulation hypotheses. I was also able to statistically analyze and model the large scale hydrologic landscape, but hypotheses regarding ecological production rates, nutrient processing, and other processes require fine-scale hydraulics and hydraulic retention estimates that can only be obtained from 2- and 3-dimensional hydraulic models. I was able to compare land cover associations from a relatively local scale (i.e., Pool), up to pool reaches, geomorphic reaches, and floodplain reaches. Temporal differences were apparent at all scales, but spatial associations became cluttered at finer scales. Pool Reach and Geomorphic Reach scale results were very similar, indicating the Pool Reach is an appropriate scale for ecosystem restoration planning.

Recommendations to achieve system-scale ecosystem restoration objectives differ among floodplain reaches because there are significant differences in river-floodplain geomorphology, hydrology, biota and climate among the reaches. Each ecosystem restoration project requires detailed site-specific planning and design, but there are many broad recommendations to be considered that have emerged from this multiple reference condition analysis. I propose the following large scale ecosystem management recommendations:

- A return to something similar to the St. Paul District pre-1973 water regulation operating manual would be desirable in the Upper Impounded Reach. Restoring stage variation keyed to natural discharge variability should benefit shallow littoral and wetland habitats. Navigation channel dimensions can be maintained deeper to accommodate drawdowns, at least in some parts of the Upper Impounded Reach.
- Structural diversity (geomorphic pattern) is an important system-wide geomorphic objective that is achieved through multiple site specific projects and flow manipulation. Planners may consider incorporating specific types of geomorphic features and processes into future restoration projects to restore a more complete pattern of river and floodplain habitats.
- Land conversion from crops to native communities has large ecosystem benefits. Long term acquisition plans are helpful because they can be used to target resources effectively when opportunities like flood buyouts, charitable donations, or stimulus spending arise.
- A mixed use floodplain management plan can achieve multiple benefits within the existing levee and drainage district infrastructure. Multifunctional agriculture can provide increased ecosystem and economic benefits.
- Water level management at several scales has proved to be ecologically effective. An alternative to permanent levees for site scale water level management would be to close off narrow openings to backwater lakes and pump them dry through the summer growing season to simulate summer low flow river stages. The practice could be rotated among lakes to ensure benefits every year.

- Secondary channels are critically important off-channel habitat throughout the UMRS. In the MMR and Alton Pool secondary channels represent some of the limited remaining aquatic habitat outside the main channel and should be warranted the highest priority for restoration.
- Opportunities for restoring tributary confluences are, by nature, site-specific projects, but there are different restoration opportunities among reaches. Managers have sought to increase the diverse habitat provided by natural tributary fans, so active deltas need to be protected. Channelized tributaries are a more common problem in the South, but occur throughout the river. Benefits among watershed and mainstem restoration programs could be effectively coordinated.

The objectives and recommendations above have refined a list of potential restoration subareas from over 600 to around 60 for the whole UMRS. Planning and Prioritizing among 60 sites is still a challenging task that UMRS planners have faced before during prior restoration planning. A structured decision making process was tested previously using simple land cover metrics. I propose that formal structured decision making be implemented to prioritize UMRS restoration sites using hydro-geomorphic factors, potential vegetation mapping, and the gap analysis approach presented here.

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APPENDIX A: GEOMORPHIC REACHES

Geomorphic classes were mapped and summarized by river mile (see Figure 15), but the river system is so large it is difficult to display in a single map image. Individual geomorphic reaches are discussed as follows and presented in maps and charts individually or in pairs depending on their size. These geomorphic reach definitions refine the classification presented by Knox and Schumm (in WEST Consultants, Inc., 2000) by delineating reaches at their geomorphic characteristics rather than at dam locations.

Minnesota River Reach:

The Minnesota River geomorphic reach extends from Minneapolis-St. Paul, Minnesota to Lake Pepin (see Table 3, Figure A-1). The Minnesota and St. Croix Rivers were important influences in historic and contemporary periods. These tributaries and the headwaters drain silty loess and loam fill plains from the west and sandy regions to the north and east. The river valley was cut deep by the Warren and Glacial St. Croix Rivers and has filled over 120 feet during the Holocene (Madigan and Schirmer 1998). Knox and Schumm (in West Consultants, Inc., 2000) discussed the oldest terrace sequence, Bagley Terrace, remnants on both sides of the river. The reach was growing downstream into Lake Pepin at a rate of 25-feet/yr on average for the last 10,500 years until the modern era where photographs between 1940 and 1989 identified a rate up to 185-ft/yr (Knox and Schumm in West Consultants, Inc., 2000). Impoundment effects in the lower parts of each navigation pool inundate large areas of low elevation active floodplain. Natural levees are prominent in the lower one-half of the reach.

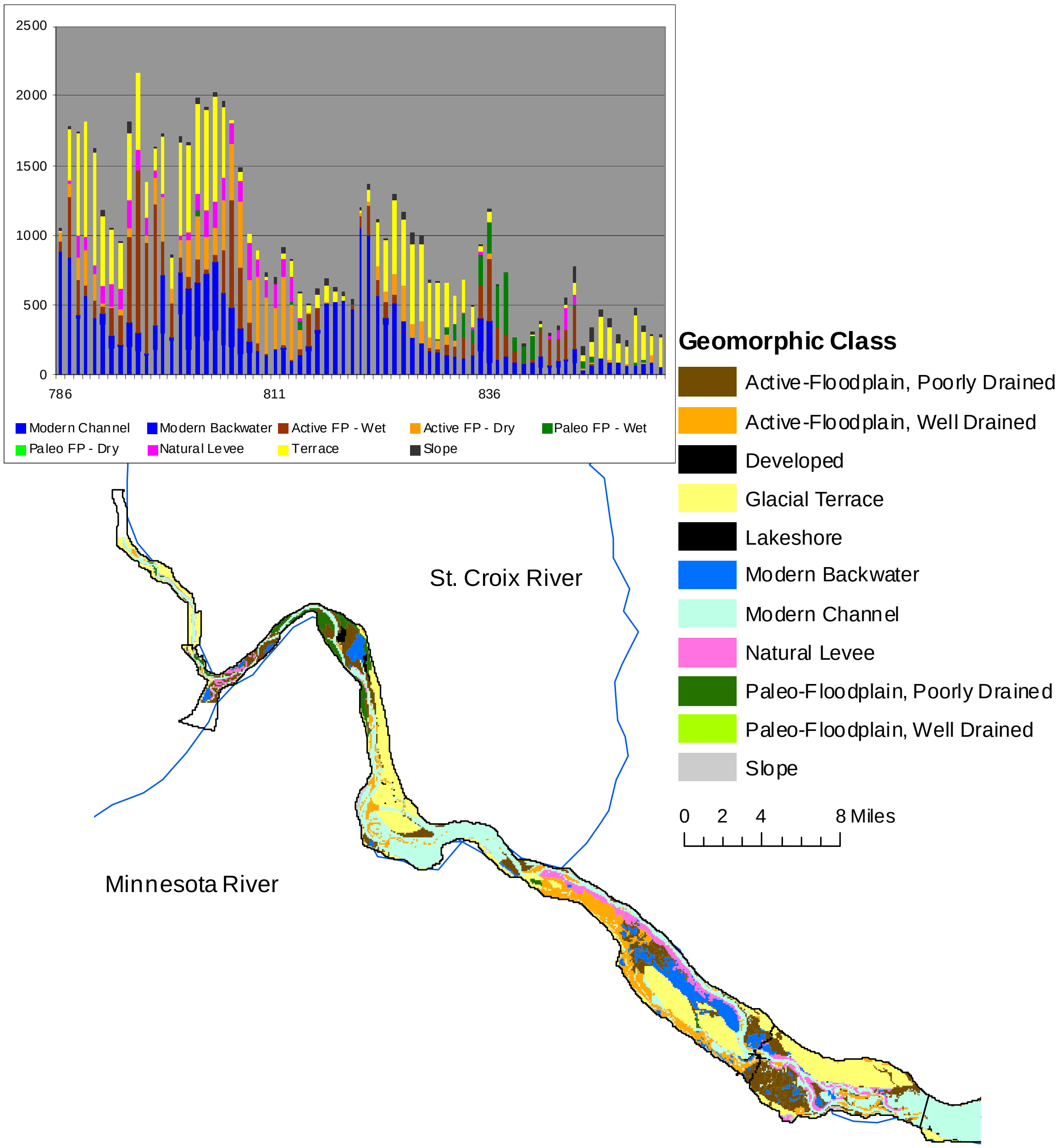


Figure 79A-1. Minnesota River geomorphic reach, Upper Mississippi River System.

Lake Pepin Reach:

Lake Pepin (Figure A-2) is a large tributary delta lake formed by sediment outwash from the Chippewa River into the deep Mississippi River valley (Fremling, 2005). The lake is believed to have reached to St. Paul but has filled 50 miles since then (see above, West Consultants, Inc., 2000). The lake is shallow compared to the deep valley, with maximum depth around 50 feet and average depth about 20 feet. It is destined to fill someday and potentially change the character of the upper river with the loss of the sediment and nutrient trap. The lake presently captures much of the high suspended sediment load coming from the agriculturally developed Minnesota River basin (Minnesota Pollution Control Agency, 2008).

Chippewa River Reach:

The Chippewa River Reach is a long reach that is also influenced by the Black River (Figure A-3). The reach is steep and island braided (see Figure 5) with an “enormous” sandy bed load (Knox and Schumm in WEST Consultants, Inc., 2000) from the major tributaries. The reach has many more islands and a much greater total area of islands than other reaches, but they are of similar size as those in other reaches (see Figure 24). All are overtopped most years. Minor tributaries influence valley margins. The upper part of the reach is slightly wider with outcrops of sandstone bedrock, narrowing downstream where outcrops of dolomite bedrock dominate the valley walls (Knox and Schumm in WEST Consultants, Inc., 2000). Terraces are abundant in the wider upper part of the reach (Figure A-3). Active floodplain is present at tributary mouths and upper pool areas where impoundment effects are less apparent (Theiling and Nestler, 2010), but it is inundated in the lower pool. Paleo-floodplain is not abundant in most of the reach and is likely inundated. Modern aquatic areas fill 20 to 100 percent per river mile in some areas. The Holocene geomorphology is visible in the riverine upper segments of each navigation pool.

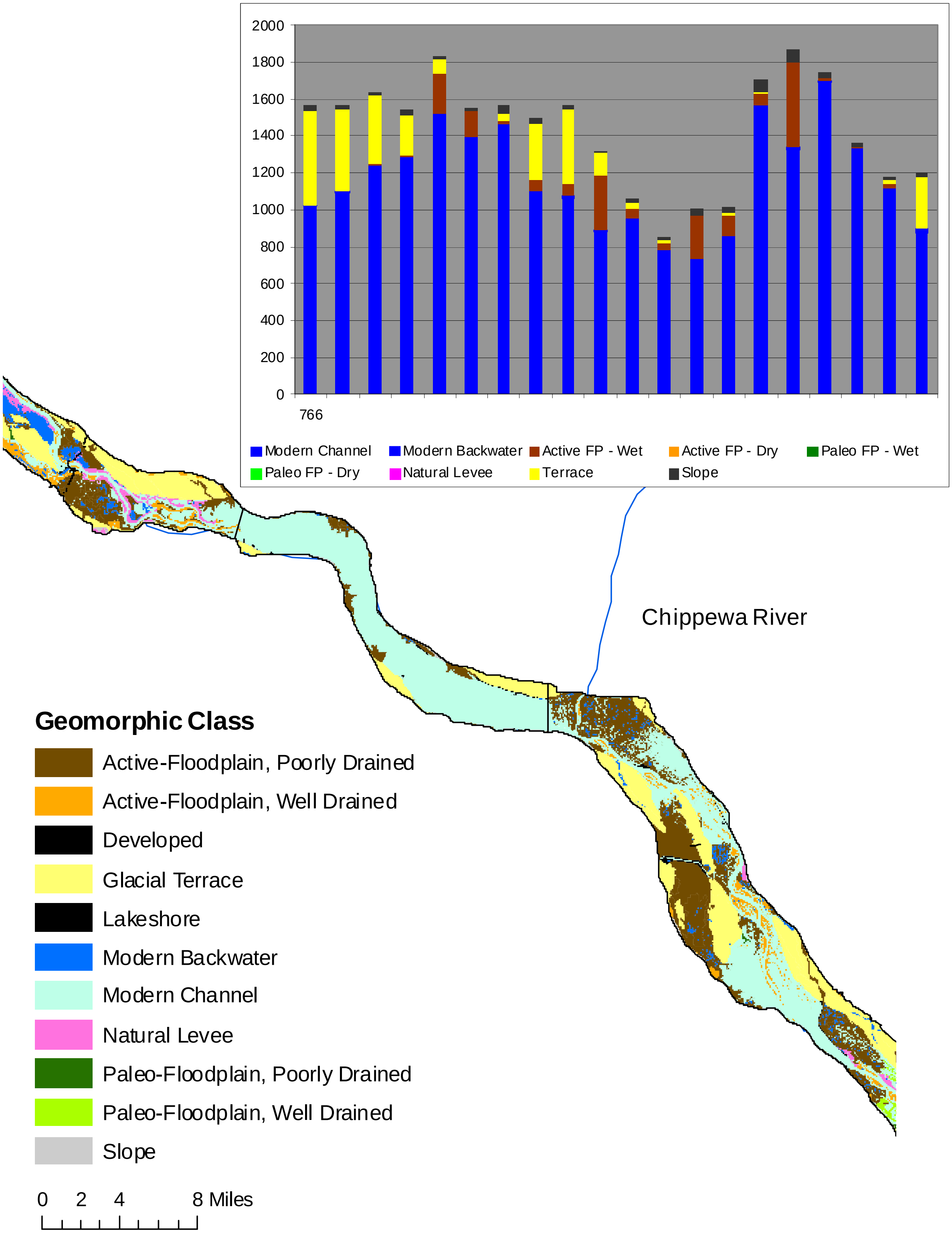


Figure A-2. Lake Pepin geomorphic reach, Upper Mississippi River System.

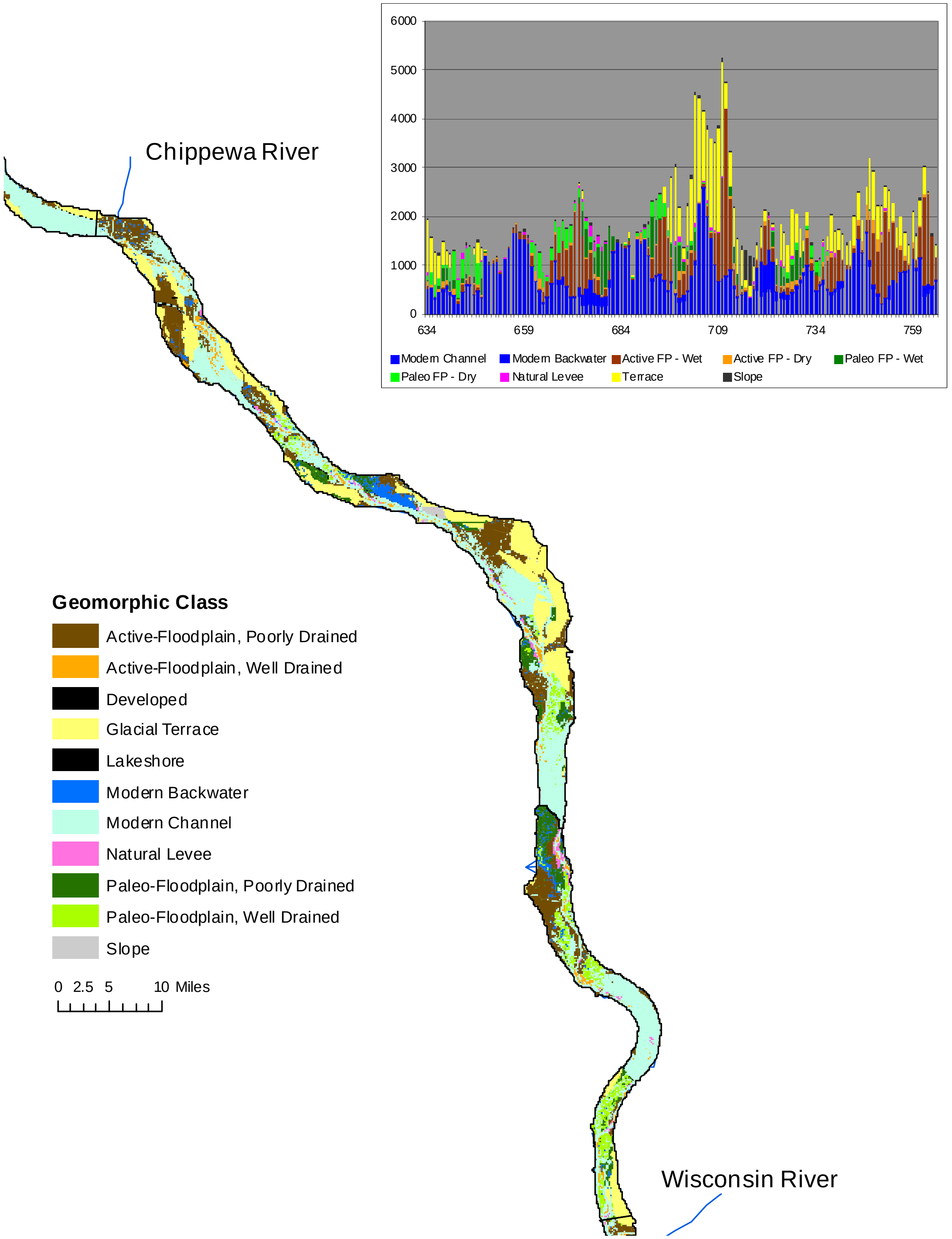


Figure 80A-3. Chippewa River geomorphic reach, Upper Mississippi River System.

Wisconsin River Reach:

The Wisconsin River Reach (Figure A-4) is in a deep, narrow reach with abundant dolomite limestone outcrops along valley walls. The acreage of islands is low compared to the reach upstream from it, but similar to other reaches (Figure A-4). There are fewer islands than may be expected because valley filling floods were common and the current velocity is high in the narrow gorge (Knox and Schumm in WEST Consultants, Inc., 2000). There is a low proportion of active floodplain and terraces, but paleo-floodplain is more common than other reaches.

Maquoketa River Reach:

The Maquoketa River Reach (Figure A-5) is at the downstream end of the Driftless Area where the river widens into broader reach of erosive shale between constricted reaches upstream and downstream. Glacial rivers have flowed in many directions several times in this area, creating oversized valleys for the Wapsipinicon, Mississippi, and Rock Rivers which converge in this area (Trowbridge, 1959). Glacial terraces and active floodplain are the dominant landforms in the reach (Figure A-6). The Maquoketa River Reach has an unusually high topographic diversity. Impoundment effects inundate contemporary lower Pool 13, but they are minimal in most of the reach.

Rock Island Gorge Reach:

The Rock Island Gorge Reach (Figures A-5 and A-6) is a young younger reach formed about 21,000 years BP. It was a tributary of the ancient Iowa River that was captured by the Mississippi River during the peak of the Wisconsin glaciation when an ice-dammed lake cut through limestone bedrock to the ancient Iowa River Valley. The reach is steep (see Figure 10), with rapids that were a notable navigation hazard in the steamboat era. The mid section of the reach includes terraces and benched that the Quad Cities, Illinois and Iowa are built on, but the lower part of the reach has low elevation floodplain because impoundment effects are minimal and sedimentation from the Rock River and other tributaries is high.

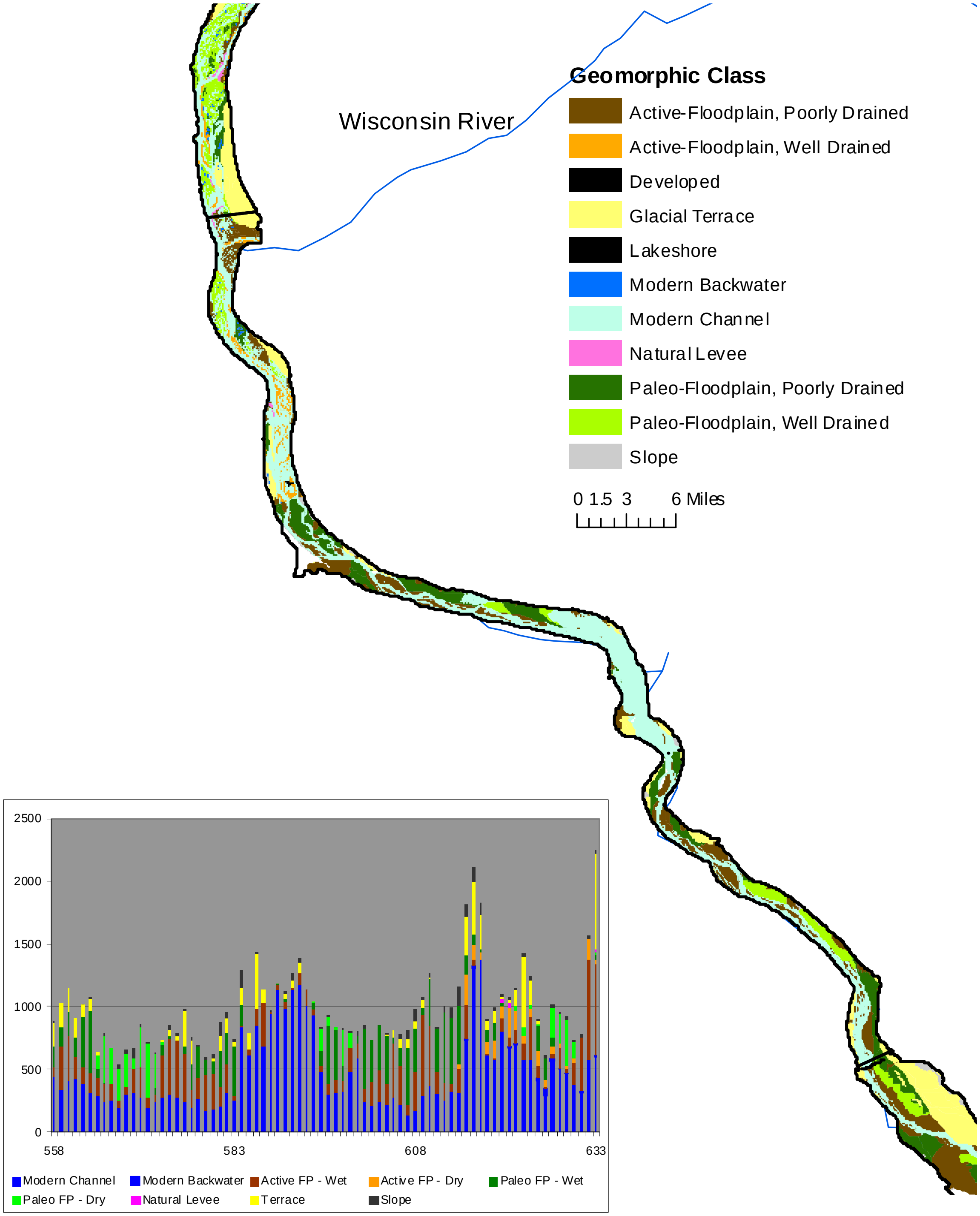


Figure A-4. Wisconsin River geomorphic reach, Upper Mississippi River System.

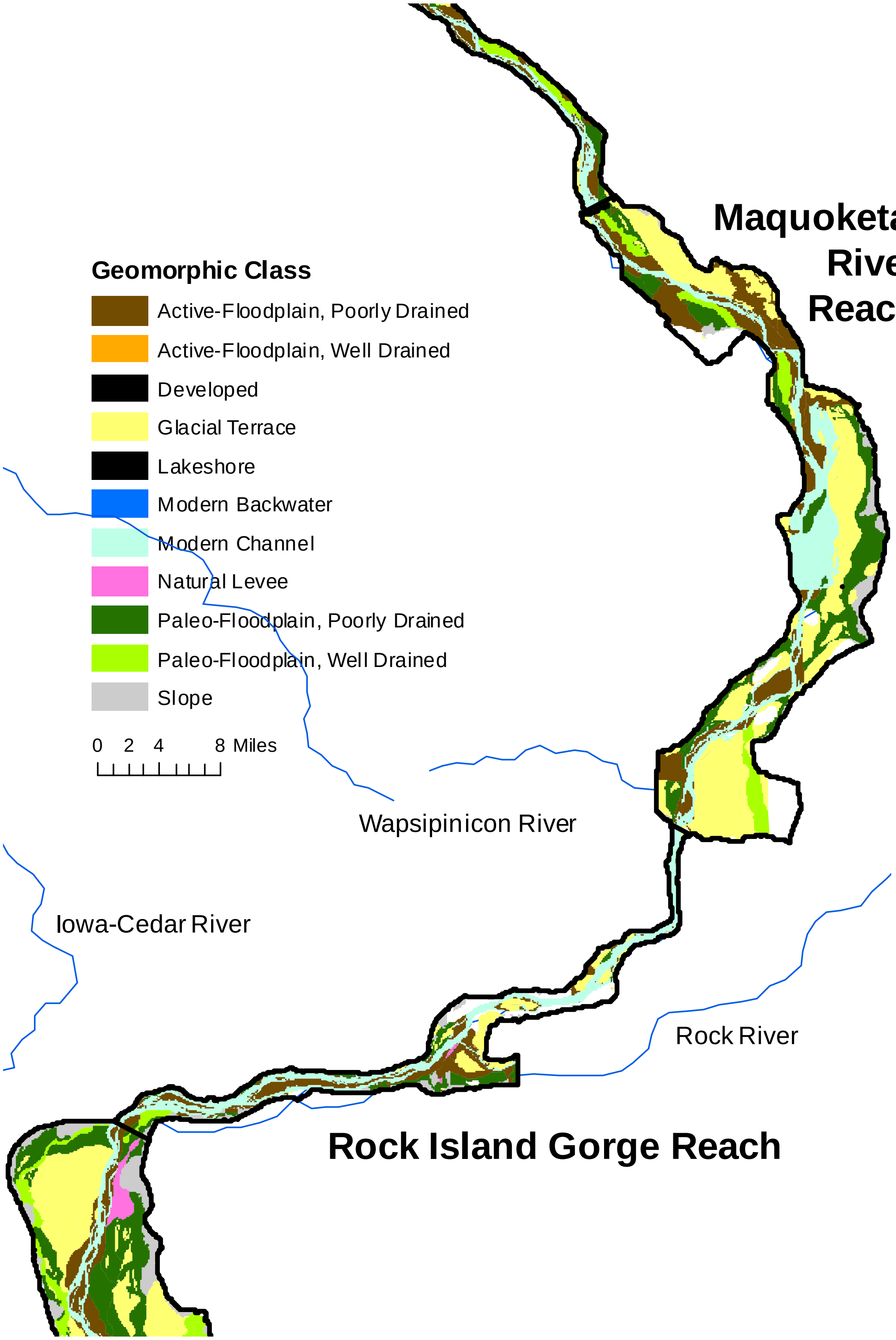


Figure A-5. Maquoketa River and Rock Island Gorge geomorphic reaches, Upper Mississippi River System.

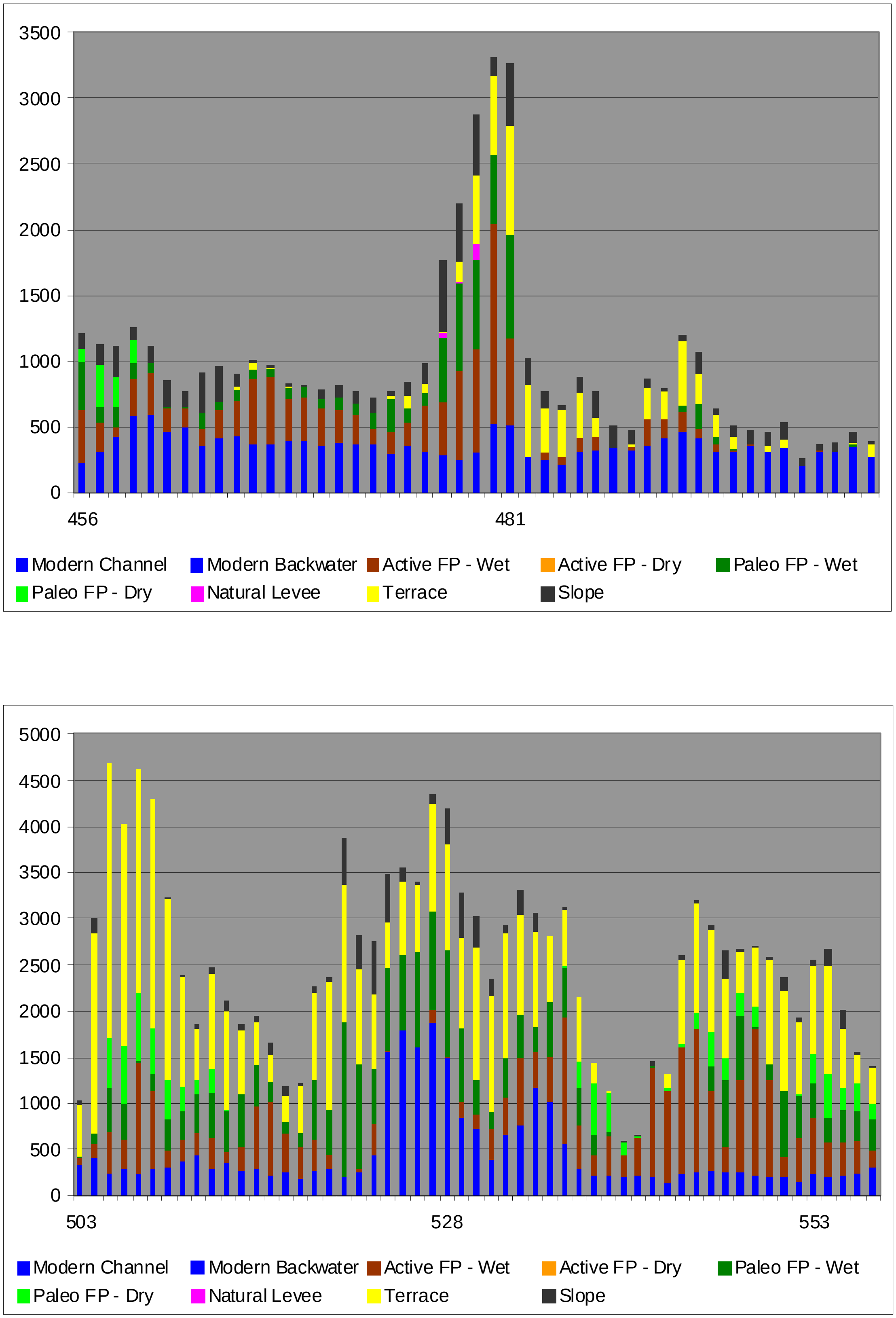


Figure A-6. Maquoketa River and Rock Island Gorge geomorphic reaches LSA distribution in acres.

Iowa River Reach:

The river-floodplain character changes considerably below the Rock Island Gorge where a combination of intersecting a buried channel and a change in bedrock lithology control on width of the valley at and below Muscatine, Iowa opens into the Iowa River Reach that was formed by the ancient Iowa and Mississippi Rivers (Figure A-7). Sediment flushing out of the Rock Island Gorge and the Ancient Iowa River deposited a mound of heavy alluvial sediment when currents slowed in the wider valley below Muscatine, Iowa (Knox and Schumm in WEST Consultants, Inc., 2000). Sediment load from the Iowa River was high, which contributes to an abundance of smaller islands compared to the Des Moines River Reach (see Figure A-8). The riverbed drops from the Iowa River confluence and encounters a bedrock high at the Edwards River several miles downstream (see Figure 10). Very large high terraces occur on the Illinois side and in valley bends on the Iowa side. Anabranch meander belts are incised into terraces and, paleo-floodplain occurs as paleo-channels and bars on the mid-elevation floodplain. The active floodplain occurs at tributaries and near the channel where not inundated by the modern channel.

Keokuk Gorge Reach:

The Keokuk Gorge (Figure A-7) is gorge cut through limestone bedrock to create a narrow and steep valley. The reach was a formidable rapids prior to impoundment for hydropower in 1913 separate from the navigation system. The Keokuk dam was the first span across the Mississippi River and was a significant engineering feat.

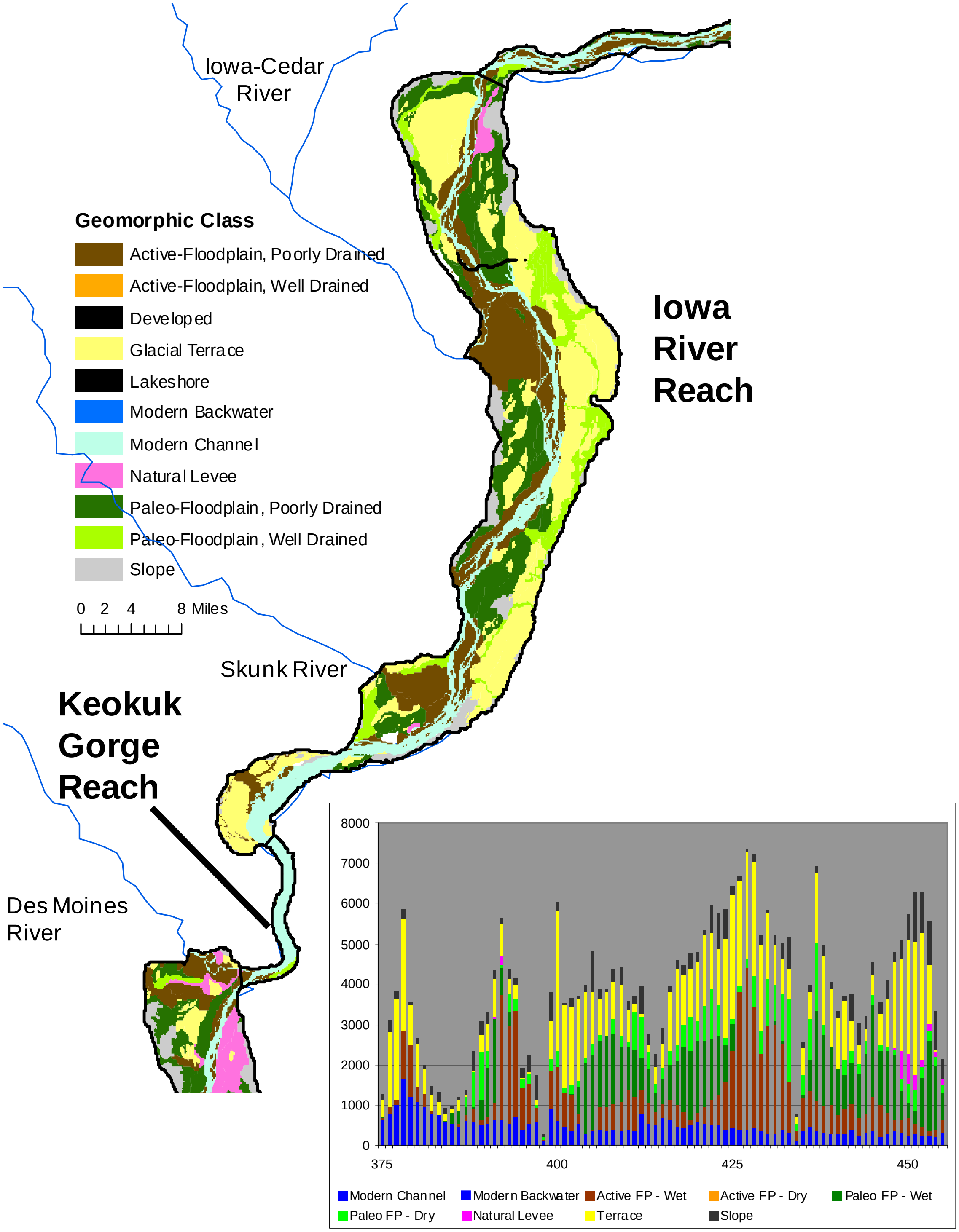


Figure A-7. Iowa River and Keokuk Gorge geomorphic reaches, Upper Mississippi River System.

Des Moines River Reach:

The Des Moines River Reach (Figure A-8) is dominated by a very large sediment fan at the top of the reach. The fan creates great diversity of high and low elevation floodplain at the confluence of the Keokuk gorge and the Des Moines River. A large levee and crevasse splay develops over paleo-floodplain and becomes interfingered with colluvial material formations along the east side of the channel area. The river channel crosses the floodplain several times in the reach. Active floodplain is coincident with tributaries on the Missouri side of the river. Islands occur as fewer, larger individual islands with a moderate total area compared to other reaches (see Figure 24). Island abundance increases at the lower end of the reach (Figure A-8).

Quincy Anabranch Reach:

In the Quincy Anabranch Reach the river runs close to the Missouri bluffs and a sequence of nearly continuous levee and crevasse splays, Yazoo meander belt, and colluvial slope progress across the floodplain to the Illinois bluff line (Figure A-8). The colluvial slope is a dominant feature that forms an extensive, nearly continual, well-drained elevated apron along the eastern bluff line. Active floodplain area increases downstream through the reach and at the Salt River tributary fan which moves the river off the Missouri bluff for several miles before it moves back to the bluff. The natural levee forms a partial barrier between the river and backswamps which have hydraulic connections back to the bluffs (Bettis et al., 1996).

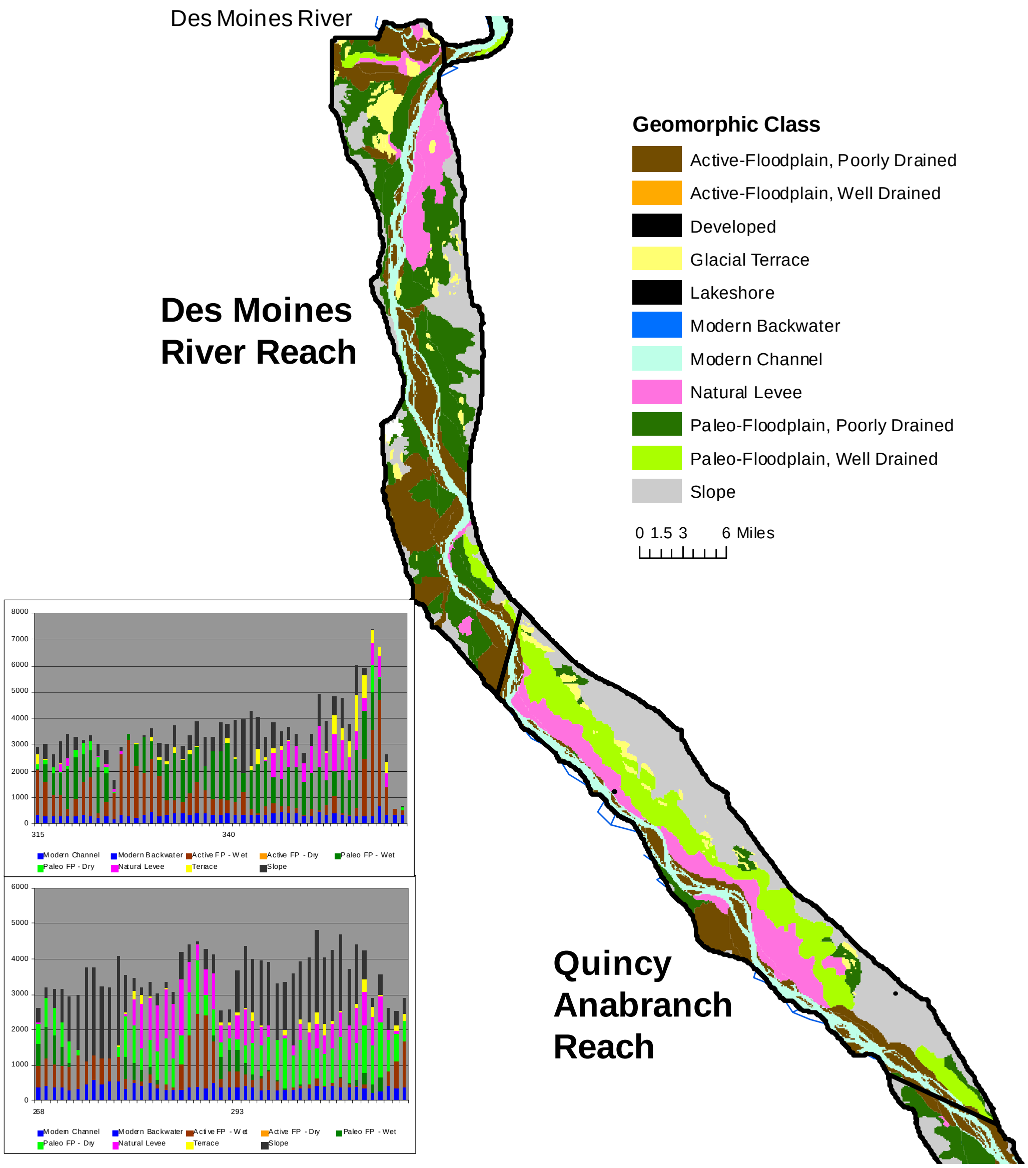


Figure A-8. Des Moines River and Quincy Anabranch geomorphic reaches, Upper Mississippi River System.

Sny Anabranch Reach:

The Sny Anabranch Reach (Figures A-9 and A-10) is a low elevation floodplain that flattens toward the Missouri River confluence. The river crosses the floodplain at the upper end of the reach and flows along the Illinois bankline. The highest proportion of colluvial slopes in the valley interfinger from Illinois tributaries. Larger tributary fans and islands near the channel form patches of active floodplain. The reach has a high proportion of active and paleo-floodplain area and a low abundance of higher elevation terraces or natural levees (Figure A-10). The reach falls in the mid-range of island characteristics (i.e., number, size, total area; see Figure 24).

Columbia-American Bottoms Reach:

The Columbia-American Bottoms Reach (Figures A-9 and A-10) is a unique confluence of three great rivers, the Illinois, Mississippi, and Missouri Rivers. The Missouri River dominates the geomorphology having deposited a huge sediment mound forming a peninsula between the Mississippi and Missouri Rivers. Below the confluence, a broad meandering form takes shape with the high suspended sediment load from the Missouri River. Bettis et al., (2008) describe the decreasing amplitude of the meanders from the middle Holocene on as river flow settled into the contemporary sediment discharge regime. The cutting and migration of channels creates paleo-bar and chute formations that define the ridge and swale topography characteristic of the reach (Heitmeyer, 2008). Large oxbow lakes formed in cut-off meanders were common in the reach (Heitmeyer, 2008). The reach had relatively few islands in 1890 (see Figure 24), but the St. Louis, Missouri area was highly developed by then.

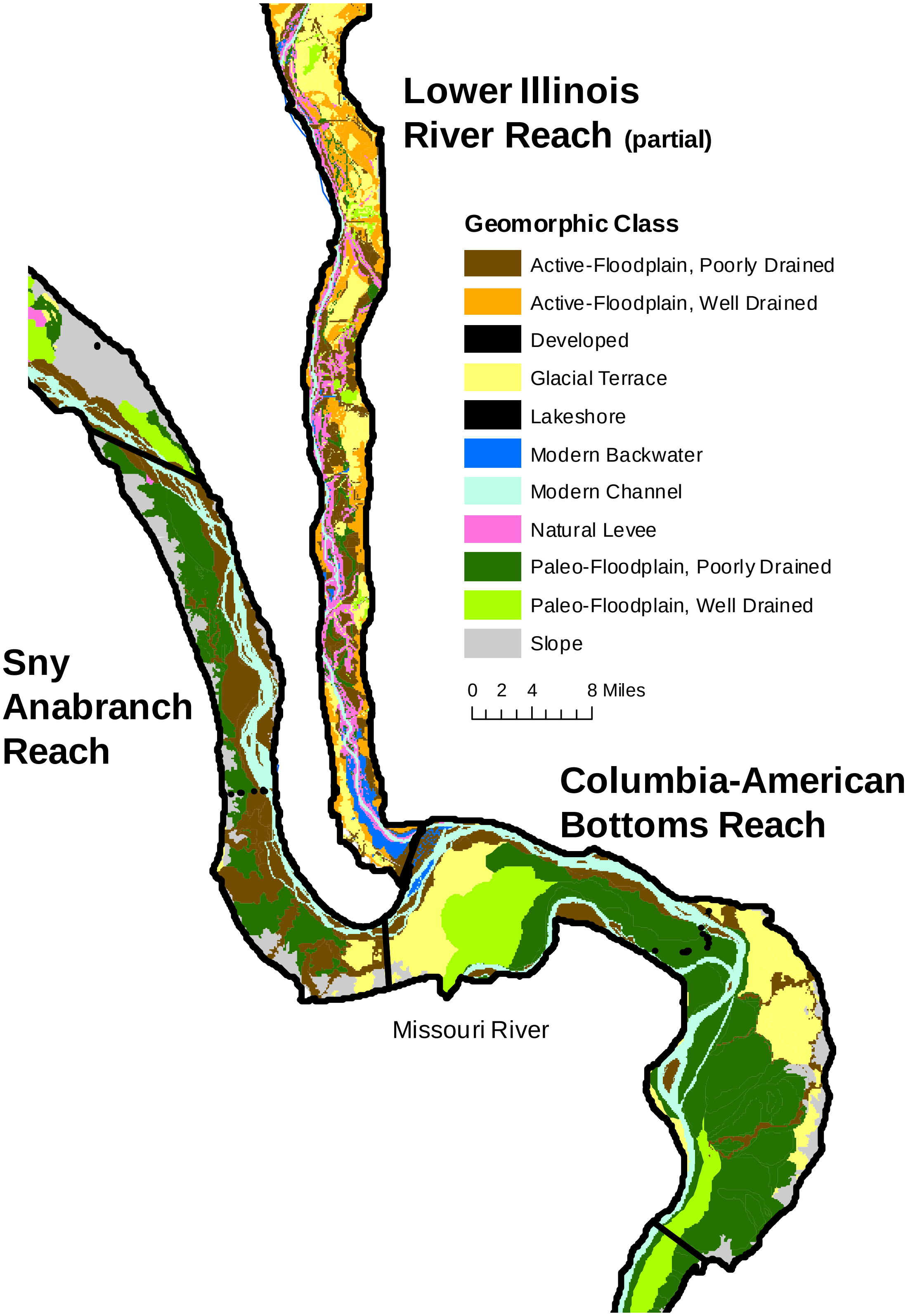


Figure A-9. Sny Anabranch, Columbia-American Bottoms, and Lower Illinois (partial) geomorphic reaches, Upper Mississippi River System.

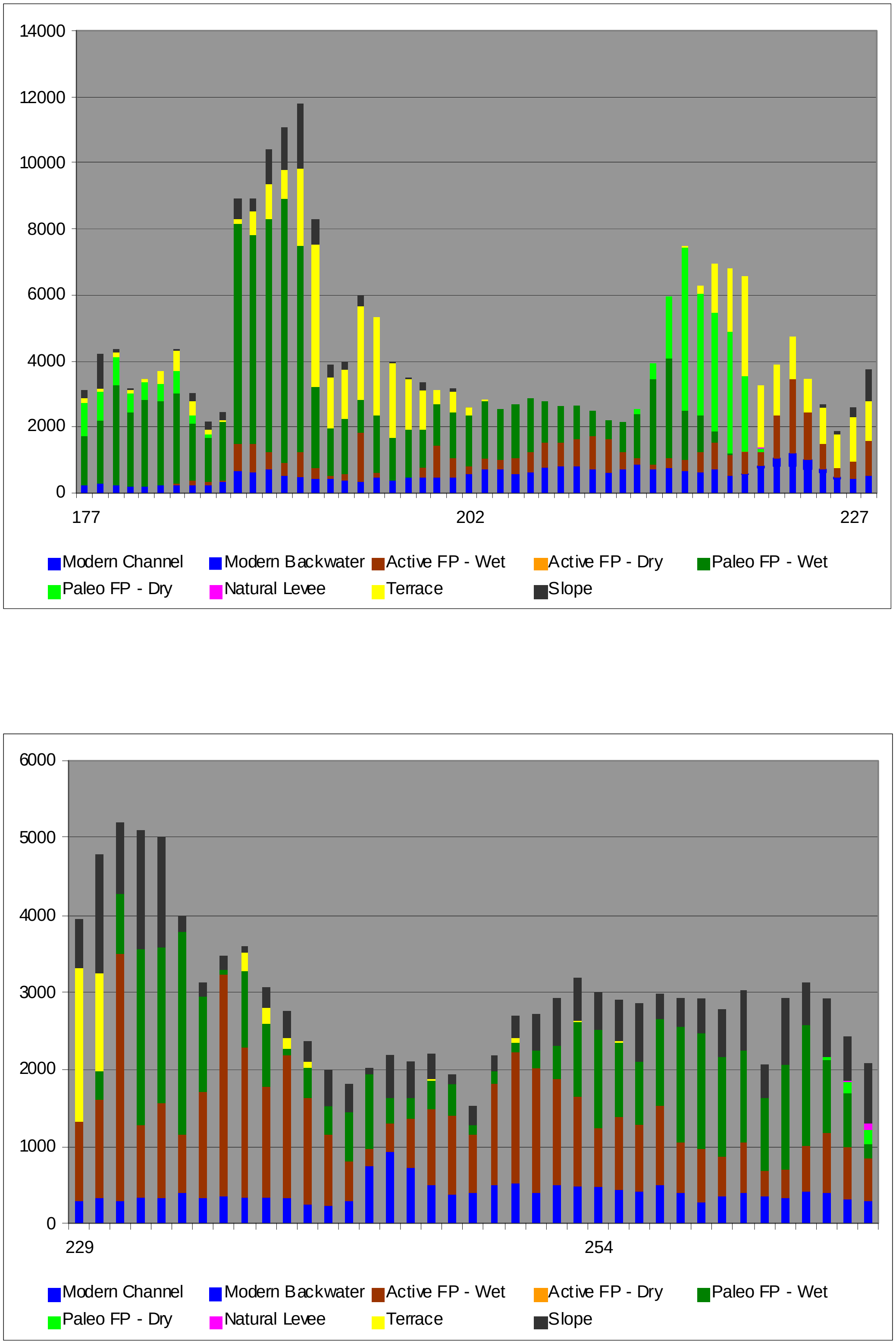


Figure A-10. Sny Anabranch, Columbia-American Bottoms geomorphic reaches LSA distribution in acres.

Jefferson Barracks Reach:

The Jefferson Barracks Reach narrows below St. Louis, Missouri and is dominated by paleo-floodplain surfaces (Figure A-11). Paleo-channels create a meandering channel form on the landscape adjacent to the modern channel. The meander scrolls create a large proportion of paleo-floodplain in the reach. The cutting and migration of channels creates the ridge and swale topography characteristic of the reach. Paleo-bar and chute formations also create the ridge and swale topography (Heitmeyer, 2008). Large lakes formed in the cut-off meanders were common in the presettlement era (Heitmeyer, 2008).

Kaskaskia River, Thebes Gap, Lower Mississippi Reaches:

The Kaskaskia River, Thebes Gap, and Lower Mississippi Reaches geomorphology have not had LSA mapping conducted in the area, but Saucier (1994) conducted an extensive analysis of the entire Mississippi Alluvial Valley. Heitmeyer (2008) also conducted an extensive hydrogeomorphic analysis of the reach. The Kaskaskia River Reach is similar in character to the Jefferson Barracks Reach except Kaskaskia Island is a very large island that skews the average island size statistic in this reach (see Figure 24). Thebes Gap, like Keokuk Gorge, is mostly channel but it is deep and navigable. The river below Thebes Gap joins with the Ohio River and forms the Lower Mississippi River Valley and is ecologically part of the Lower Mississippi River or Mississippi Alluvial Valley.

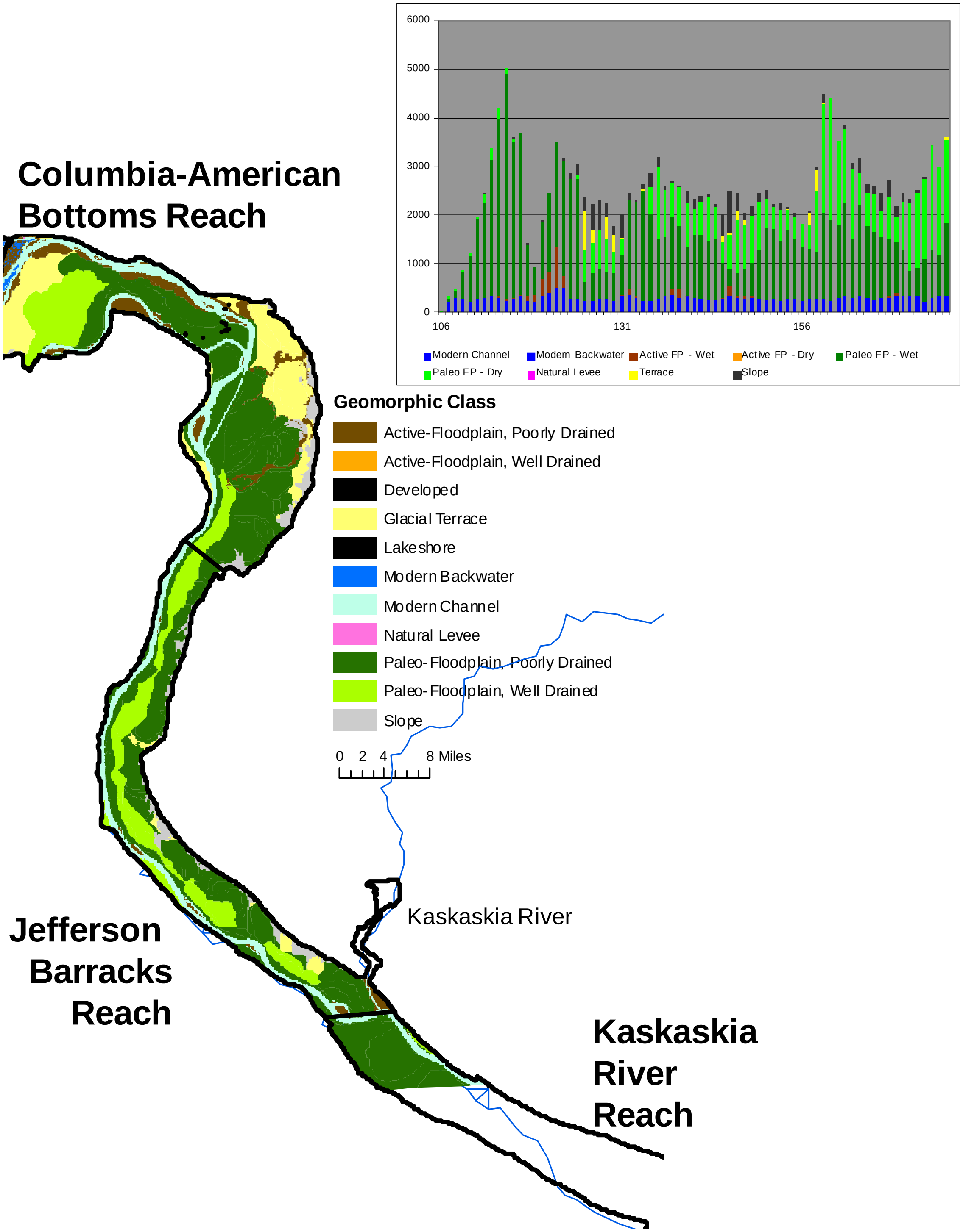


Figure A-11. American Bottoms and Jefferson Barracks geomorphic reaches, Upper Mississippi River System.

Upper Illinois Reach:

The Upper Illinois Reach predates the lower valley, but was strongly shaped by the Kankakee Torrent at the end of the Wisconsin glaciation. It is currently impounded through the valley and only terraces are visible for most of the reach. Natural levees occur at the downstream end with a trace of low elevation floodplain (Figure A-12).

Lower Illinois Reach:

The Lower Illinois River is underfit for the ancient glacial valley (Leopold et al., 1964) which was formed by the Mississippi River that flowed through the Princeton Channel to the “Great Bend” at Hennepin, Illinois prior to about 21,000 BP. It has a large proportion of terraces, a well drained active floodplain, and natural levees (Figure A-13). Seasonal floodplain lakes occurred historically, but impoundment created large permanent lake complexes that inundate low elevation active floodplain surfaces above the Sangamon River. The Lower Illinois River appears much more diverse in terms of the number of classes and patch sizes. The reach could easily be subdivided into three or four reaches.

One likely driver of the high geomorphic diversity is the high density of bluffside tributaries depositing material over thousands of years in a stable floodplain. An expanded view from Hajic’s complete data set including local tributaries (Figure A-14) reveals the dendritic characteristics of the numerous lower valley tributaries. Backwater sedimentation surveys indicate the local bluffs contribute 40 percent of sediment to backwater lakes (Bhowmik and DeMissie, 1989).

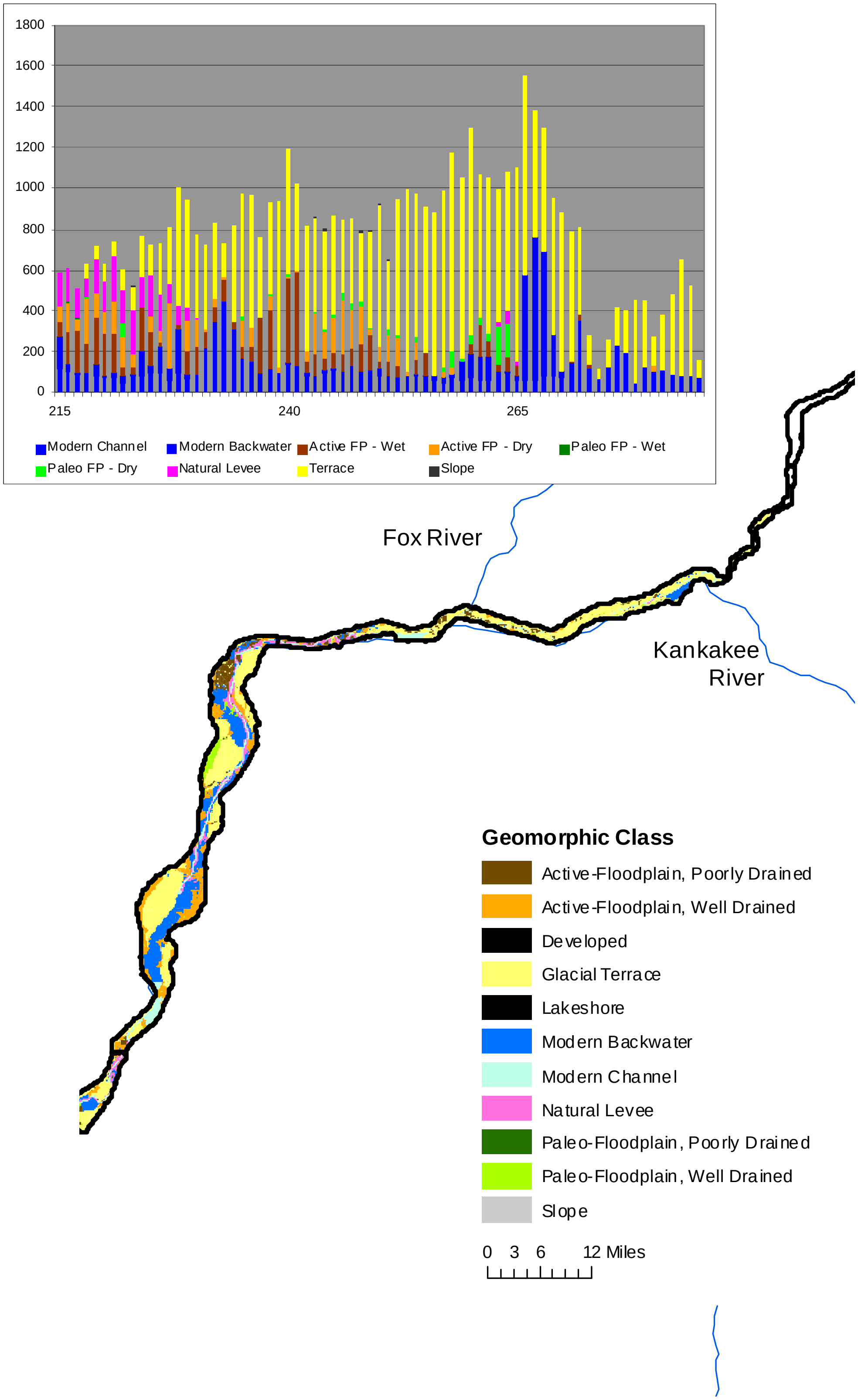


Figure A-12. Upper Illinois River geomorphic reach, Upper Mississippi River System

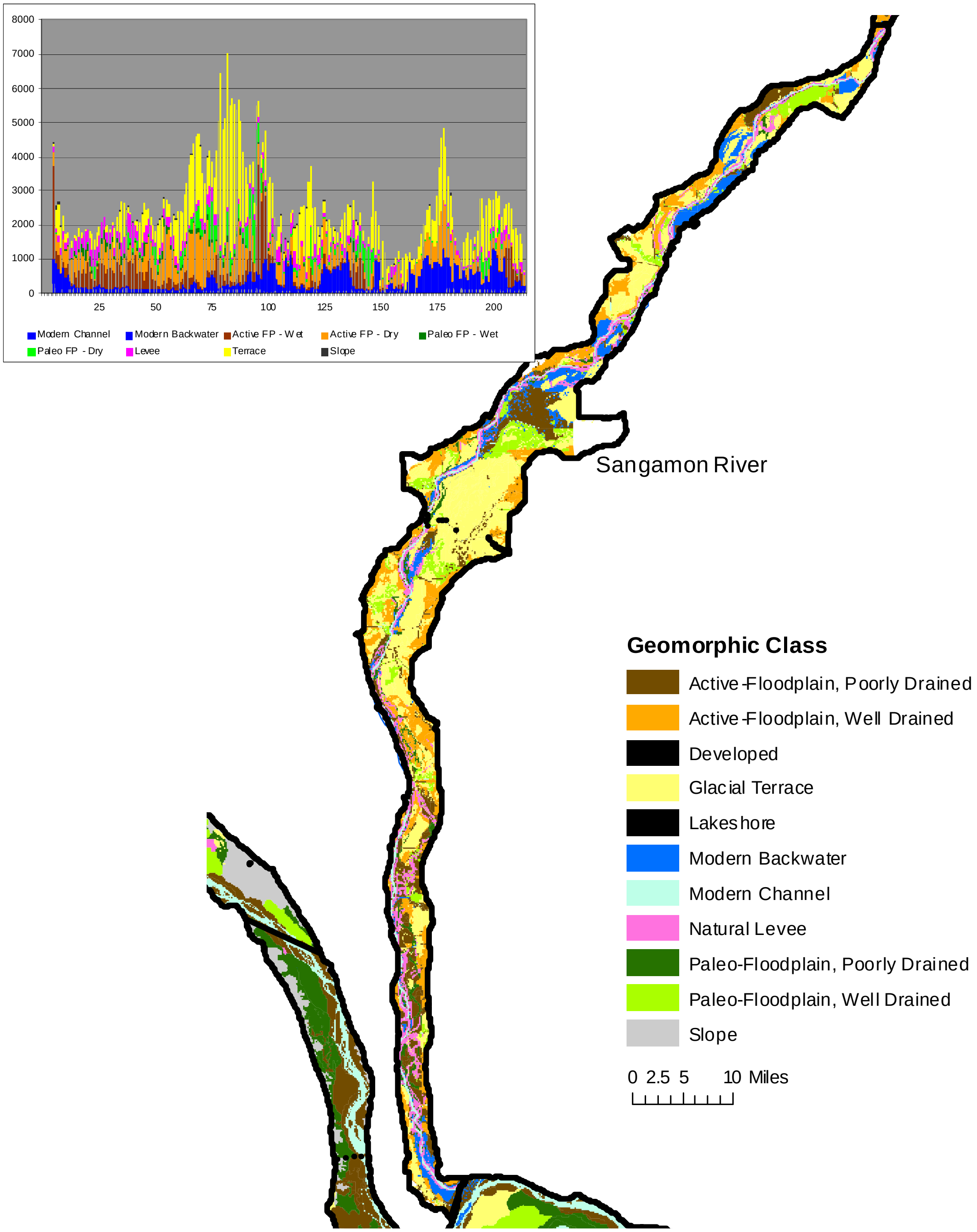


Figure A-13. Lower Illinois River geomorphic reach, Upper Mississippi River System.

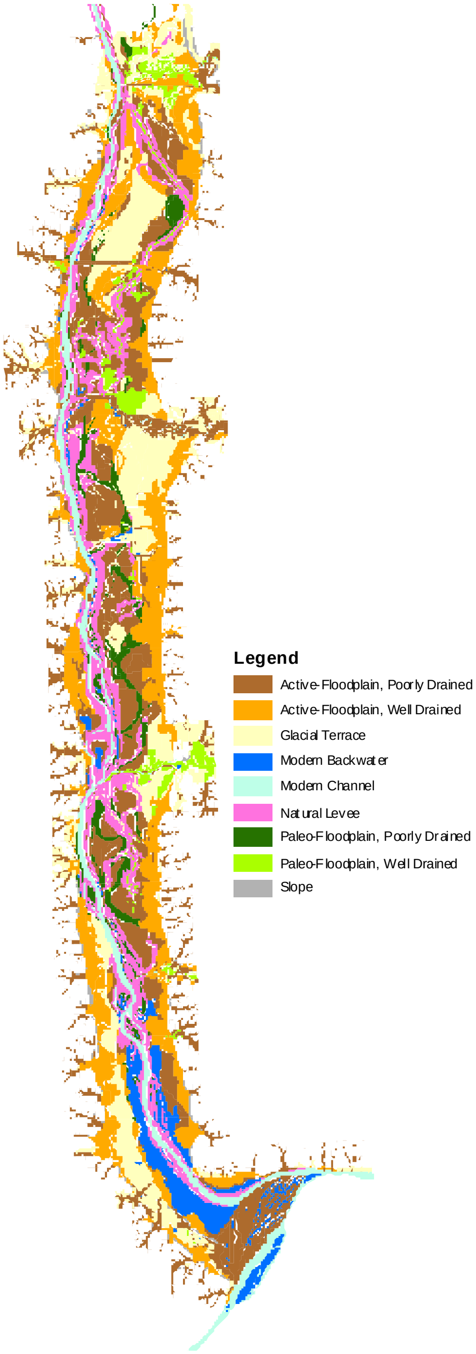
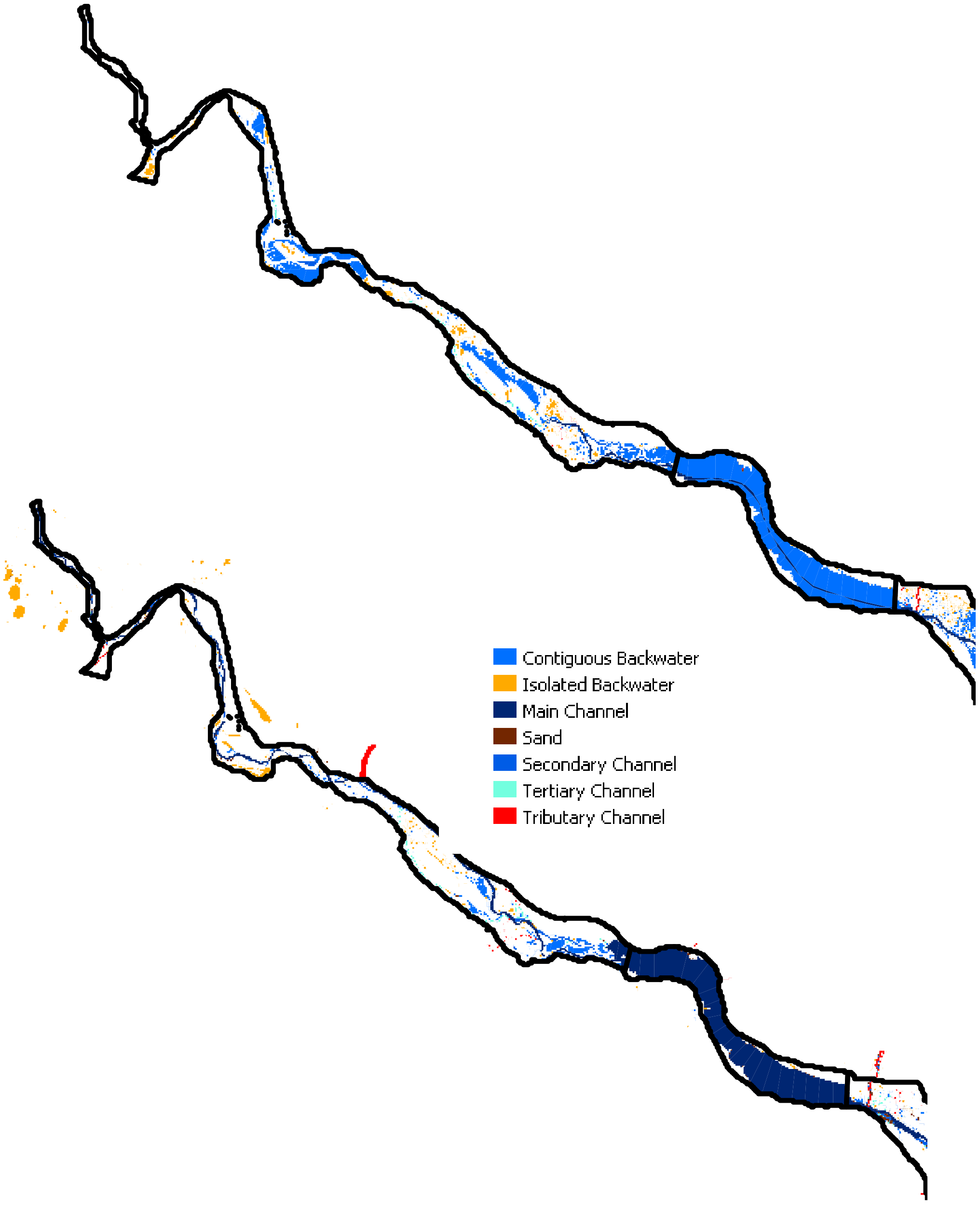


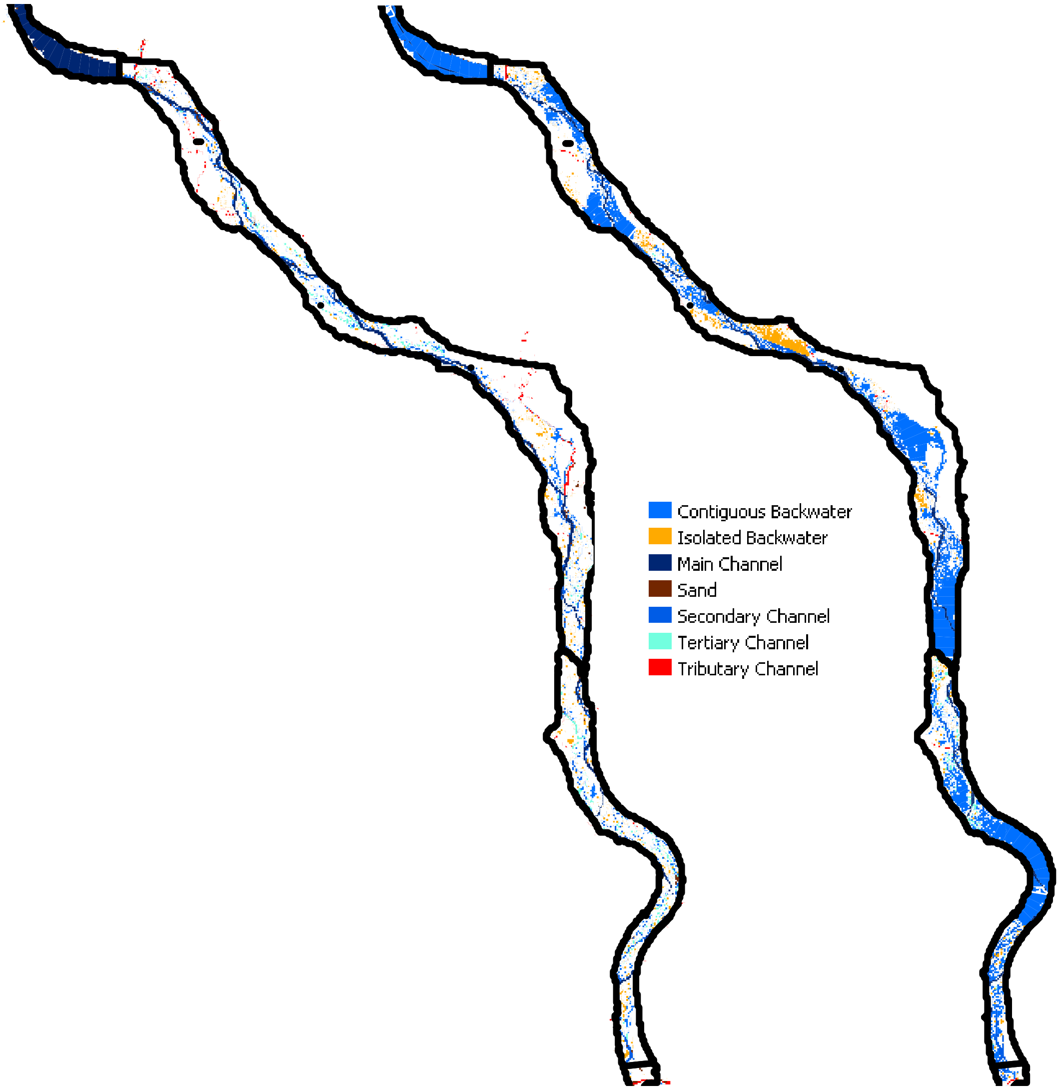
Figure A-14. Lower Illinois River geomorphic surfaces, including adjacent small tributaries (Hajic, 2000).

APPENDIX B: HISTORIC AND CONTEMPORARY UPPER MISSISSIPPI RIVER AQUATIC AREAS

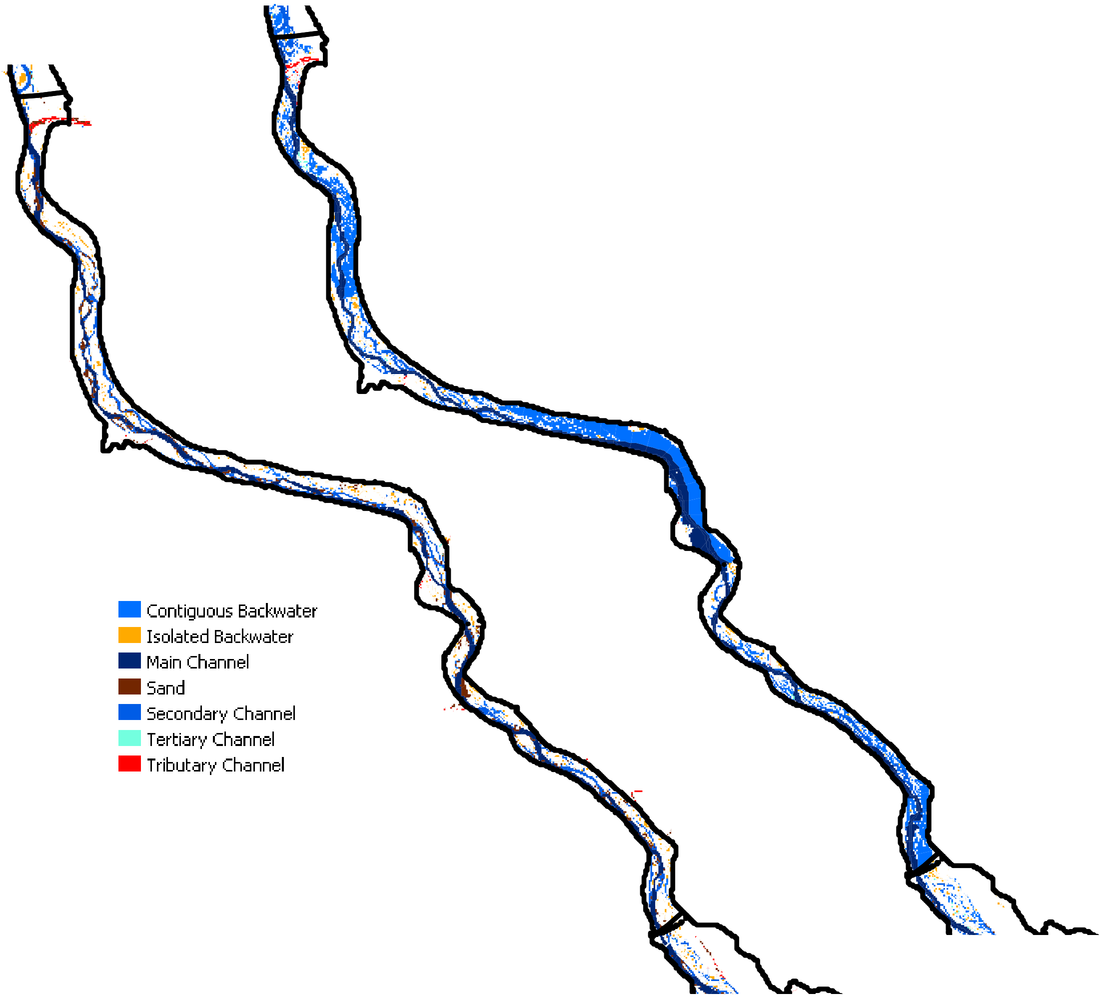
Minnesota River & Lake Pepin Reach



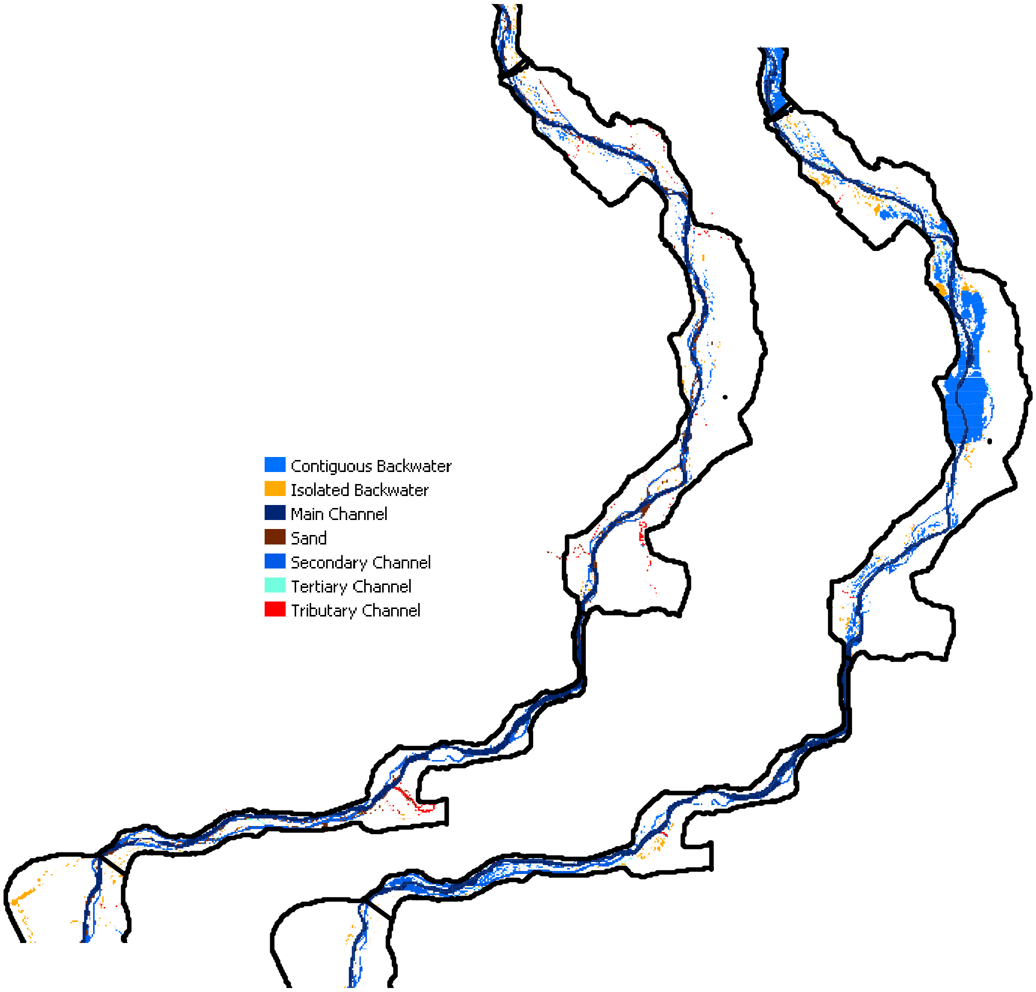
Chippewa River Reach



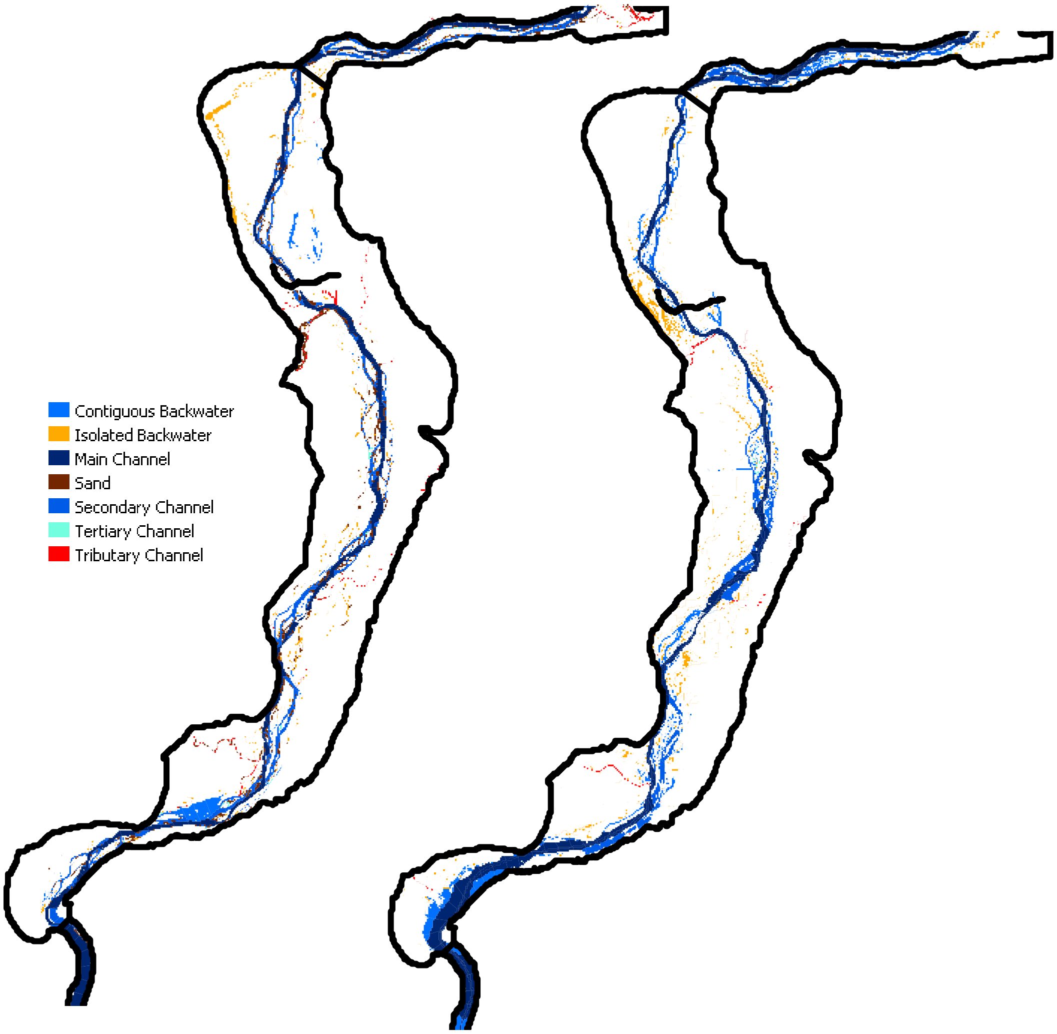
Wisconsin River Reach



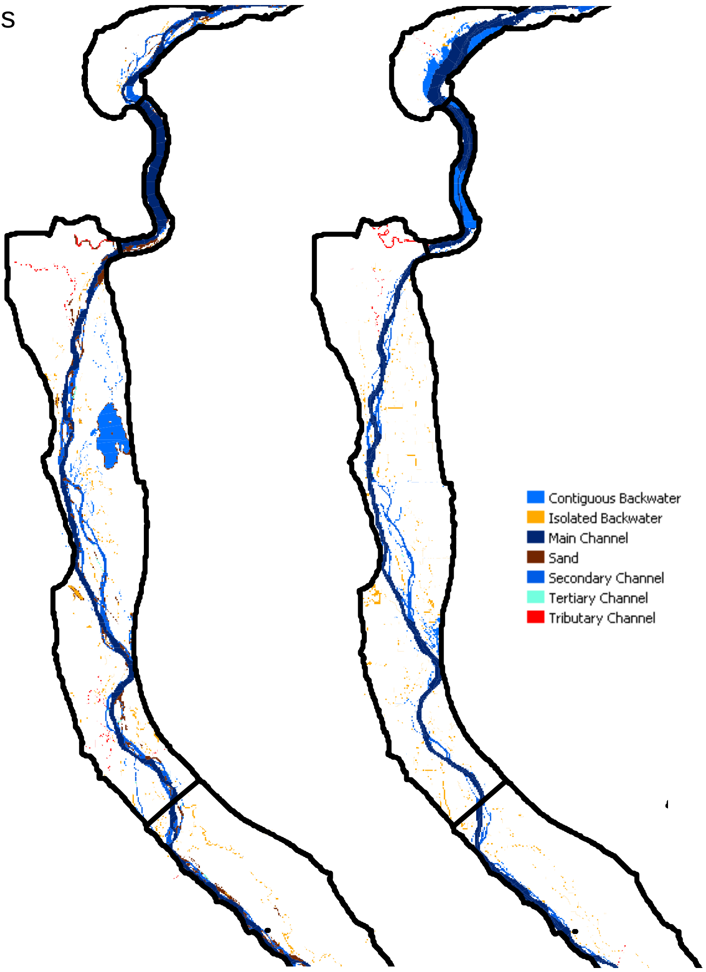
Maquoketa River &
Rock Island Gorge Reaches

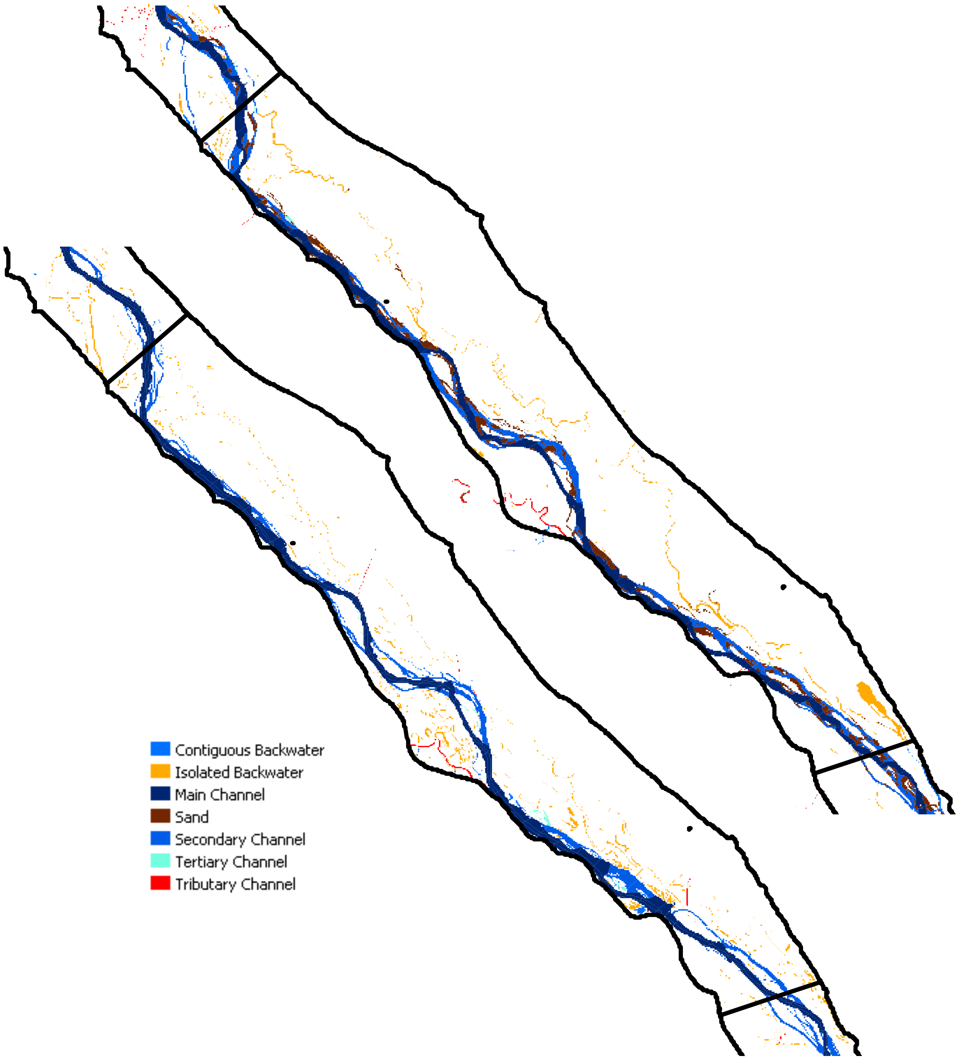


Iowa River Reach

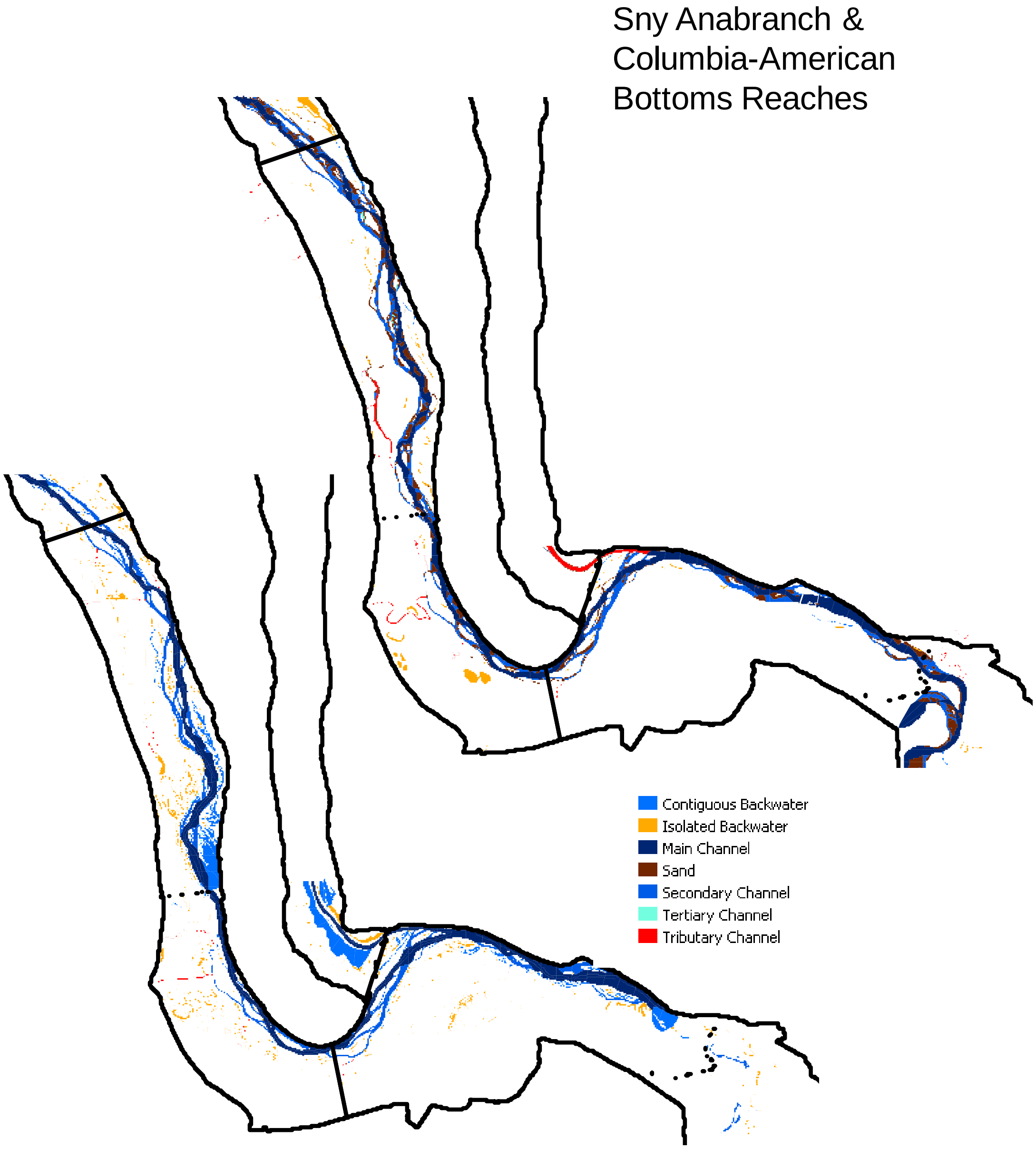


Keokuk Gorge &
Des Moines River
Reaches

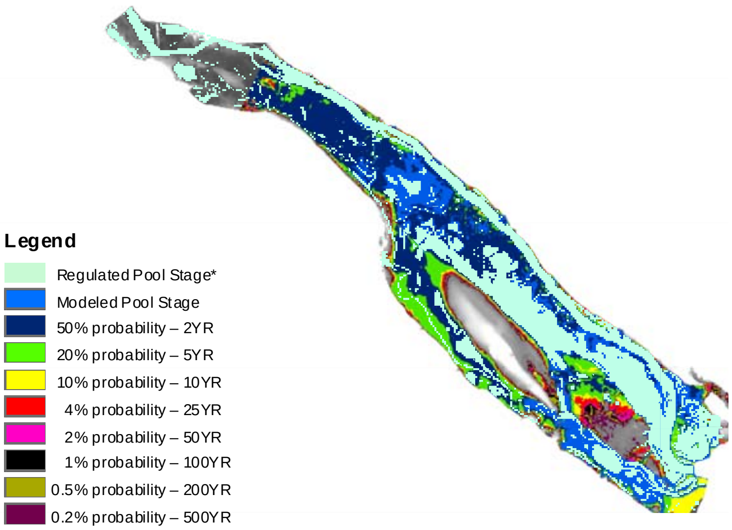




Quincy Anabranch Reach

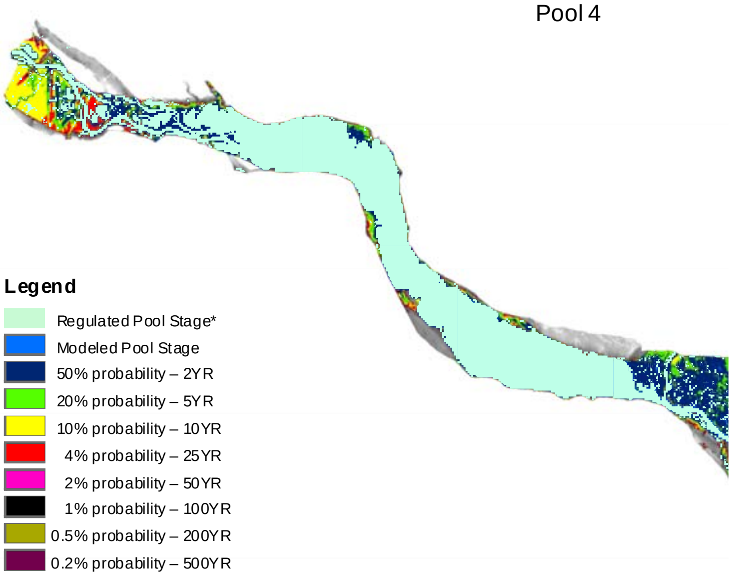

Sny Anabranch &
Columbia-American
Bottoms Reaches
Contiguous Backwater
Isolated Backwater
Main Channel
Sand
Secondary Channel
Tertiary Channel
Tributary Channel

APPENDIX C: SIMULATED FLOODPLAIN INUNDATION ANALYSIS PRESENTED AT THE NAVIGATION POOL SCALE



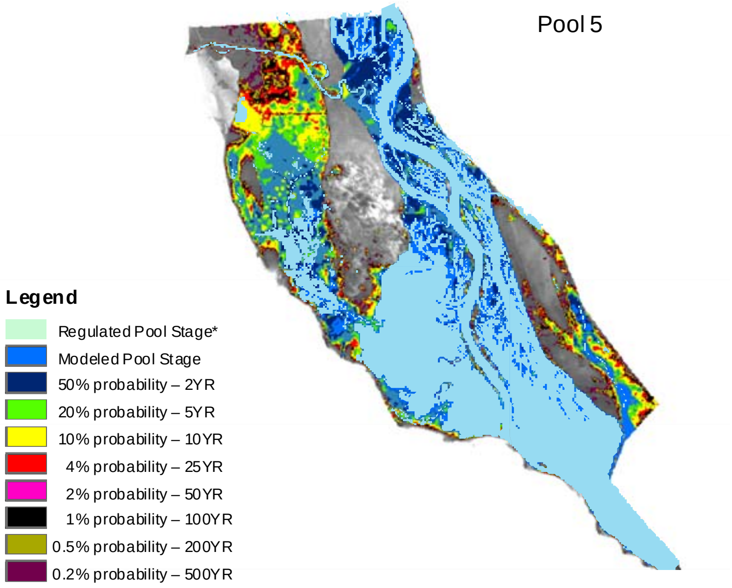
Pool 3

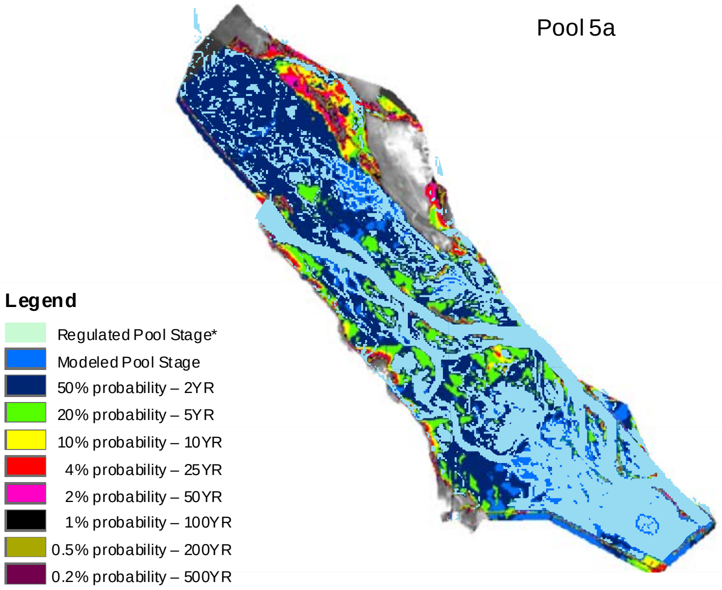
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

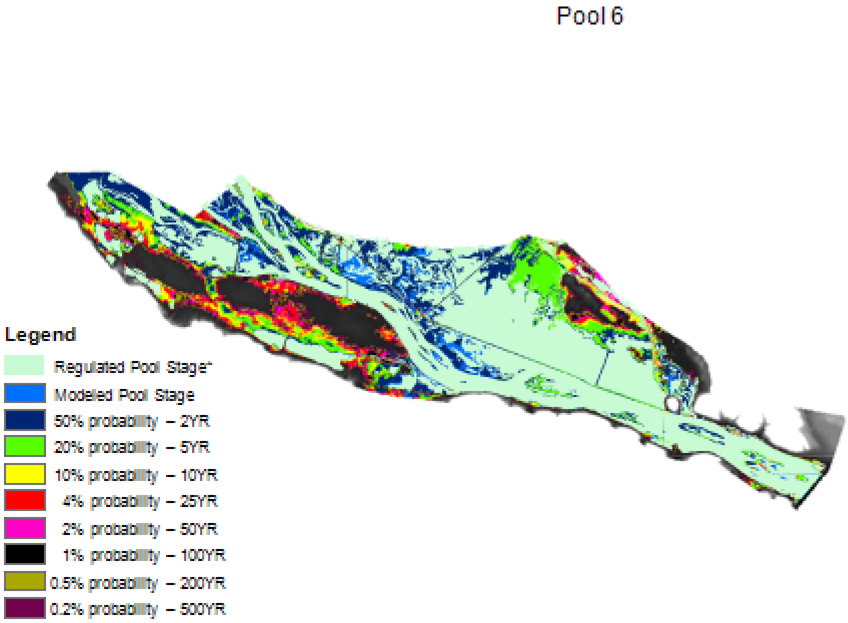


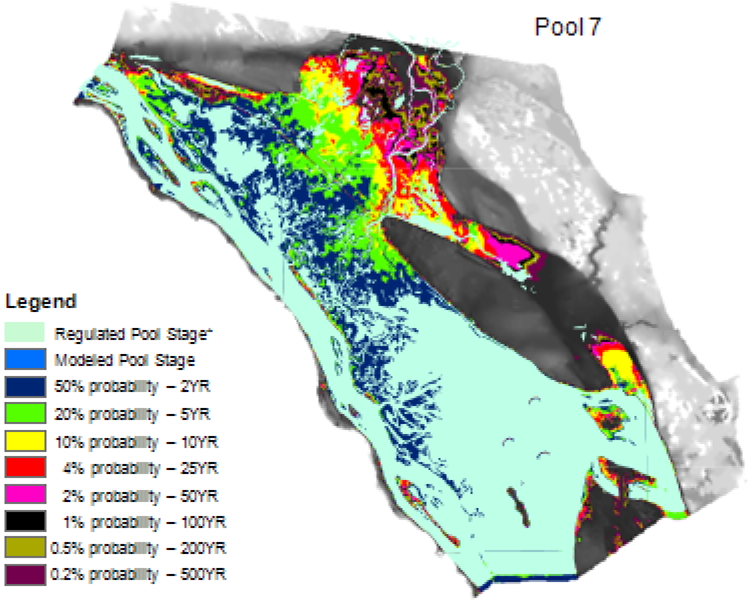
Pool 4

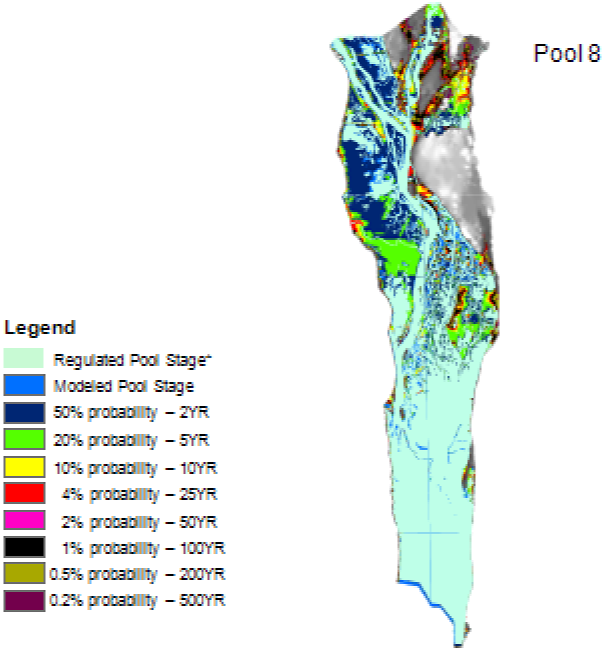
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

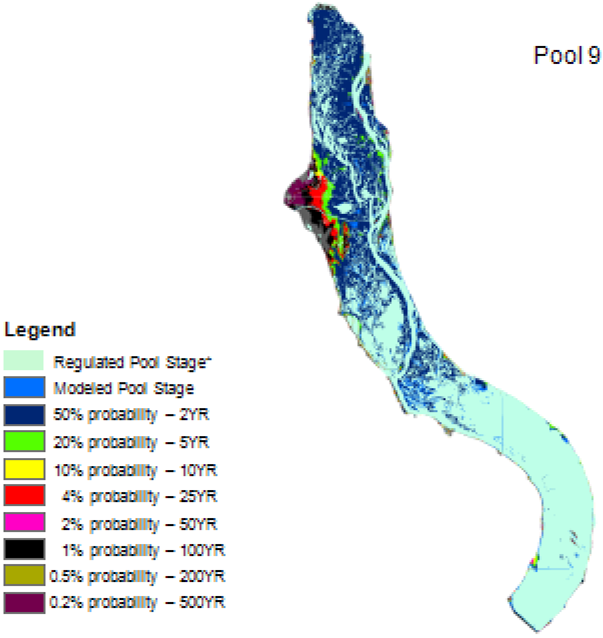

Pool 5
Legend
🟩 Regulated Pool Stage*
🟦 Modeled Pool Stage
🟦 50% probability – 2YR
🟩 20% probability – 5YR
🟨 10% probability – 10YR
🟥 4% probability – 25YR
🟪 2% probability – 50YR
⬛ 1% probability – 100YR
🟫 0.5% probability – 200YR
🟫 0.2% probability – 500YR

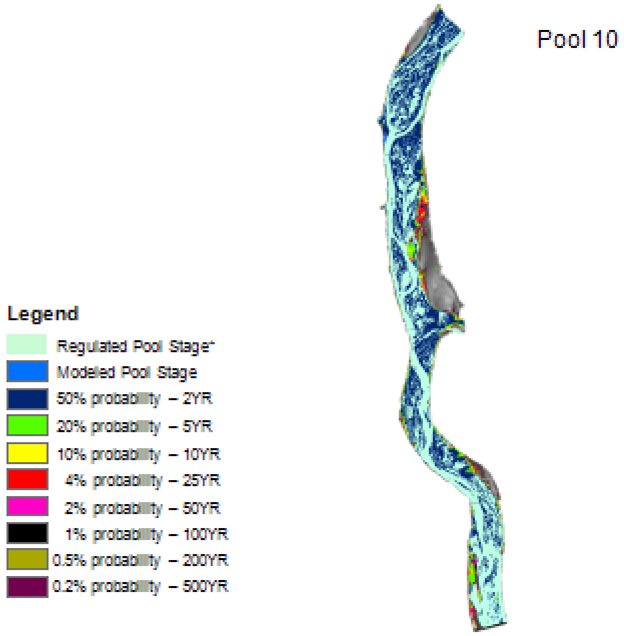

Pool 5a
Legend
🟩 Regulated Pool Stage*
🟦 Modeled Pool Stage
🟦 50% probability – 2YR
🟩 20% probability – 5YR
🟨 10% probability – 10YR
🟥 4% probability – 25YR
🟪 2% probability – 50YR
⬛ 1% probability – 100YR
🟫 0.5% probability – 200YR
🟫 0.2% probability – 500YR

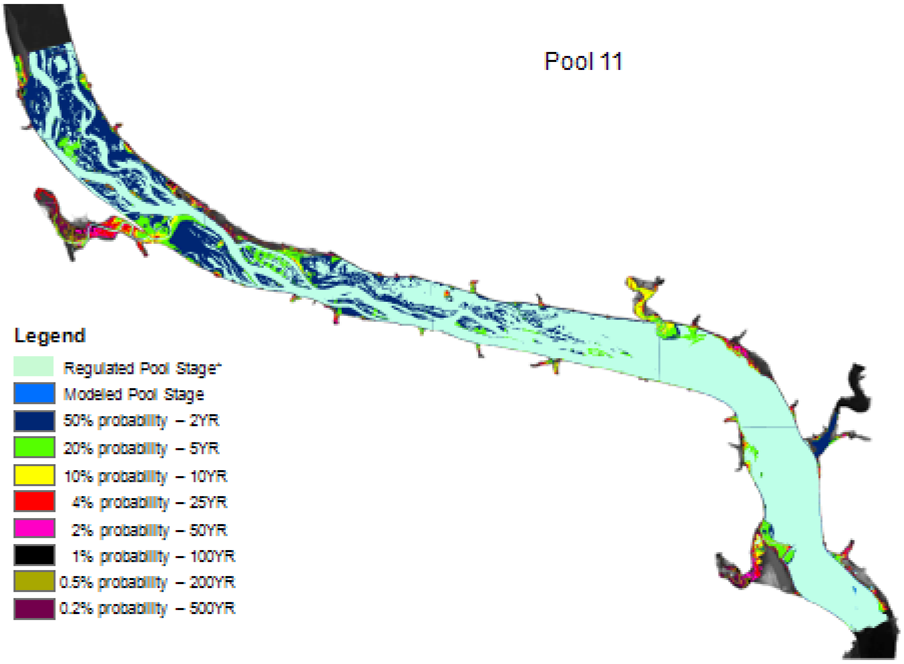

Pool 6
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

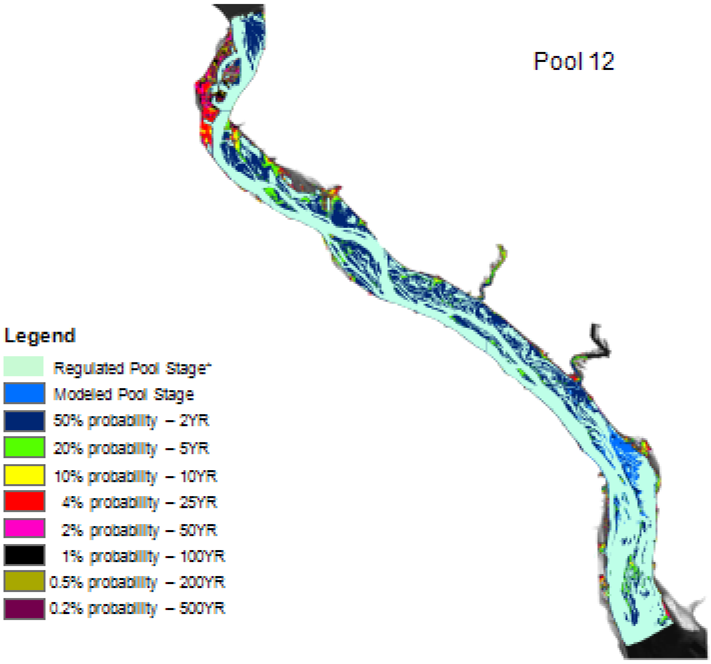

Pool 7
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

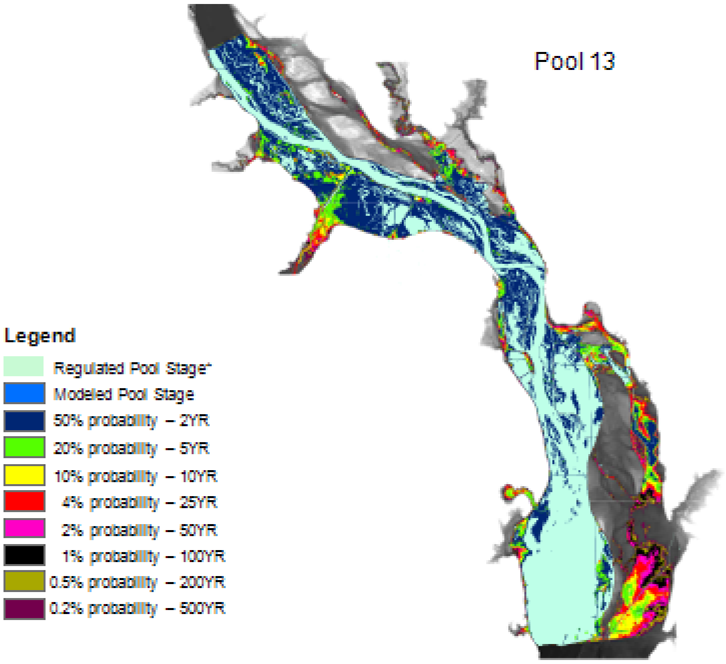

Pool 8
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

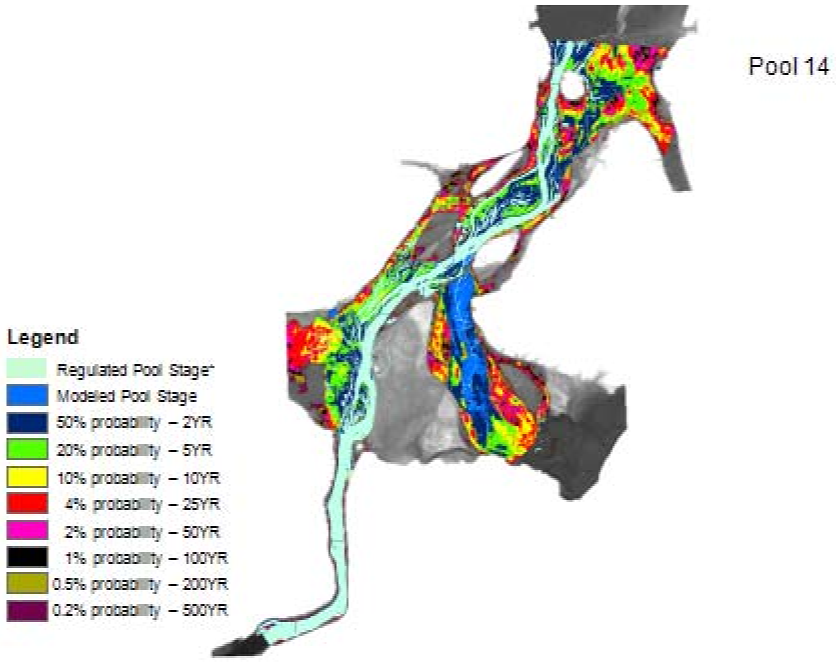

Pool 9
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

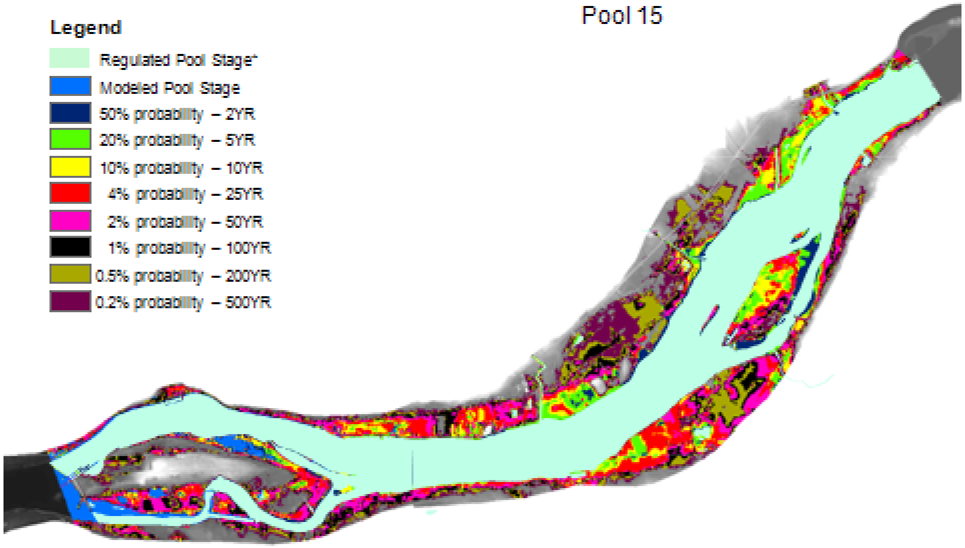

Pool 10
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

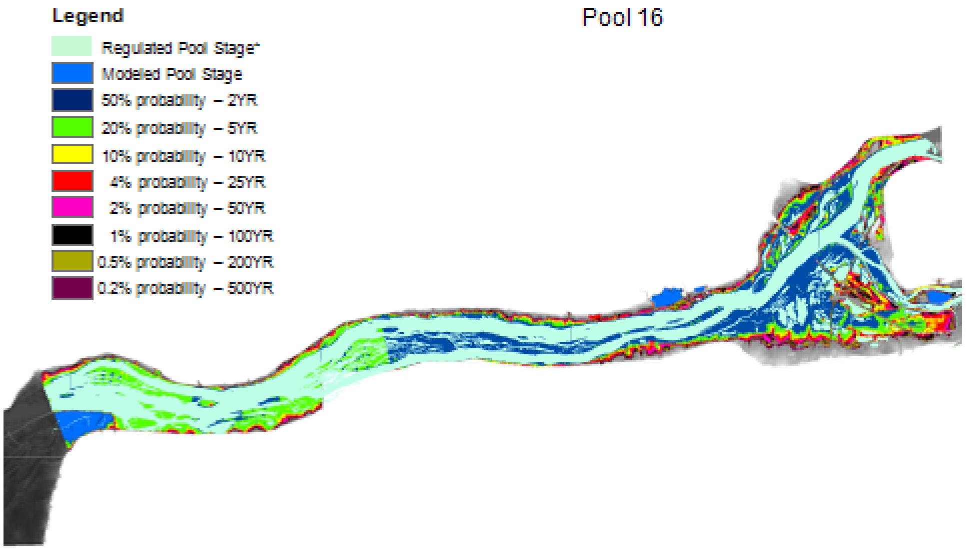

Pool 11
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

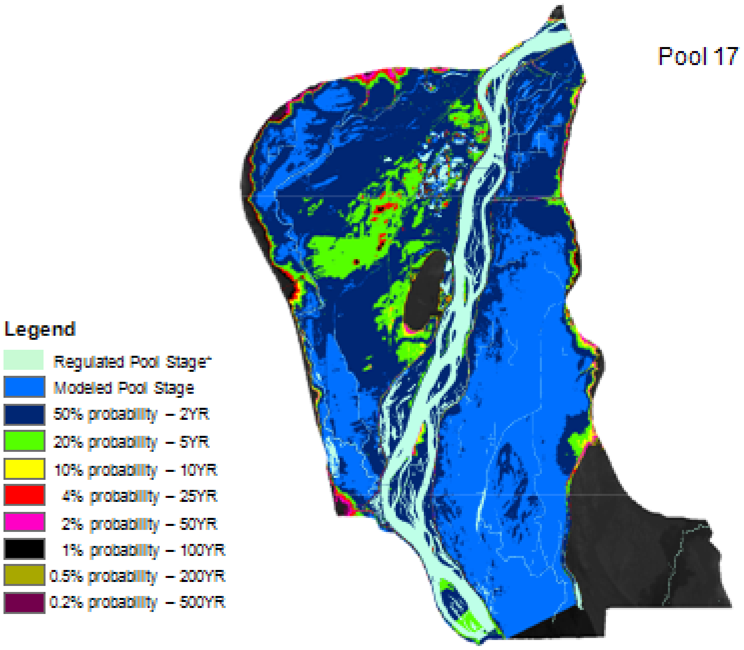

Pool 12
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

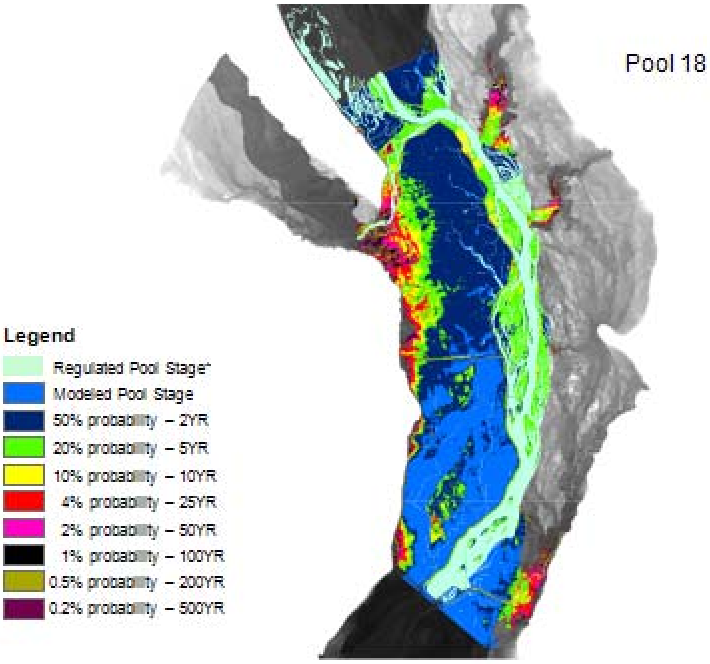

Pool 13
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

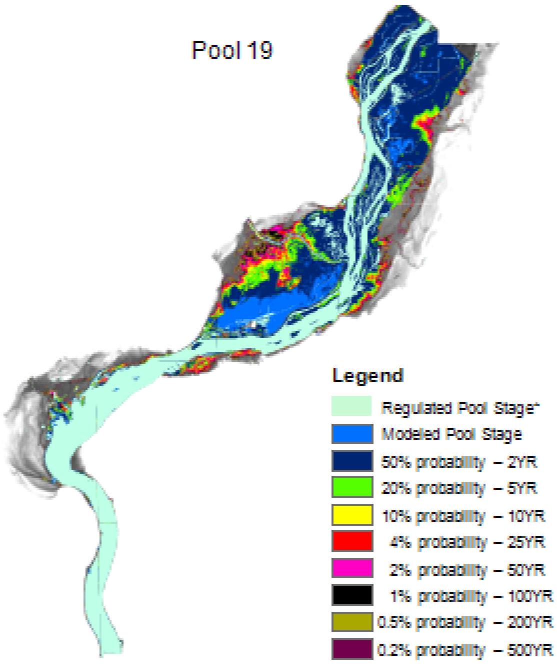

Pool 14
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

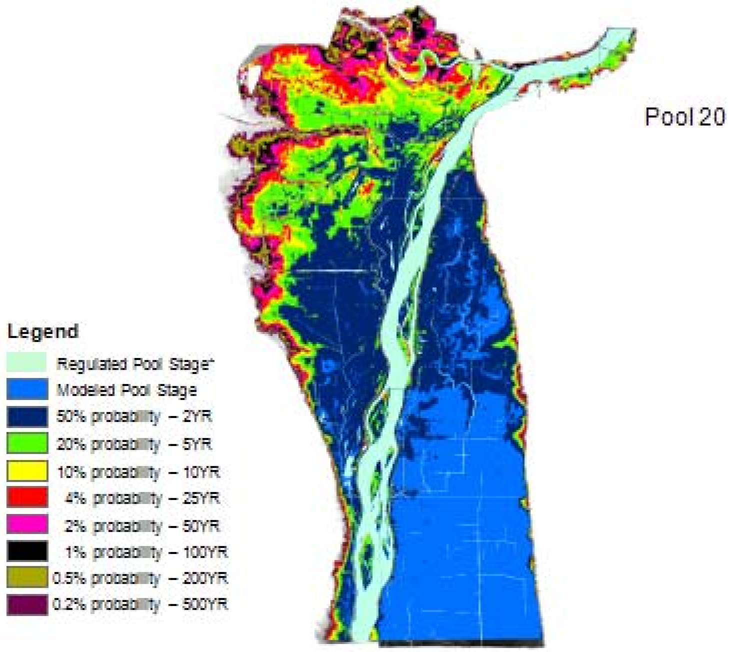

Pool 15
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

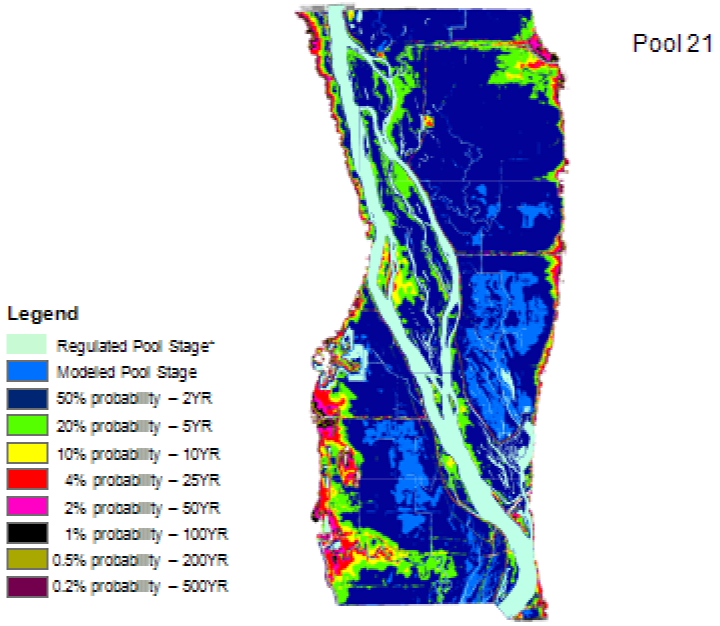

Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR
Pool 16

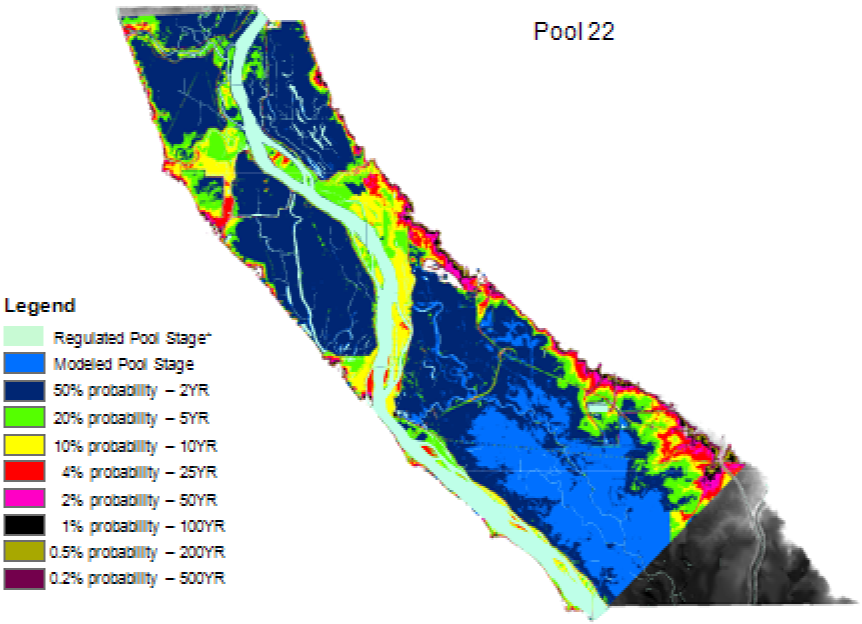

Pool 17
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

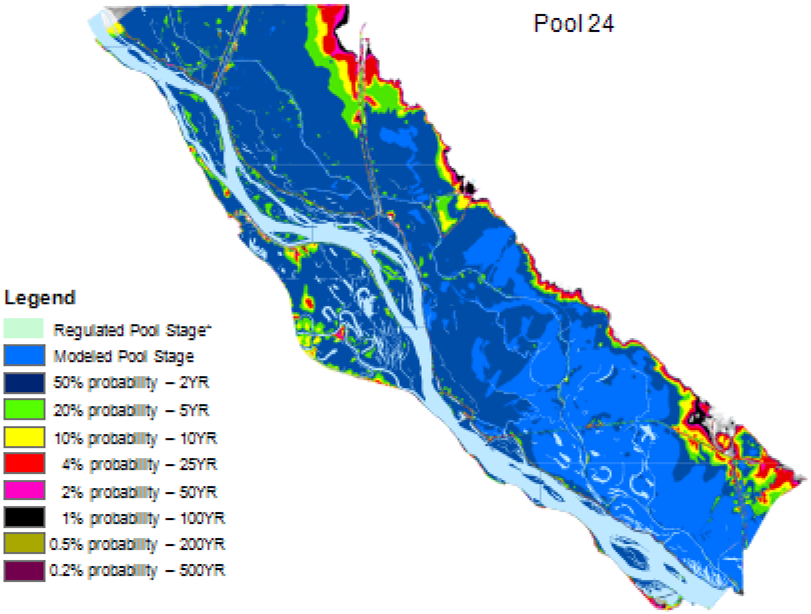

Pool 18
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

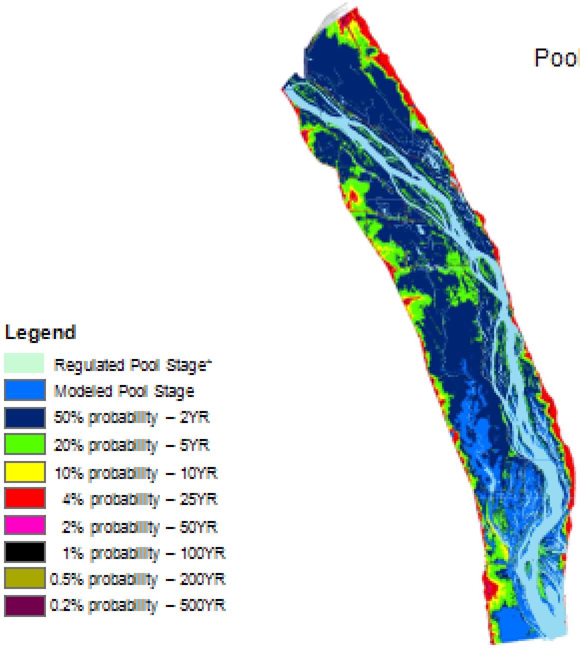

Pool 19
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

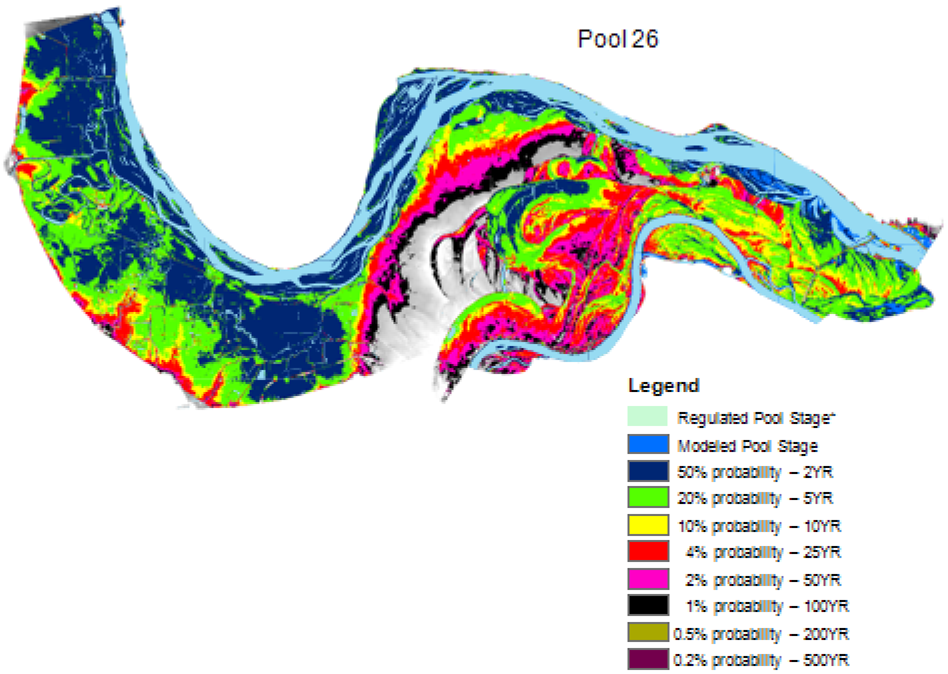

Pool 20
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

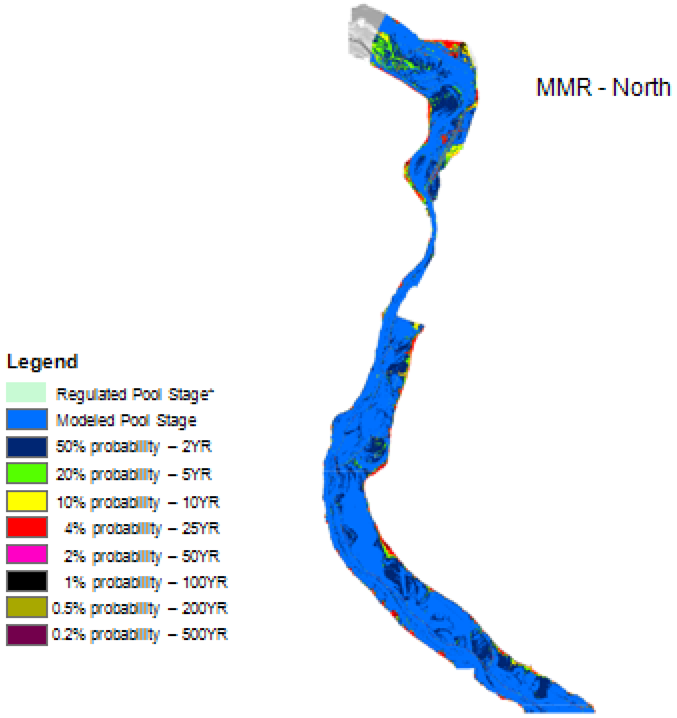

Pool 21
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

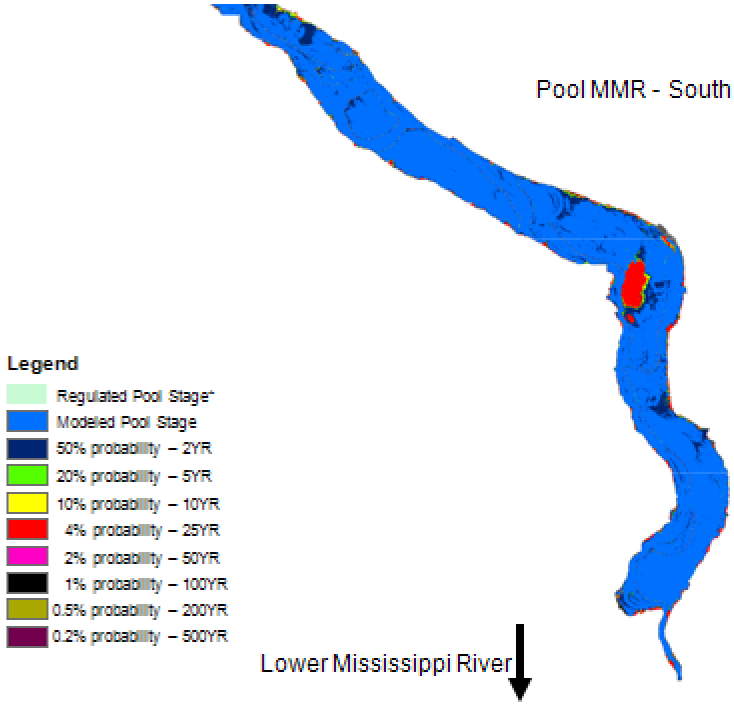

Pool 22
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

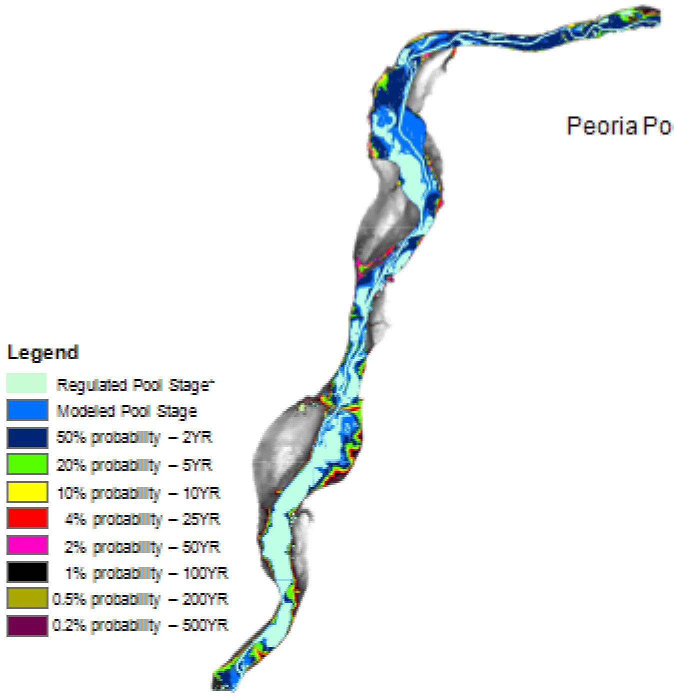

Pool 24
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

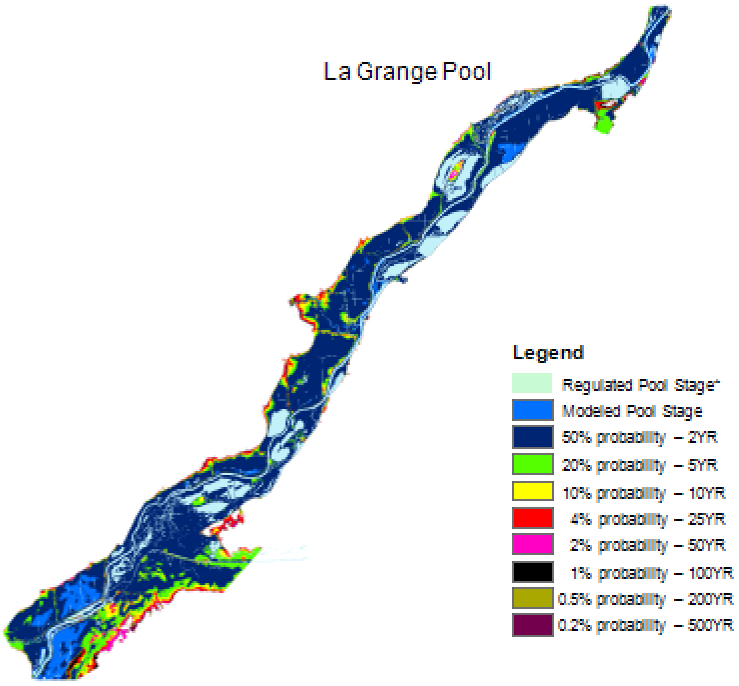

Pool 25
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

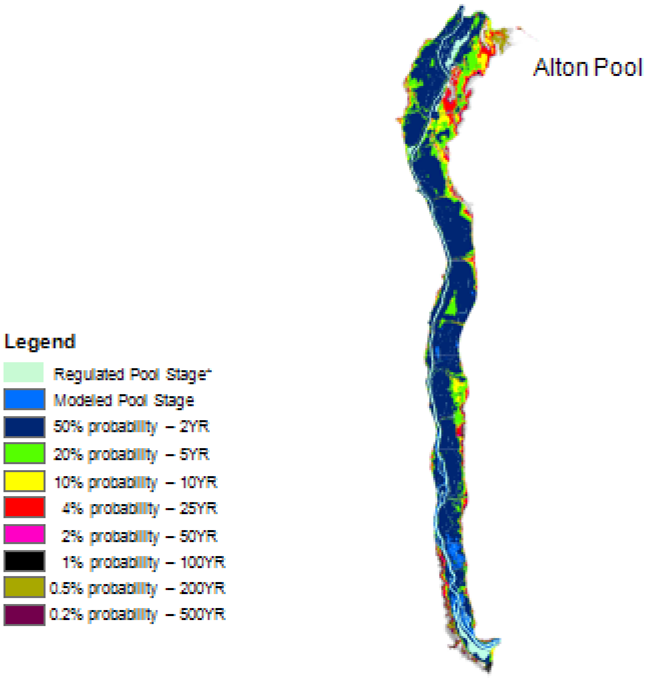

Pool 26
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR


MMR - North
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

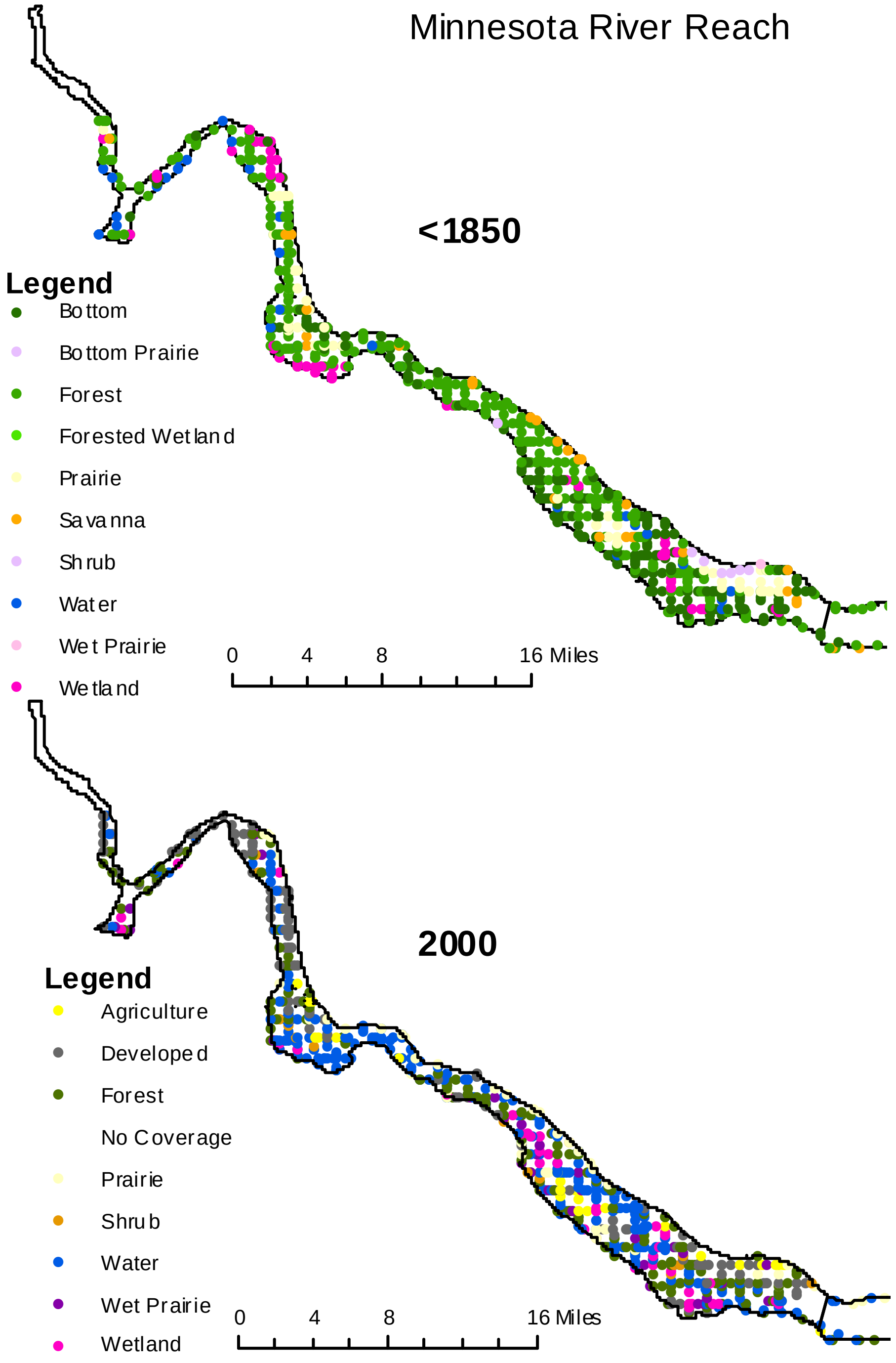

Pool MMR - South
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR
Lower Mississippi River


Peoria Pool
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

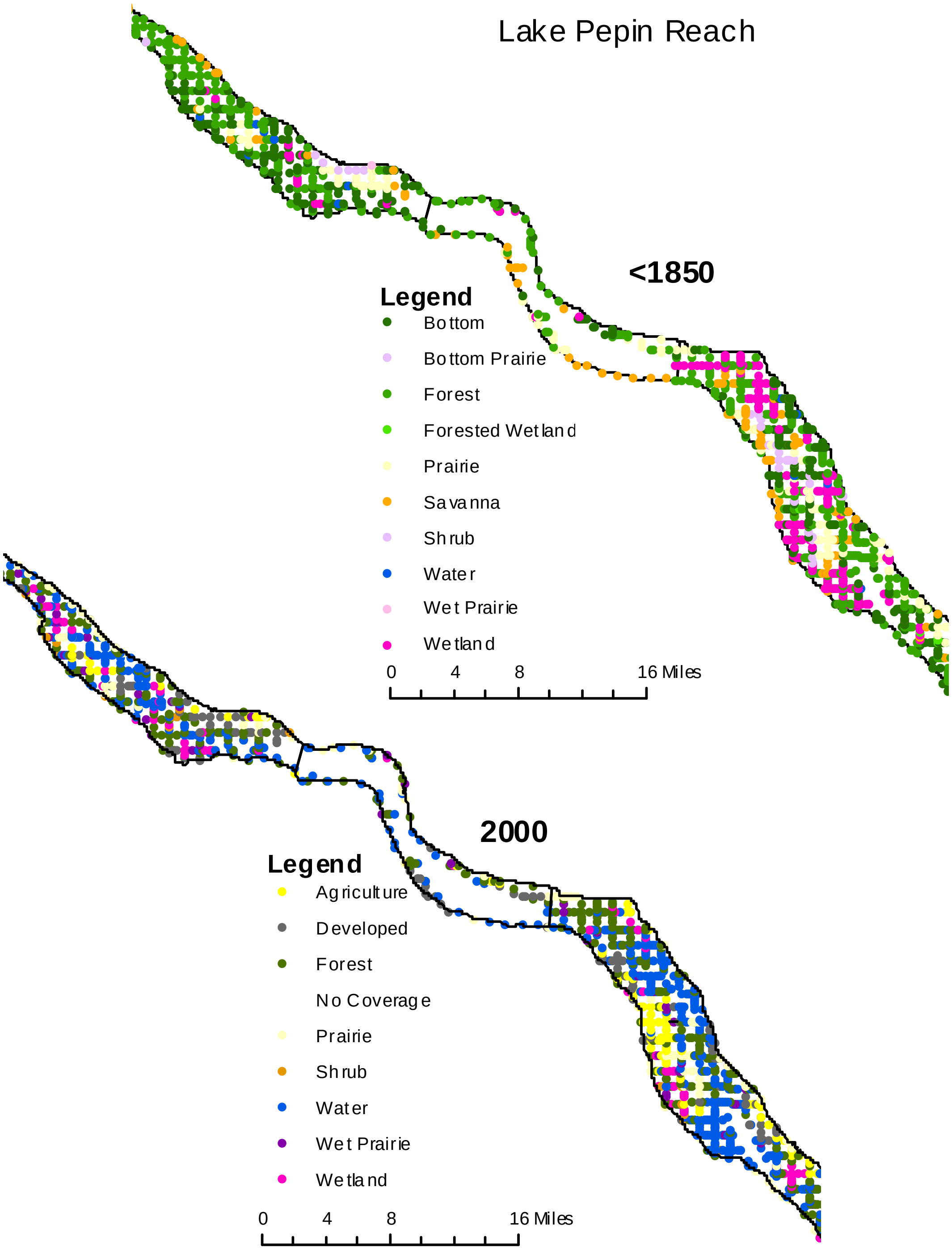

La Grange Pool
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR


Alton Pool
Legend
Regulated Pool Stage*
Modeled Pool Stage
50% probability – 2YR
20% probability – 5YR
10% probability – 10YR
4% probability – 25YR
2% probability – 50YR
1% probability – 100YR
0.5% probability – 200YR
0.2% probability – 500YR

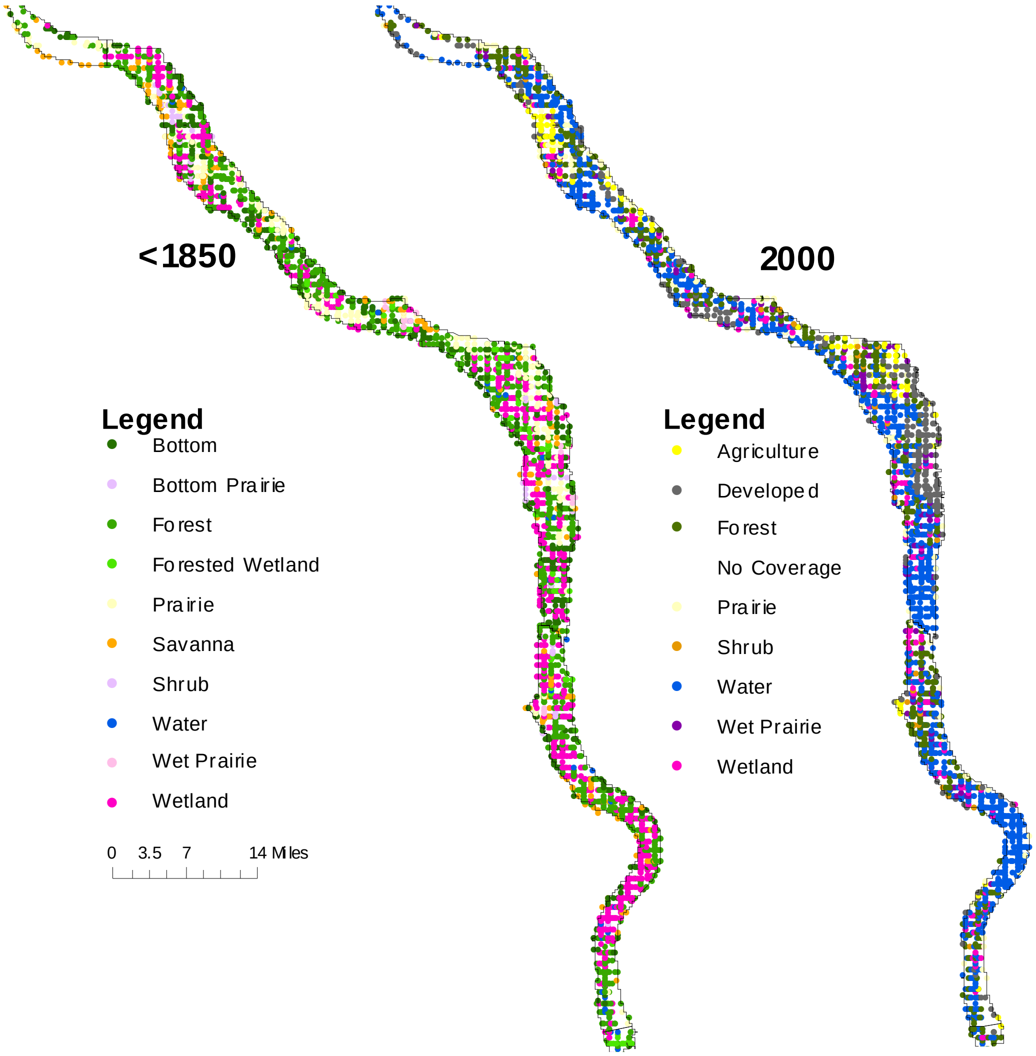
APPENDIX D: UPPER MISSISSIPPI RIVER SYSTEM PRESETTLEMENT (<1850) AND CONTEMPORARY (2000) LAND COVER

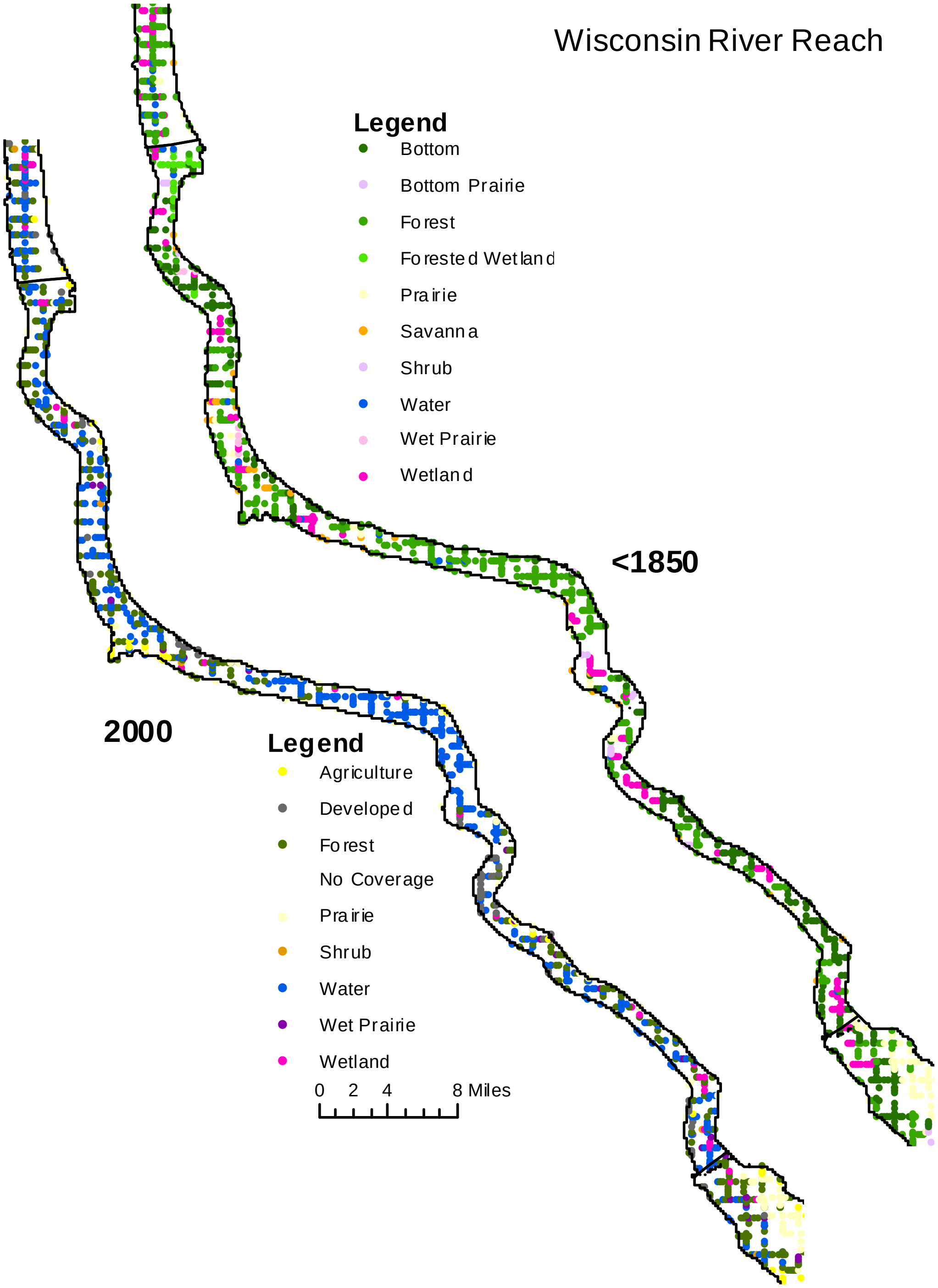

Minnesota River Reach
<1850
Legend
Bottom
Bottom Prairie
Forest
Forested Wetland
Prairie
Savanna
Shrub
Water
Wet Prairie
Wetland
0
4
8
16 Miles
2000
Legend
Agriculture
Developed
Forest
No Coverage
Prairie
Shrub
Water
Wet Prairie
Wetland
0
4
8
16 Miles

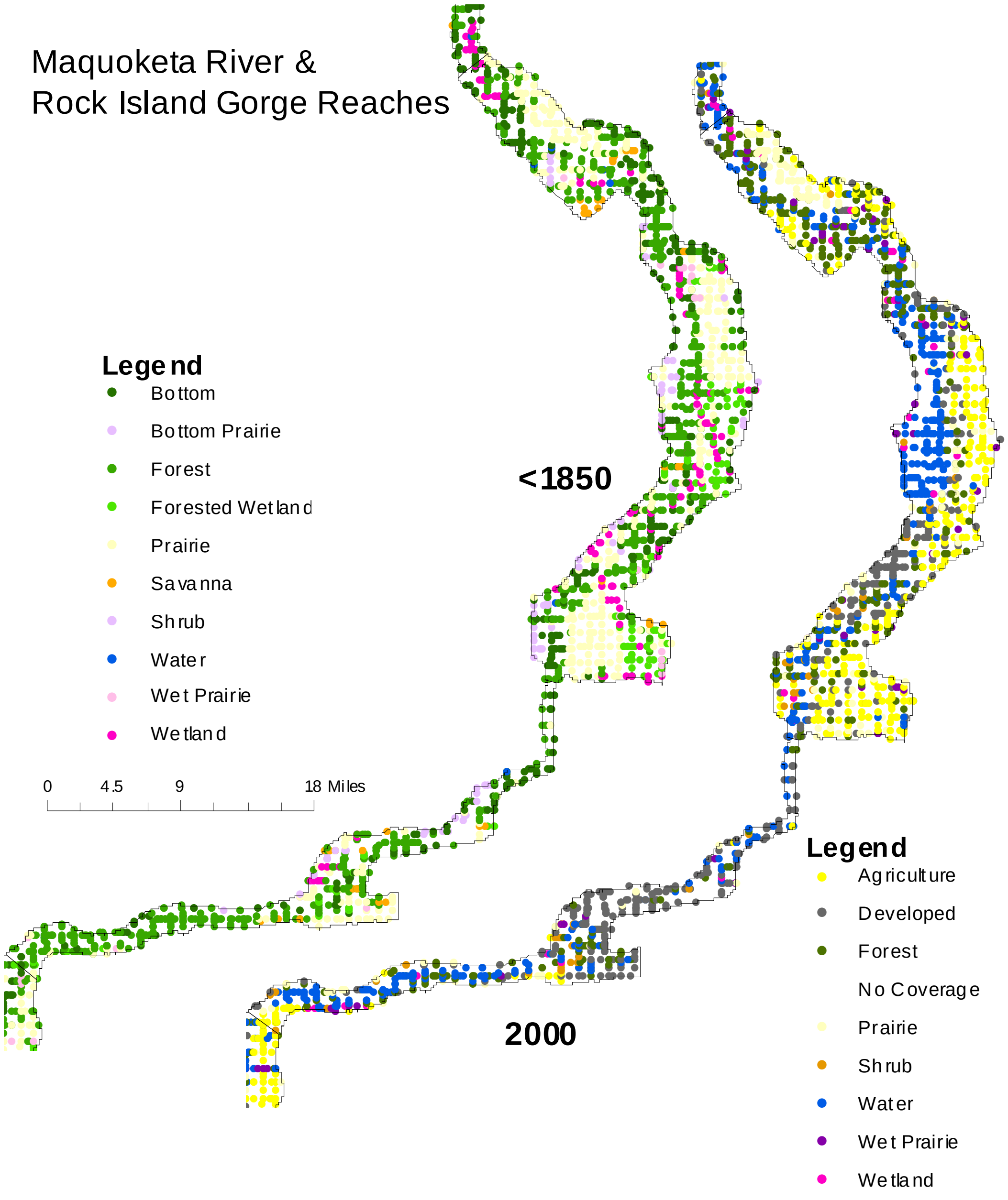
Lake Pepin Reach

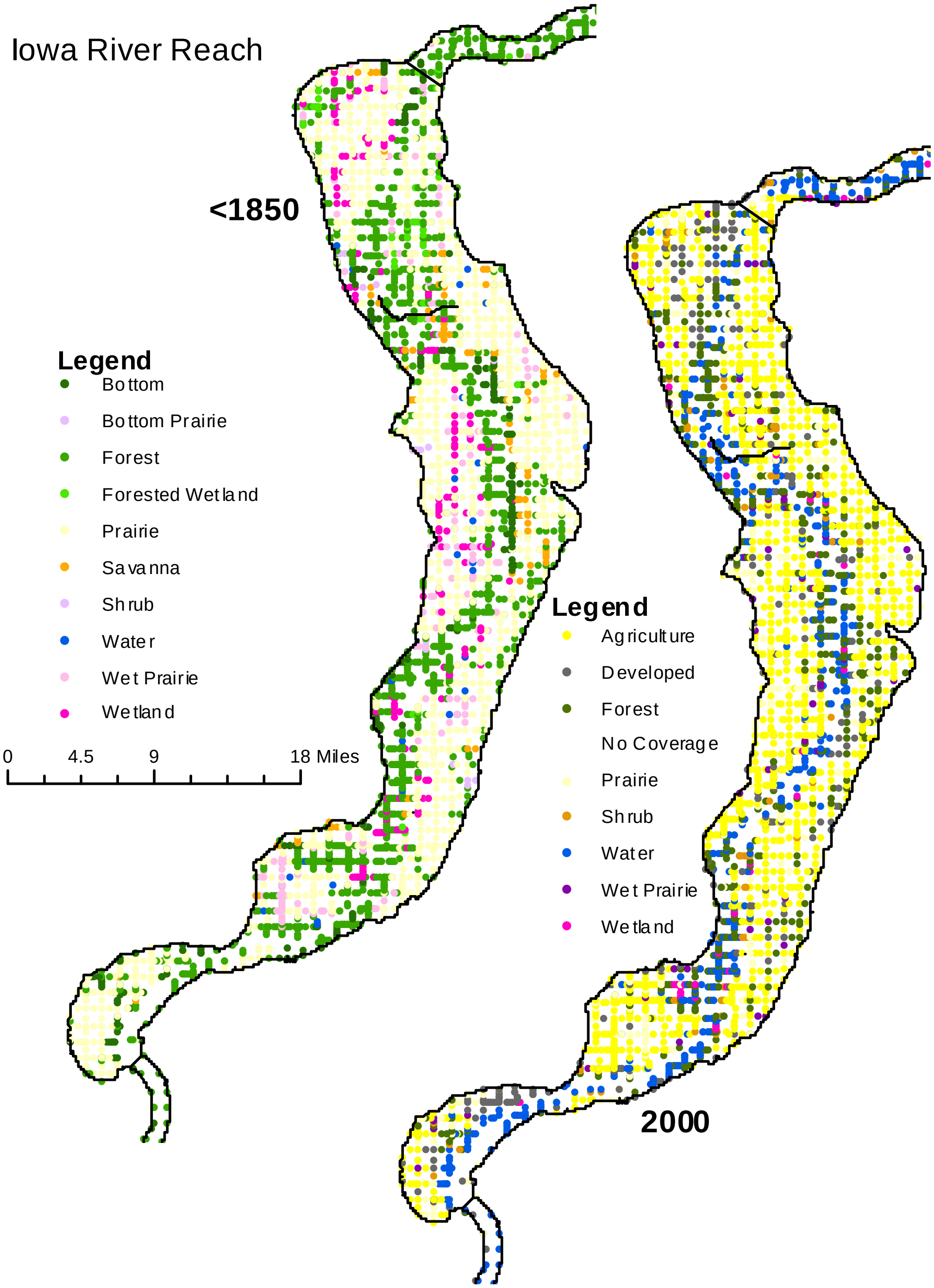


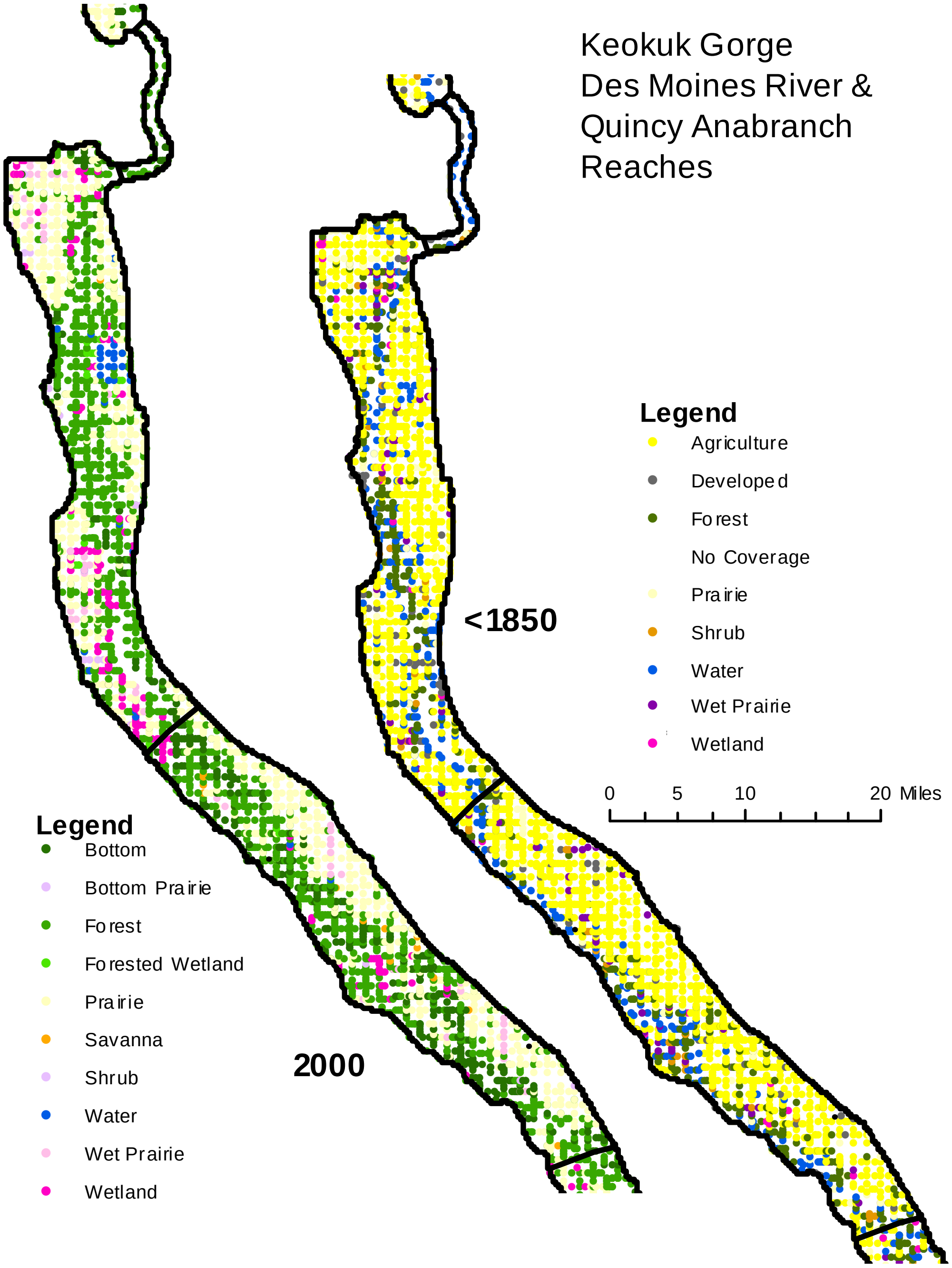
Chippewa River Reach

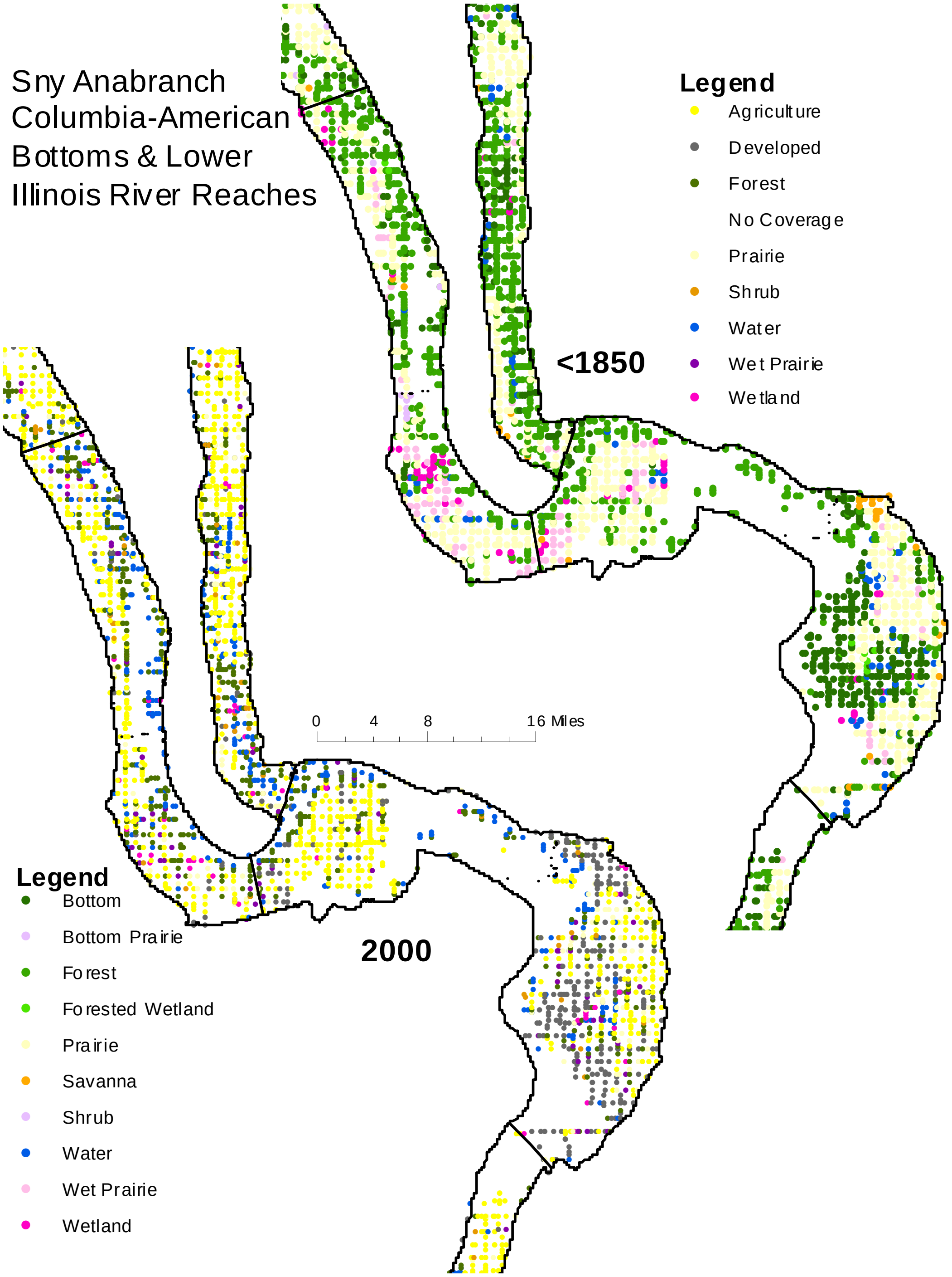


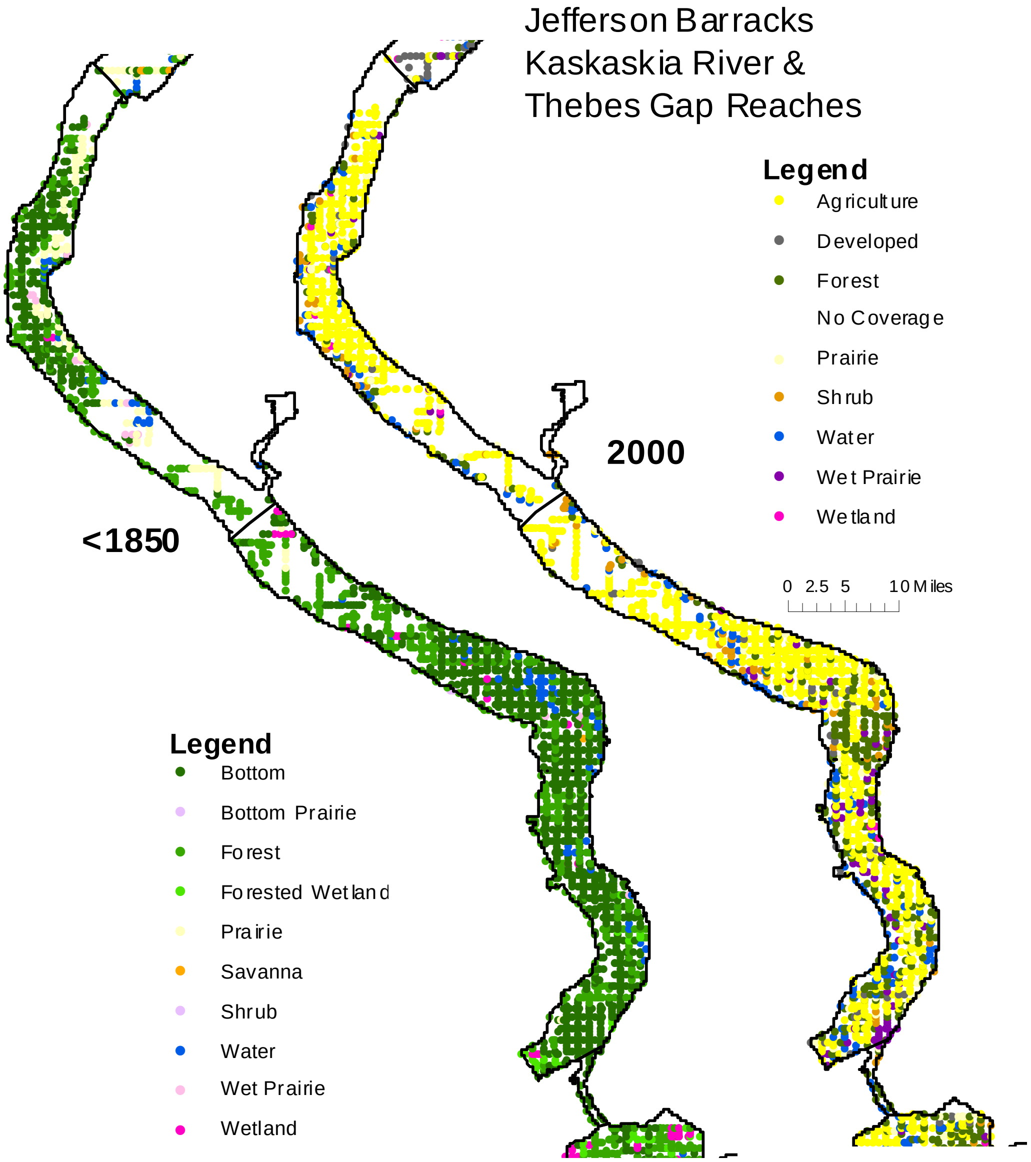

Wisconsin River Reach
Legend
Bottom
Bottom Prairie
Forest
Forested Wetland
Prairie
Savanna
Shrub
Water
Wet Prairie
Wetland
<1850
2000
Legend
Agriculture
Developed
Forest
No Coverage
Prairie
Shrub
Water
Wet Prairie
Wetland
0
2
4
8 Miles


Maquoketa River &
Rock Island Gorge Reaches
Legend
● Bottom
● Bottom Prairie
● Forest
● Forested Wetland
● Prairie
● Savanna
● Shrub
● Water
● Wet Prairie
● Wetland
0
4.5
9
18 Miles
<1850
2000
Legend
● Agriculture
● Developed
● Forest
No Coverage
● Prairie
● Shrub
● Water
● Wet Prairie
● Wetland

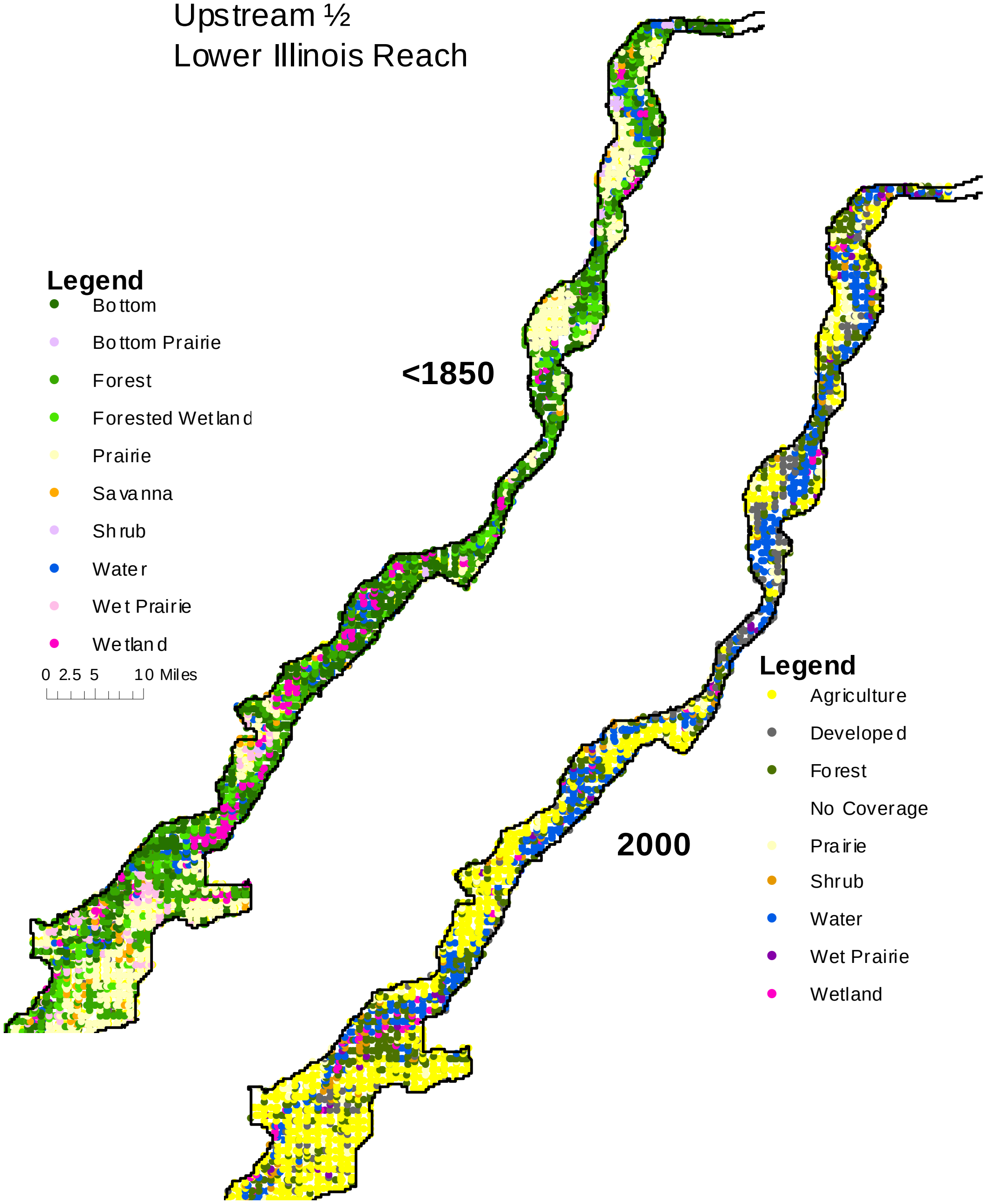

Iowa River Reach
<1850
Legend
Bottom
Bottom Prairie
Forest
Forested Wetland
Prairie
Savanna
Shrub
Water
Wet Prairie
Wetland
0
4.5
9
18 Miles
Legend
Agriculture
Developed
Forest
No Coverage
Prairie
Shrub
Water
Wet Prairie
Wetland
2000

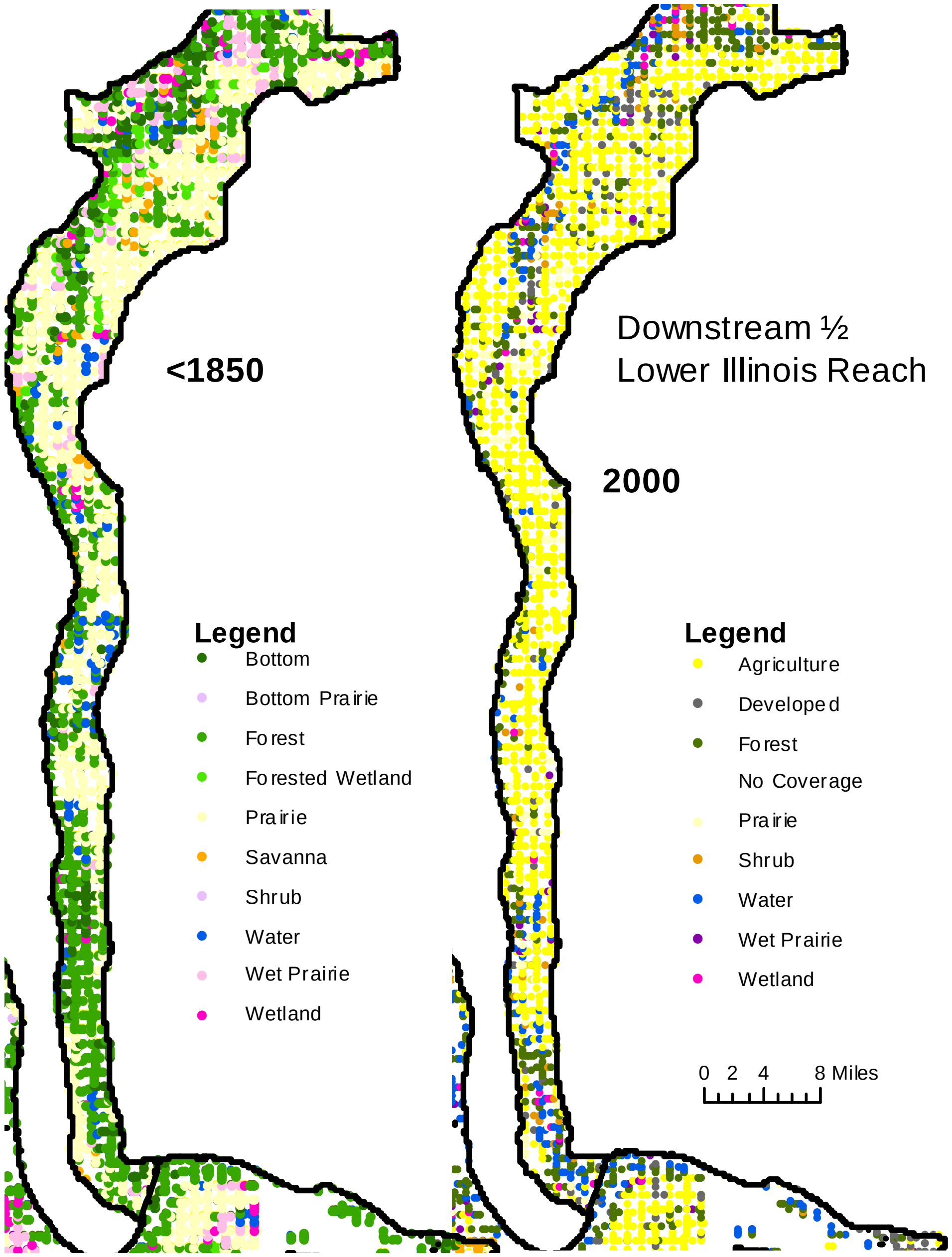

Keokuk Gorge
Des Moines River &
Quincy Anabranch
Reaches
Legend
● Agriculture
● Developed
● Forest
No Coverage
● Prairie
● Shrub
● Water
● Wet Prairie
● Wetland
0 5 10 20 Miles
<1850
Legend
● Bottom
● Bottom Prairie
● Forest
● Forested Wetland
● Prairie
● Savanna
● Shrub
● Water
● Wet Prairie
● Wetland
2000


Sny Anabranch
Columbia-American
Bottoms & Lower
Illinois River Reaches
Legend
Agriculture
Developed
Forest
No Coverage
Prairie
Shrub
Water
Wet Prairie
Wetland
<1850
0
4
8
16 Miles
Legend
Bottom
Bottom Prairie
Forest
Forested Wetland
Prairie
Savanna
Shrub
Water
Wet Prairie
Wetland
2000


Jefferson Barracks
Kaskaskia River &
Thebes Gap Reaches
<1850
2000
Legend
● Bottom
● Bottom Prairie
● Forest
● Forested Wetland
● Prairie
● Savanna
● Shrub
● Water
● Wet Prairie
● Wetland
Legend
● Agriculture
● Developed
● Forest
No Coverage
● Prairie
● Shrub
● Water
● Wet Prairie
● Wetland
0 2.5 5 10 Miles

Upstream ½
Lower Illinois Reach




Downstream ½
Lower Illinois Reach
<1850
2000
Legend
Bottom
Bottom Prairie
Forest
Forested Wetland
Prairie
Savanna
Shrub
Water
Wet Prairie
Wetland
Legend
Agriculture
Developed
Forest
No Coverage
Prairie
Shrub
Water
Wet Prairie
Wetland
0 2 4 8 Miles