# Hydro-Geomorphic Classification and Potential Vegetation Mapping for Upper Mississippi River Bottomland Restoration

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## 1. Introduction

Ecosystem restoration that incorporates process and function has become well known among ecosystem restoration practitioners (Society for Ecological Restoration, 2004; Palmer et al., 2005; Kondolf et al., 2006;). It has been recommended for the Upper Mississippi River System (UMRS; Figure 1) by expert advisory panels (Lubinski and Barko, 2003; Barko et al., 2006) and in Federal policy (U.S. Water Resources Development Act 2007, Section 8001). Our conceptual model for the UMRS integrates process and function among five Essential Ecosystem Components (EECs; Harwell et al., 1999), with hydrology, geomorphology, and biogeochemistry strongly influencing habitat and biota (Lubinski and Barko, 2003; Jacobsen, in press). The primary ecological driver of large floodplain river landscapes is hydrology (Junk et al., 1989; Poff et al., 1997; Sparks et al., 1998; Whited et al., 2007; Klimas et al., 2009), with discharge and river stage being the most common indicators of system condition and variability. Hydrology and hydraulics are conditioned by the geomorphic setting, or geomorphic landscape, which establishes river stage and floodplain inundation response to variable discharge (Clarke, et al., 2003; Thoms, 2003; Newson, 2006; Stallins, 2006; Thorp et al., 2008). Geomorphology is frequently presented as planform aquatic features (i.e., channel, secondary channel, backwater, floodplain, etc.), the river cross-section, floodplain topography, or soil profiles and maps. Flood inundation patterns are mapped less frequently, but they are strongly influenced by both regional and local hydrology and geomorphology (Thorp et al., 2008).

The UMRS is an institutional designation that includes the Upper Mississippi River Valley (UMV), the Illinois River Valley (IRV) and small parts of several tributaries (U.S. Water Resources Development Act 1986, Section 1103) which together span about 1,200 miles of 9-foot deep channels (Figure 1; USACE, 2004a). Channel clearing and stabilization under Federal authority began in 1824 and culminated with 37 lock and dam sites and thousands of channel training structures (USACE, 2004a). Chronic and sporadic shoaling requires dredging every year despite construction of low head navigation dams and channel regulating structures.

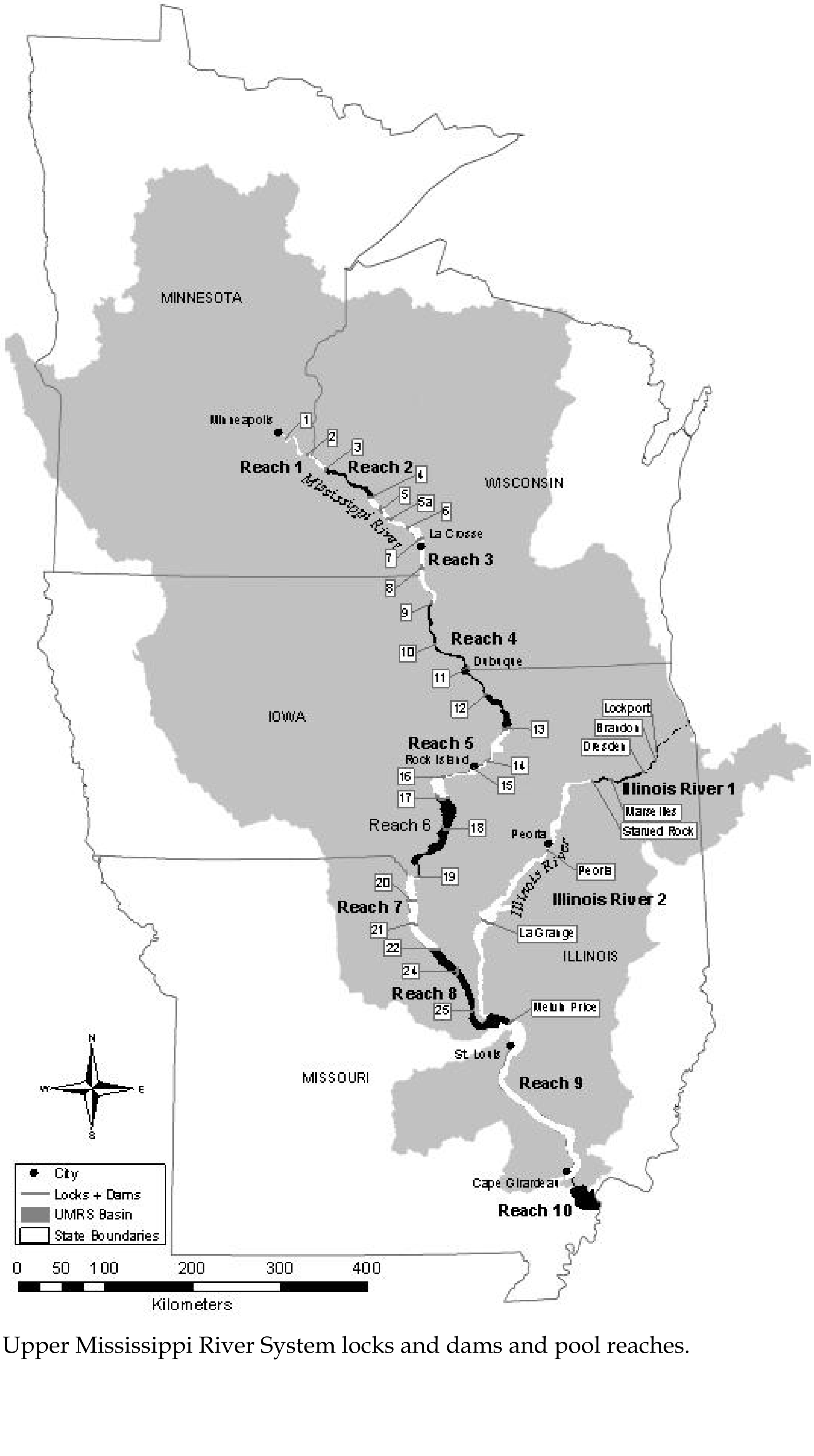


Fig. 1. Upper Mississippi River System locks and dams and pool reaches.

The entire river-floodplain covers more than 2.6 million acres (Theiling et al, 2000). The river includes four large "floodplain reaches" (Figure 2) defined by large scale valley features and social impacts (Lubinski, 1999). There are also 18 "geomorphic reaches" which were defined using riverbed slope, valley and channel features, and tributary confluences (WEST Consultants, Inc, 2000; Theiling, 2010). Geomorphic reach characteristics are important determinants of environmental response to development and floodplain land use objectives. Floodplain reaches and geomorphic reaches are analogous with Functional Process Zones and River Reaches, respectively, defined by Thorp et al. (2006, 2008) in their River Ecosystem Synthesis.

Floodplain development occurred concurrent with European settlement and industrialization. Increased shipping demand and the introduction of steamboats consumed massive amounts of wood from the floodplain (Norris, 1997) and necessitated channel improvements to carry larger loads during low flow periods and droughts. When forests were cleared for fuelwood and lumber, agriculture moved in to exploit the rich alluvial environment. Individual farmers connected natural levees to increase crop success initially and later constructed formal levee and drainage systems (Thompson, 2002).

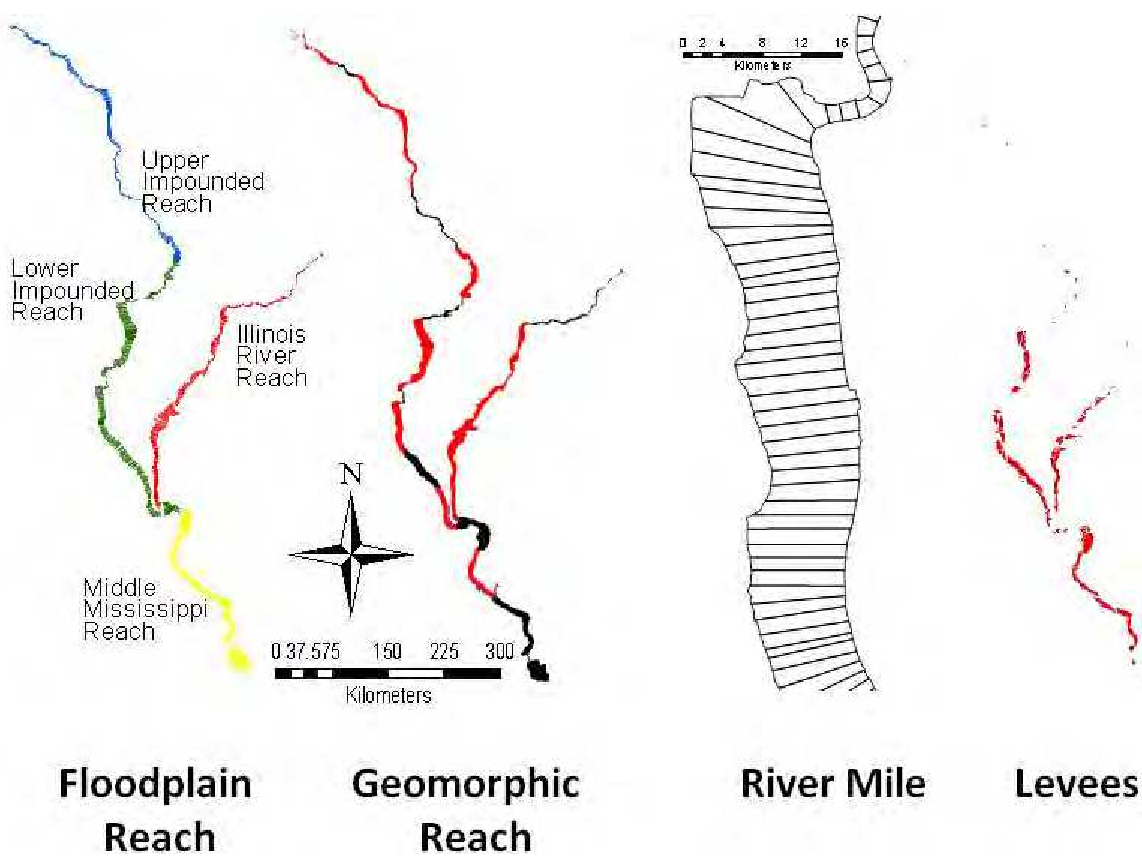


Fig. 2. Upper Mississippi River geomorphic scaling includes large, glacial controlled floodplain reaches, fluvial geomorphic controlled reaches, and structured (river mile) or political (levee district) segmentation schemes.

Levees (Thompson, 2002; USACE, 2006), water diversions (Starrett, 1971), and dams (Chen and Simmons, 1986; Fremling et al., 1989) were completed at system-wide scales to manage the distribution and conveyance of surface waters to control flooding, dilute municipal pollution, support navigation, and enhance habitat. The outcomes of these changes differ depending on location in the river system (Theiling and Nestler, 2010).

Alterations to hydrology, geomorphic structure, and direct impacts from historical land use change have substantially altered the form and function of ecological communities and processes in the UMRS. The flow of energy is a critical function in ecosystems and alterations to energy pathways can cascade through ecosystems in many ways (Welcomme, 1979; Vannote et al., 1980, Ward and Stanford, 1983; Junk et al., 1989; Ward et al., 1989). Early formal models for stream ecosystem energetics emphasized linear pathways transporting and utilizing metabolic energy differently along a river continuum (Vannote et al., 1983). The early stream ecosystem conceptual models were then tailored to account for nutrient cycling (Newbold et al., 1982), anthropogenic disturbances (Ward et al., 1999), different types of rivers (Junk et al., 1989; Wiley and Osborne, 1990), internal processes (Thorp et al., 1994), watershed influence (Benda et al., 2004 ), and geomorphic structure (Thoms, 2003). We developed system scale data to focus on the relationships expressed in the hydrogeomorphic methodology (Brinson, 1993; Klimas et al., 2009) and the River Ecosystem Synthesis (Thorp et al., 2006, 2008). Land cover, aquatic area, hydrology, and geomorphology data were derived for the entire UMRS for historic, contemporary, and simulated conditions. They can be compared among functional units such as Functional Process Zones or Hydrogeomorphic Patches defined by Thorp et al. (2008) or reference conditions (Nestler et al., 2010; Theiling and Nestler, 2010; SER, 2004) to create simulations of potential vegetation communities under alternative management scenarios.

Ecosystem restoration initiatives require estimates of the natural resource benefits that may be achieved by alternative project plans or project features to ensure accountability and success in Federal projects (USACE, 2000). Recent guidance also calls for the use of adaptive management in Federal water resource planning (Section 2039 of U.S. Water Resources Development Act 2007; Council on Environmental Quality, 2009). The models described here are important elements of adaptive management because they can estimate anticipated outcomes for comparison during monitoring and evaluation stages of the adaptive management cycle (Christianson et al., 1996; Walters, 1997; Williams, 2009). Many restoration plans include plant community or habitat models that estimate community response to physical forces (U.S. Water Resources Council, 1983; USACE, 2000; Council on Environmental Quality, 2009). Predicted plant and habitat response can then be used to support species or community habitat suitability models (USFWS, 1980). Dynamic physical forces are well known ecological drivers in large rivers (Doyle et al. 2005). Methods and data presented here can help estimate physical-ecological cascades resulting from hydrologic and geomorphic alteration of large rivers. We have made great progress developing data needed for potential vegetation models for the entire system. We also discuss the need for a rigorous landscape analysis that includes forest composition in the pre-settlement land cover data.

## 2. Methods

### 2.1 Geomorphology

Riverbed slope, channel geometry, and substrates are well known for engineering purposes. System-wide topographic mapping and channel surveys undertaken for each significant channel improvement plan were completed in 1890 and 1930. Surveys are much more frequent in the modern era. The Valley's floodplain has been mapped to document the relative age of geomorphic surfaces and associated deposits to help manage cultural resources (Bettis et al., 1996). The studies developed Landform Sediment Assemblages (LSA) which are mappable landforms and their underlying deposits that occur with predictable characteristics (Figure 3; Hajic, 2000). U.S. Department of Agriculture (USDA) soil maps are widely available, but generally lack detail in frequently flooded parts of the floodplain.

Geomorphic mapping in the Valley generally followed the protocol defined by Bettis et al. (1996) with slight variations. U.S. Geological Survey topographic quadrangle maps, aerial photos, soils maps, boring records, and literature were used to construct geomorphic maps. Geomorphic classifications were done at several different scales which allows for more detailed site-specific analysis than reported here. Mapping under modern aquatic areas was not possible and most of the low elevation features (active floodplain and some paleo-floodplain) were inundated in the lower ends of navigation pools 2 through 13 between Minneapolis, Minnesota and Clinton, Iowa. We unioned four separate LSA data sets (Bettis et al., 1996; Madigan and Schirmer, 1998; and Hajic, 2000) and reclassified them using a common classification scheme in GIS. The data were clipped to the bluff to bluff floodplain extent (Laustrup and Lowenburg, 1994). LSAs were summarized using a river mile segmentation floodplain overlay. River mile segments are unequal because the width of the floodplain varies and there are curves in the river that create wedge-shaped polygons. These results are a first approximation and open to further interpretation. Higher resolution mapping and analysis will be required for site-specific studies (Heitmeyer, 2010), but this generalized classification matches flood inundation mapping, historic land cover mapping, and regional habitat assessments (Theiling et al., 2000) quite well.

Our LSA geomorphic classification has nine classes described below. Characteristics were derived from Bettis et al. (1996), Madigan and Schirmer (1998), and Hajic (2000) and mapped as follows:

- **Modern Aquatic Classes** (Modern Channel, Modern Backwater) are primarily the result of navigation dams that inundated low elevation active and paleo-floodplain geomorphic classes, leaving levees and ridges exposed as islands in impounded aquatic areas in Pools 2 to 13. Aquatic area is generally <10 percent of the total floodplain area south of Rock Island, Illinois, but 20 to 60 percent in the north upstream from Rock Island. Modern aquatic area ranges from a few hundred to over 1,800 acres per river mile. Aquatic area is <500 acres for most river mile segments except at Illinois River miles where large lakes occur and on the Mississippi River where impoundment effects are exhibited in Pools 3 to 13.
- **Active Floodplain – Poorly Drained** is low elevation floodplain of vertical accretion origin that would have been or is flooded most years. These areas are often associated with tributary confluences. 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 inundated in the lower portions of all navigation pools. Some of these areas occur riverward of the flood control levees where they are exposed to altered hydrology and material transport. Similar areas behind levees are isolated from the river and may maintain more of their historic characteristics. Active floodplain is most abundant in the mid valley Mississippi River reaches and lower Illinois River. That is likely due to the limited effects from impoundment and the drainage of low elevation floodplain in agricultural drainage districts.

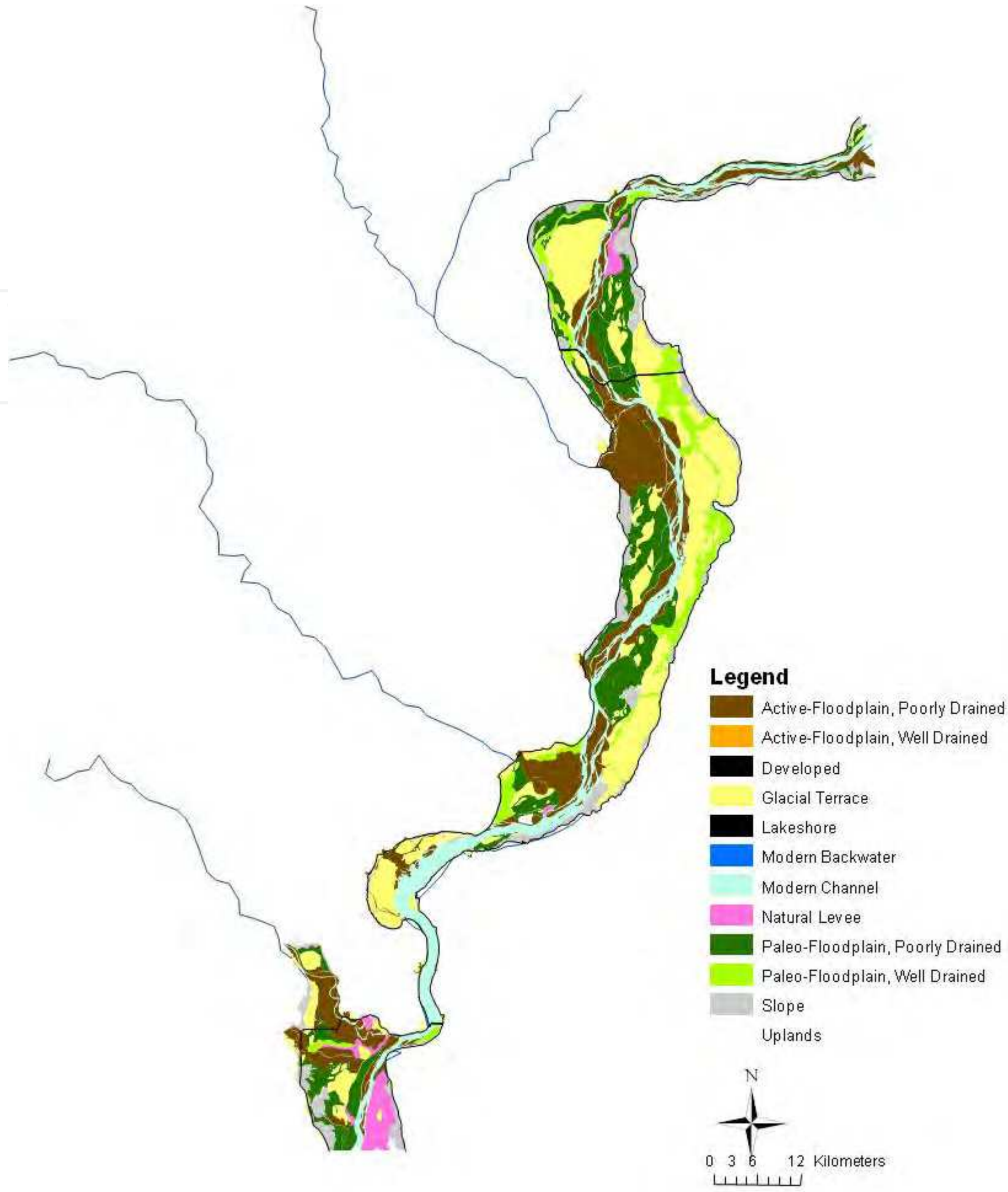


Fig. 3. Landform Sediment Assemblage maps characterize surficial and underlying characteristics that help define local edaphic factors. This map depicts parts of Pools 16 to 20 between Muscatine, Iowa and the junction of the Des Moines River.

- **Active Floodplain – Well Drained** is frequently flooded low elevation floodplain of lateral accretion origin. It is underlain by less than 1.5 meters of fine-grained alluvium that buries sand and pebbly sand. 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. This class was not mapped in the Rock Island and St. Louis Districts.
- **Paleo-Floodplain – Poorly Drained** 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. Deposits and soils are variable with fine silt, loams, and clays overlying pebbly sand. They function as overflow channels on the rising and receding flood or as ponded groundwater at high river stage. They

formed backwater lakes and sloughs prior to significant floodplain drainage (Heitmeyer, 2008).

- **Paleo-Floodplain – Well Drained** is infrequently flooded mid elevation floodplain of lateral accretion origin that includes inactive scrolls, bars, meander belts, and splays. Soils are variable with fine silt, loams, and clays overlying sand and pebbly sand. Paleo-Floodplain is mapped mostly in the Rock Island and St. Louis Districts. 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. In the St. Louis District this LSA comprises large meander scrolls that occupy a major proportion of the more elevated floodplain area. There is almost no paleo-floodplain in the St. Paul District because Holocene channel incision has isolated older surfaces as infrequently flooded terraces. Older surfaces in the St. Paul District occur as terraces.
- **Natural Levees** are slightly elevated, well-drained areas that parallel relatively stable channel reaches. Levees may also occur at crevasse splays that extend from channels cut into the natural levee and spreading into adjacent low-lying wet paleo-floodplain. Deposits of this LSA are stratified loam, sand, silt, clay, and sand. Levees are discontinuous linear areas that appear most abundant on the Illinois River because the Illinois River mapping was done at a smaller scale (higher resolution; Hajic, 1990). Several large levee areas are mapped in the Rock Island District and smaller levee areas are common along the channel in the St. Paul District where they are not submerged.
- **Alluvial/Colluvial Aprons** are elevated, bluff-base areas underlain by a variety of sediments derived from adjacent slopes and small tributary valleys. This LSA typically is quite messic and is rarely inundated. The most notable abundance of this LSA occurs in Illinois near Quincy where there are other high floodplain features.
- **Sandy Terraces** occur throughout the river and were formed during the last glacial period (Knox and Schumm in West Consultants, Inc., 2000). They are most abundant in the Illinois, Minnesota, Chippewa, Maquoketa, and Iowa River reaches. Downstream of the Iowa River Reach this LSA merges with the paleofloodplain LSA.

### 2.2 Hydrology

High resolution topographic data and updated river stage-discharge relationships were developed following the "Great flood of 1993" when there was a comprehensive review of floodplain management (Interagency Floodplain Management Review Committee, 1994). Photogrammetric methods were used to create a high accuracy digital elevation model for the entire Upper Mississippi floodplain for use in hydrologic modeling to re-define the river stage frequency rating curves. We created GIS overlays of the water surface elevation profiles corresponding to the rating curves, superimposed on the high resolution topography to map potential flood inundation patterns (Figure 4) for 8 annual exceedance probability floods: 50, 20, 10, 4, 2, 1, 0.5 and 0.2 percent (i.e., 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-yr expected recurrence interval flood).

#### 2.2.1 Topographic data

The U.S. Geological Survey National Elevation Database available through the National Map Seamless Server provided online access to digital elevation data in an easily accessible and well documented format. Upper Mississippi, Illinois, and Missouri Rivers floodplain elevation data were updated in 1998 using high resolution stereographic techniques (Interagency Floodplain Management Review Committee, 1994; Scientific Assessment and Strategy Team (SAST), David Greenlee, USGS EROS Data Center, Sioux Falls, South Dakota, personal communication). The 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; U.S. Army Corps of Engineers, 2003, 2004b). 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 for this project on the Lower Illinois River. The NED2003 floodplain elevation data were used for the Illinois River floodplain inundation mapping. Issues regarding vertical datum conversions were evaluated and determined to be insignificant at the scale and intended application for this study (Theiling, 2010).

Data can be accessed at several levels of resolution, we used the default 1 arc second download format to conserve data processing requirements over large geographic regions and because subsequent hydrologic modeling analyses were completed at similar resolution. Rectangular tiles covering about 100 miles each were downloaded and data extracted by a mask of the floodplain as represented by the prior defined floodplain extent for each pool (Laustrup and Lowenburg, 1994). We combined the pool scale DEMs into a DEM for the entire floodplain using default mosaic procedures in ArcGIS. Metric elevations were converted (i.e., times 3.281 in Raster math) to English units to match river stage in feet and discharge in cubic feet per second (cfs) which is the vernacular of the Flow Frequency Study.

### 2.2.2 Flow frequency study

Hydrologic analyses were accomplished with 100 years of record from 1898 to 1998 using the log-Pearson Type III distribution for unregulated flows at gages. Mainstem flows between gages were 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 were defined by developing regulated versus nonregulated relationships for discharges, extreme events were determined by factoring up major historic events, and the UNET unsteady flow program was used 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 the Mississippi and Illinois Rivers (Figure 4; USACE, 2004b).

A hydraulic analysis was required to establish the water surface elevation associated with each frequency of discharge at each location or cross section along the river reach. The main procedures were to use the UNET unsteady flow numerical modeling tool with recent channel hydrographic surveys (routinely obtained for navigation channel maintenance), and floodplain digital terrain data collected in 1995 and 1998. Levee overtopping was established 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 elevation profiles (USACE, 2003).

### 2.2.3 Floodplain inundation

Triangulated Irregular Network (TIN) files were created from the cross section feature lines for each separate flood stage frequency (Figure 4). Each flood stage TIN: 50%, 20%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% annual exceedance probability (i.e., 2-yr, 5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 200-yr, 500-yr expected recurrence interval flood) was overlayed in a cut-fill analysis on the high resolution floodplain topography for each navigation pool or reach. The area represented as inundated by the cut-fill procedure for each flood stage 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 m cells below the elevation of the water surface elevation (Figure 4). This value was exported to a spreadsheet where grid counts were converted to area estimates (acres) for the navigation pool scale at which they were created. The resulting GRID was converted to a shapefile to merge with other layers to create system-scale layers of the potential water distribution at each flood stage (Figure 4).

Floodplain inundation classes (i.e., 50, 20, 10, 5, and 1 percent annual exceedance probability floods) were summarized by river mile and compared by geomorphic reach. Leveed areas were then extracted from inundation layers to assess changes in flood distribution attributable to levees. These data were also summarized by river mile and 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 annual exceedance probability flood) and data were normalized as percent of maximum inundation area.

## 2.3 Land cover

### 2.3.1 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 (Carlander, 1954). 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). 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. Initial pilot studies reconstructing PLS surveys in the UMRS (Nelson et al., 1996) proved to be very valuable, so The Nature Conservancy's Great River Partnership 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 bluff to bluff extent for this initial analysis. The Nature Conservancy dataset, and recently available statewide PLS plat map GIS coverages, provide a snapshot to speculate on ecological community associations in the undeveloped landscape.

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 on about only 16 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; Theiling, 2010).

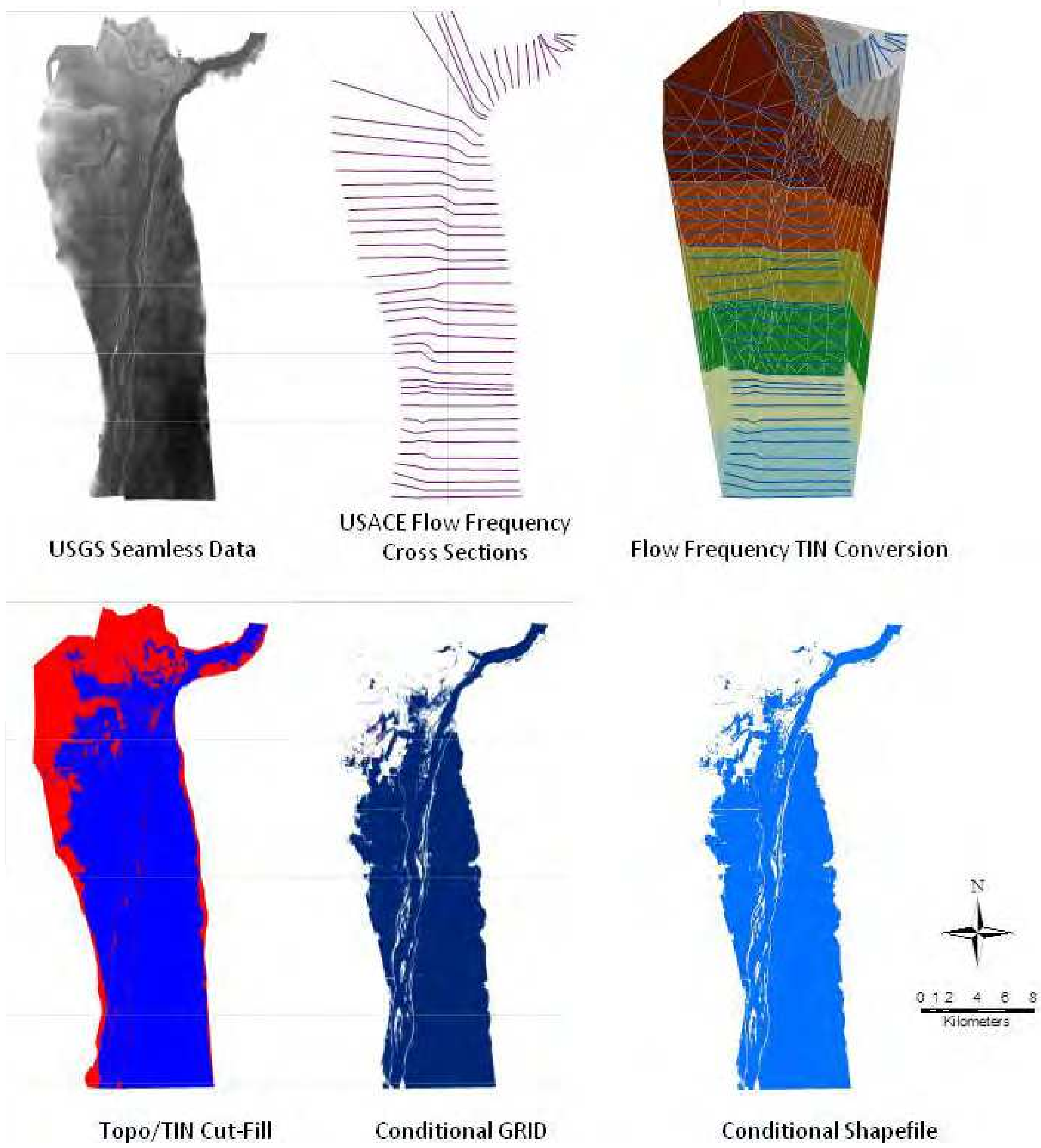


Fig. 4. Images depicting examples of elevation data, hydraulic model cross-sections, derived TINs, cut/fill interpolation, and grid and shapefile products.

### 2.3.2 Contemporary land cover

Environmental Management Program Long Term Resource Monitoring (LTRM) has compiled several system-wide land cover 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 compatible with the PLS data (Theiling, 2010). LTRM land cover data were combined in a spatial join to replicate the point sampling scheme of the PLS on the contemporary data.

### 2.3.3 Land cover classes

Land cover data from historic and contemporary periods were generalized to a common 12 class scheme (Theiling, 2010). The classification scheme combined several forest classes from the contemporary classification and two from the historic classification. The savanna class combined 11 classes from the PLS surveys, but none from the modern surveys because the habitat is only rarely present in the modern landscape. 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 aquatic classes depended on the presence of vegetation. Agriculture and developed classes were not common in the historic data, but they were very important in the modern data. PLS data have been criticized for inaccurate and inconsistent identifications and naming conventions. 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.

### 2.4 Data analysis

We overlayed the river reach segmentation schemes on land cover layers to provide proportional estimates for each land cover class to show plant community composition change along the river. A GIS extension was built to complete point counts for each land cover class at each river mile (Tim Fox, U.S. Geological Survey, Upper Midwest Environmental Sciences Center, La Crosse, Wisconsin). We also summed point counts by geomorphic class and hydraulic inundation frequency. Data were normalized as a 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 by river mile here and also used in multivariate statistical analyses examining the distribution of geomorphic, hydrologic, and land cover characteristics among river reaches at several scales (Theiling, 2010).

### 2.5 Hydro-geomorphic methodology

The HGM process of evaluating ecosystem restoration and management options relies heavily on eight types of data, most of which require geospatial digital information usable in an ArcGIS/ArcMAP format. These data include historic and current information about: 1) soils, 2) geomorphology, 3) topography/elevation, 4) hydrology/flood frequency, 5) aerial photographs and cartography maps, 6) land cover and vegetation communities, 7) presence and distribution of key plant and animal species, and 8) physical anthropogenic features.

The three-stages of HGM are as follows: first, the historic condition and ecological processes of an area and its surrounding landscapes are determined from a variety of historical and current information such as geological, hydrological, and botanical maps and data. Public Land Survey (PLS) maps and notes are especially useful to understand historic vegetation composition and distribution. A key element of HGM is developing a "matrix" of understanding of which plant communities historically occurred in different geomorphological, soil, topographic, and flood-frequency settings (Table 1). For example, in the Mississippi-Missouri River Confluence Area, wet bottomland prairie that was dominated by prairie cordgrass historically occurred at elevations greater than 417 feet, on relict alluvial floodplain terrace surfaces, on silt loam soils, and between the two- and five-year flood frequency zones (Heitmeyer and Westphall, 2007). Contemporary areas that offer these conditions, especially surface, soil, and flood frequency attributes now offer the best edaphic conditions for restoring wet bottomland prairie communities.

Second, alterations in hydrological condition, topography, vegetation community structure and distribution, and resource availability to key fish and wildlife species are determined by comparing historic vs. current landscapes. This analyses is essentially a qualitative "best professional judgment" assessment of current condition and the types and magnitudes of changes, including assessment of which communities are most resilient and which types of change are the most/least reversible.

Third, options and approaches are identified to restore specific habitats and ecological conditions. The foundation of ecological history coupled with assessment of current conditions helps to determine which system processes (e.g., periodic dormant season flooding) and habitats (e.g., forest composition) can be restored or enhanced, and where this is possible, if it is at all. Obviously, some landscape changes are more permanent and less reversible (e.g., mainstem levees on the Mississippi and Illinois rivers) than others (e.g., clearing of bottomland forest). Through development of the HGM matrix conservation planners can identify: 1) which, and where, habitat types have been lost or altered the most and establish some sense of priority for restoration efforts; 2) where opportunities exist to restore habitats in appropriate geomorphic, soil, hydrological, topographic settings including both public and private lands; 3) how restoration can replace lost functions and values including system connectivity; and 4) what management types and intensity will be needed to sustain restored communities. HGM can be an iterative process that is well-coupled with adaptive ecosystem management (Christensen et al., 1996; Palmer et al., 2005) because new monitoring and research can be used to refine HGM models and restoration plans.

| Habitat Type | Geomorphic Surface | Soil Type | Flood Frequency |
|---|---|---|---|
| Open Water | Active river channels, side channels | Riverine Riverine | Permanent Permanent-seasonally dry |
| | Abandoned channels | Clay, silt-clay | Permanent-seasonally dry |
| Bottomland Lake | Abandoned channels | Clay, silt-clay with sand/loam plugs | Permanent to semi-permanent |
| Riverfront Forest | Bar-and-chute and braided bar | Sand, sandy loam and silt loam in swales | 1 – 2 year |
| Floodplain Forest | | | |
| Ridges | Point bar ridge | Loam, sandy loam | 2 – 5 year |
| Swales | Point bar swales and tributary riparian zones | Silt loam, slit clay veneer | 1 – 2 year |
| Bottomland hardwood forest | Backswamp, larger point bar swales and floodplain depressions | Silt loam, silty clay | 2 – 5 year |
| Slope Forest | Alluvial fans, colluvial aprons, terrace edges | Mixed erosional | >20 year |
| Savanna | Alluvial fans, colluvial aprons, terrace interface | Silt loam | 10 – 20 year |
| Bottomland Prairie | | | |
| Wet | Point bar and terrace swales and depressions | Clay, silt clay | 2 – 5 year |
| Intermediate | Point bar ridges | Silt loam | >5 year |
| Mesic Prairie | Point bar edges and terraces | Sandy loam, silt loam | >20 year |

Table 1. Hydrogeomorphic matrix of historic distribution of major vegetation communities/habitat types in the American Bottoms geomorphic reach (near St. Louis, Missouri) in relation to geomorphic surface, soils, and flood frequency.

## 3. Results

### 3.1 Gemorphology

Land Sediment Assemblage abundance plotted by rive mile illustrates the distribution of each class and the relative width of the floodplain (Figure 5, top). Geomorphic reach overlays helped identify characteristics that separated reaches in a multivariate analysis (Theiling, 2010). The Chippewa River Reach (RM 650 – 750) is separated downstream by the narrower Wisconsin River Reach (RM605-650) which runs through resistant dolomite valley walls (Knox, 2007). The floodplain widens again through erosive shale in the Maquoketa

River Reach (RM510-605) to the Rock Island Gorge (RM465-510) which presents another constrained, resistant dolomite reach (Trowbridge, 1959). Significant widening occurs just below the gorge where the Mississippi Valley intersects an ancient bedrock channel (Iowa River Reach RM420-465). Sandy terraces are abundant in the Iowa Reach and broader reaches upstream (Figure 5, bottom), but they are buried below Holocene sediments downstream of Quincy Illinois near river mile 325. Alluvial/Colluvial apron is ubiquitous, but uniquely abundant in the Des Moines River, Quincy Anabranch, and Sny Anabranch Reaches (RM240-400) where perched wetlands were once present. Paleofloodplain created from Missouri River outwash in the early Holocene is the dominant LSA class at the confluence with and south of the Missouri River (RM200; Bettis et al., 2008). Active floodplain abundance and distribution is relatively constant among reaches. The abundance of aquatic area is higher upstream from river mile 400 because of the effect of dams increasing surface water area in a series of shallow navigation pools (Theiling and Nestler, 2010).

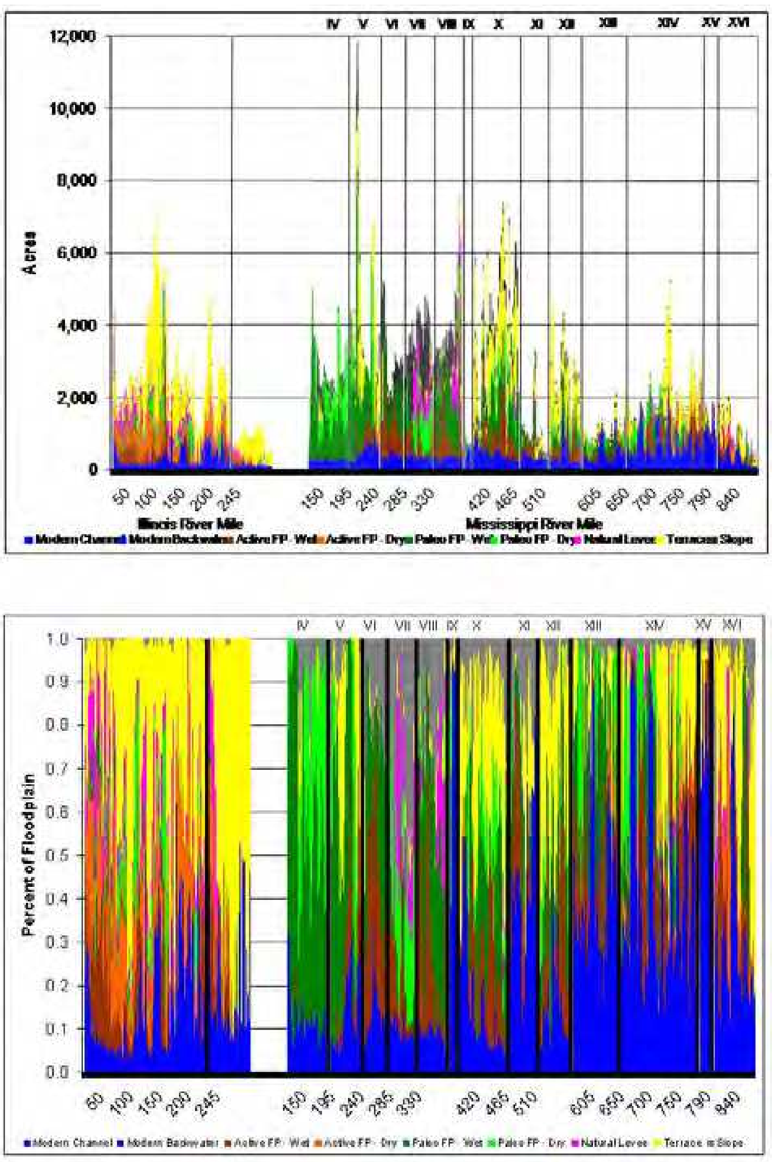


Fig. 5. Geomorphic class distribution in acres and as proportion of total floodplain area for the Upper Mississippi River System.

The Illinois River floodplain presents a diverse land sediment assemblage (Figure 5; Hajik, 2000). The Upper Illinois (> river mile 245) is deeply flooded by dams and only Sandy Terraces remain visible. The Lower Illinois River has not been subdivided into reaches here, but other authors have defined three or more reaches (Starrett, 1972; Sparks, 1992). Terraces are the most abundant floodplain feature, but natural levees are also widely distributed. Active floodplain surfaces increase at river mile 100 below the confluence with the Sanganois River, a major tributary. The Lower Illinois River is slightly narrower than the Mississippi (Figure 5) and it has a much lower gradient than most rivers (Starrett, 1972).

### 3.2 Hydrology

The abundance of water mapped at low flow periods was relatively constant in the river in 1890 (Figure 6, bottom). Several large aquatic areas: Lake Pepin – River Mile 765, Lima Lake – River Mile 350, MMR Backwaters <River Mile 200, were notable features of the floodplain in 1890, but now only Lake Pepin and degraded and disconnected MMR backwaters persist. The contemporary distribution of surface water (Figure 6) reflects the impact of navigation dams completed ~1940 (Theiling and Nestler, 2010). Water surface area increases in impounded reaches upstream of RM400 and a repeating pattern of dam effects are apparent. UMRS navigation dams are only required to maintain low flow navigation, and their impoundment effect only extends partway up each navigation pool (Theiling and Nestler, 2010). Dam gates are raised out of the river during flood stage, except at Dam 19 (hydropower), about 15 percent to 50 percent of the time (USACE, 2004c, 2004a) when discharge alone can maintain navigable depths.

The change in distribution of aquatic classes is quite striking in the floodplain upstream from the Rock Island Gorge (~River Mile 500) where impoundment effects are pronounced (Figure 7). Sandbars were lost throughout the river system coincident with increased river stages. Wooded islands were lost in the upper river reaches during the post-dam era because of wind-wave erosion of former floodplain ridges and levees exposed following impoundment (Rohweder et al., 2008). The increase in contiguous, or connected, backwaters is a very prominent change in the upstream reaches, but not very important in lower reaches. Isolated backwaters were not prominent in either period, but they are considered very important for many flora and fauna.

Floodplain inundation differs throughout river valleys in response to many natural and anthropogenic drivers. Major tributary rivers demark most geomorphic reaches and each contributes flow and its unique sediment signature to the mainstem Mississippi and Illinois Rivers. The wider banded segments in Figure 8 (bottom) represent areas of greater floodplain inundation diversity which typically occurred at tributary fans and in steep valley reaches. Areas where all the flood stages are compressed (e.g., below river mile 125) are primarily influenced by frequent floods that would fill most of the valley. The impact of the navigation system is apparent in the amount that "Pool Stage" increases as a proportion of maximum inundated area upstream from river mile 400. The distribution of the 2-year flood is prominent along the entire river where it commonly exceeds 70 percent of the total floodplain area and 90 percent in a few locations. This is a characteristic of floodwater distribution across a range of streams and rivers (Leopold et al., 1964).

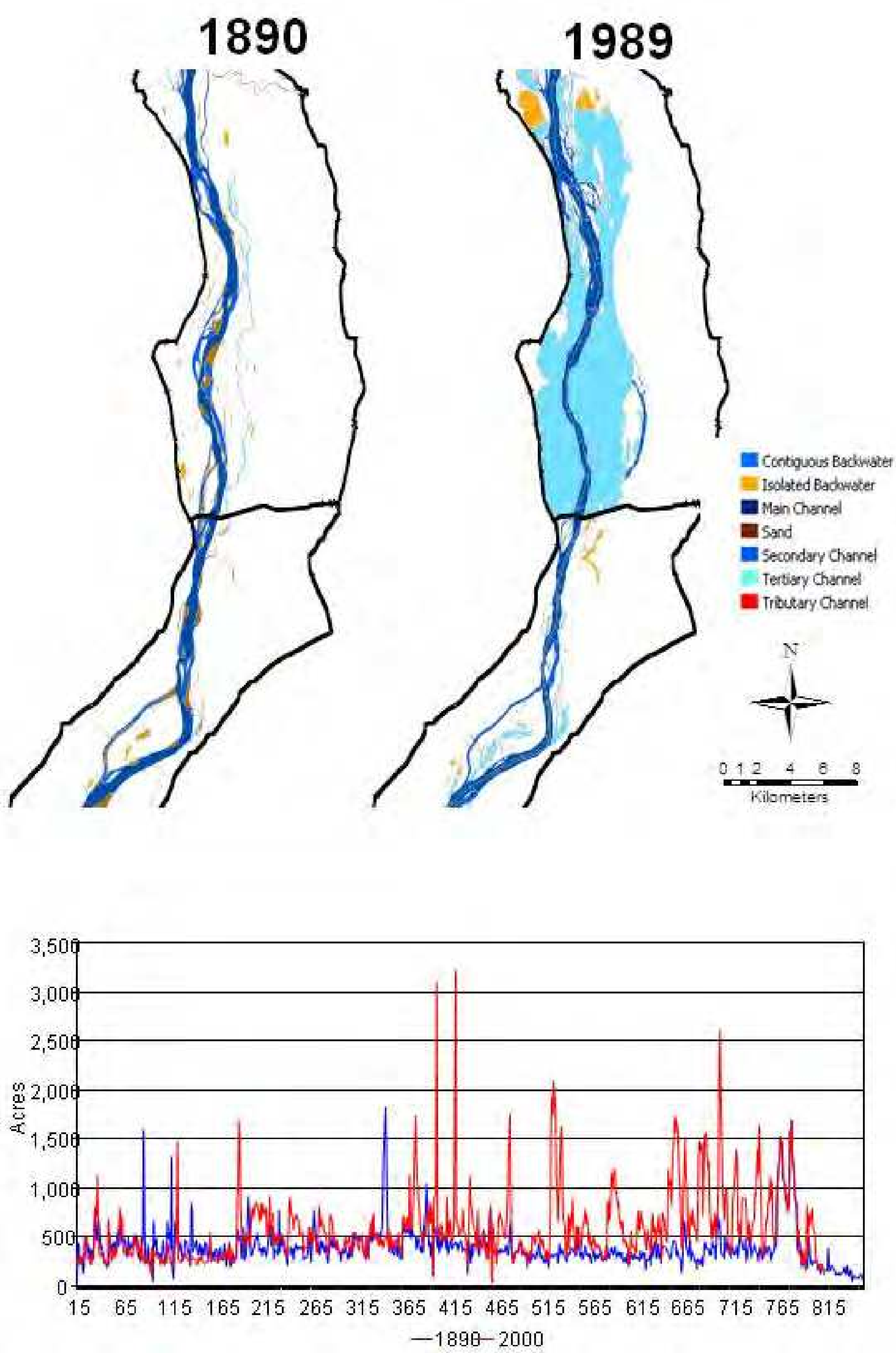


Fig. 6. Surface water impacts from impoundment differ in the northern and southern parts of the system as represented by acres of surface water (bottom) and the map of the Lock and Dam 13 area at River Mile 522. Dam effects in the upper pools are similar to the upper portion of the 1989 image with large contiguous backwaters created by dams, whereas dam effects in downstream pools are more similar to their pre-dam form as shown in the bottom part of the 1989 image.

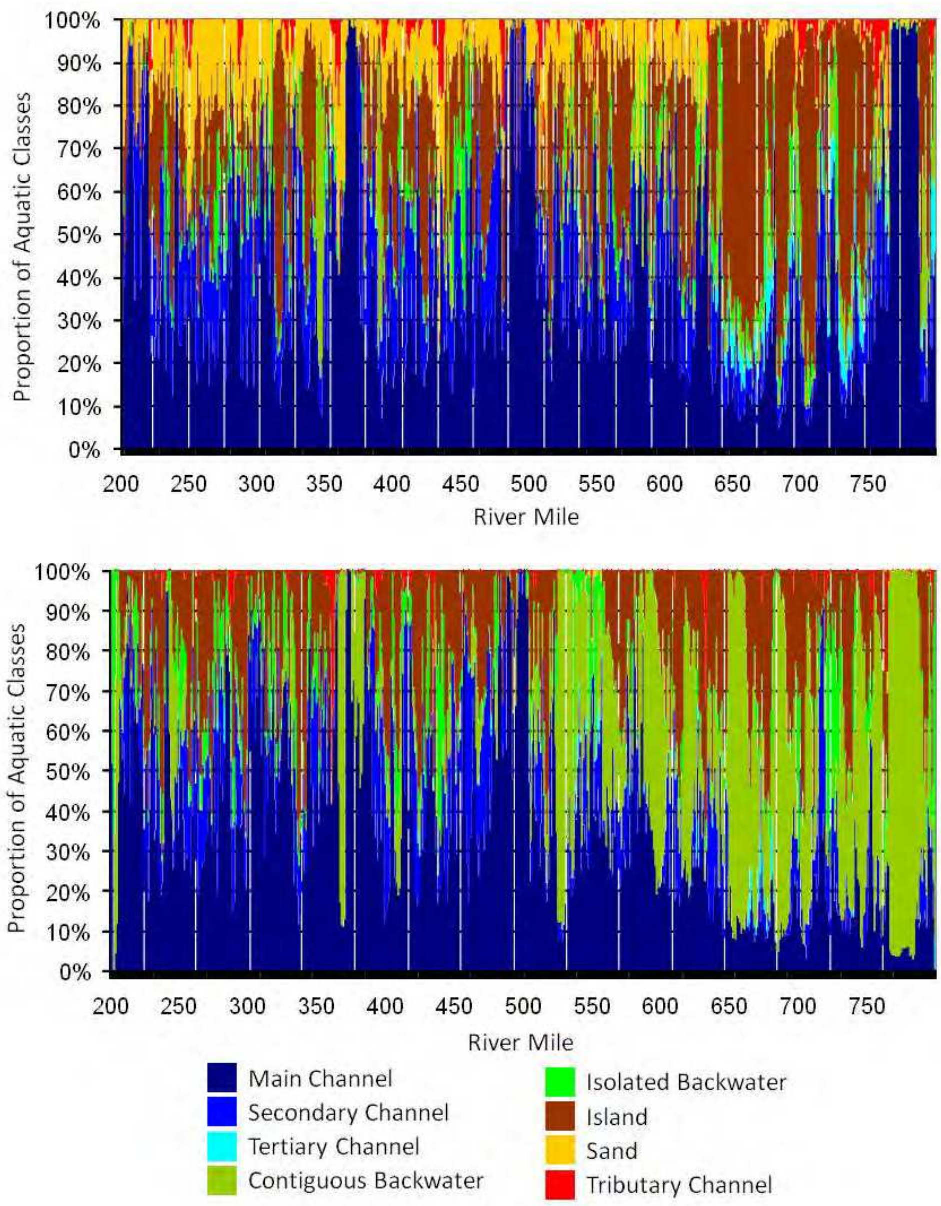


Fig. 7. Pre-development (top) and contemporary proportional distribution of aquatic area.

The UMRS geomorphic reaches neatly superimpose on our floodplain inundation simulation (Figure 8). The Minnesota (XVI) and Chippewa River (XIV) Reaches show diverse inundation patterns, with the influence of the Chippewa River delta diminishing about mid-reach. The Wisconsin River Reach (XIII) is dominated by frequent floods, but the geomorphically diverse Maquoketa River Reach (XII) influences a diverse floodplain hydrology. The importance of the 2-year flood increases through the Iowa River (X), Des Moines River (VIII), and Quincy (VII) and Sny (VI) Anabranch Reaches until it meets the massive alluvial fan deposited by the Missouri River at Columbia Bottoms (V). Hydrology is similar to upstream reaches in the Jefferson Barracks Reach (IV) between the Missouri River and the Kaskaskia River (III) where the low elevation floodplain is greatly influenced by the 2-year flood. The Illinois River shows a relatively diverse flood stage distribution that is consistent in most of the reach (Figure 8). The influence of the higher head dams above river mile 150 is apparent, whereas the influence of dams is much less in most of the rest of the river. Dam effects on the Illinois River are exhibited by much larger and permanent backwater lakes compared to isolated lake and channel networks present at low flow prior to development (Mills et al., 1966).

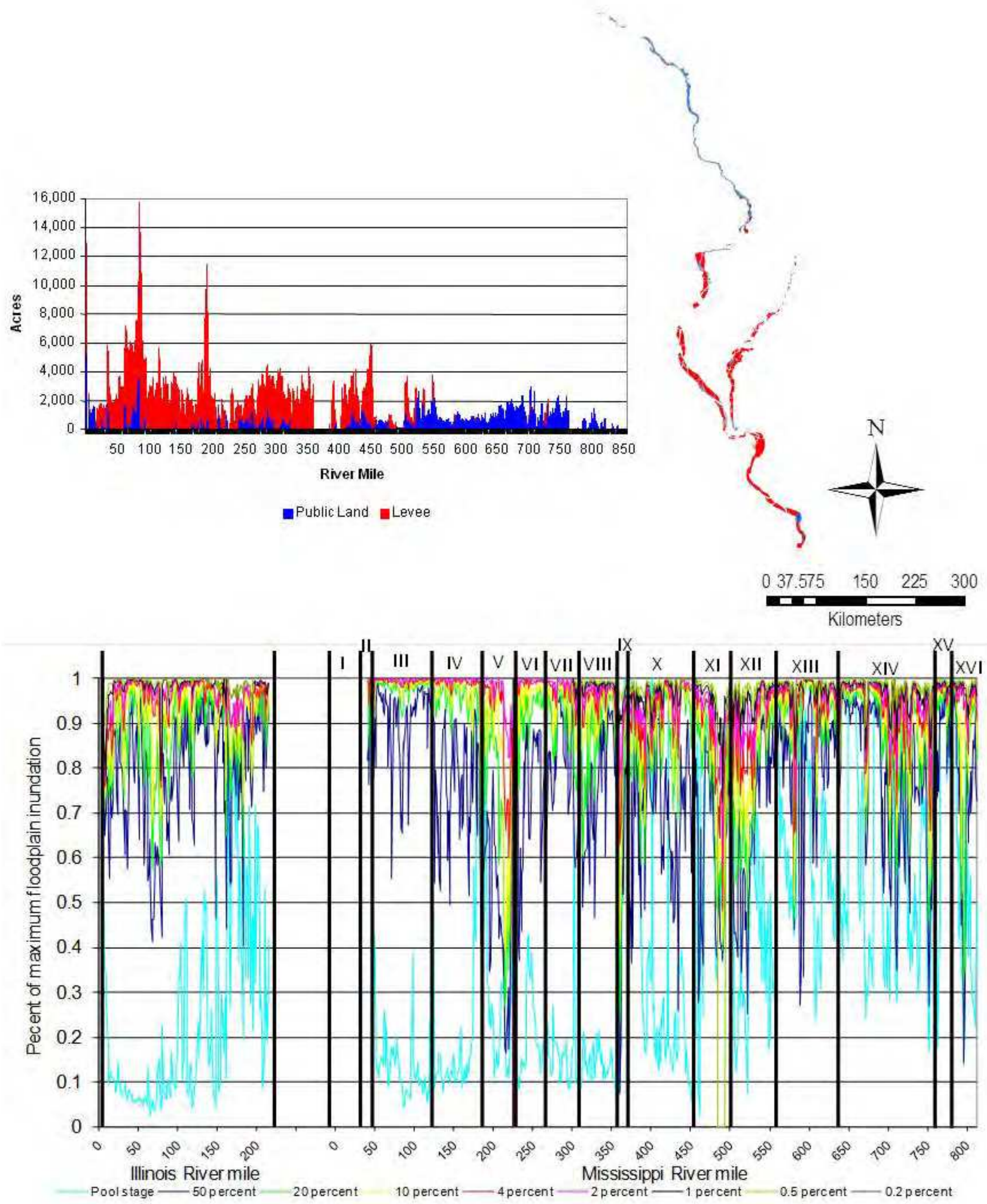


Fig. 8. Simulated floodplain inundation (bottom) and levee distribution by river mile.

Levees impede the flooding simulated above and prevent floodwater distribution in the floodplain south of river mile 450 (Figure 8). Most UMRS levee districts were established more than 100 years ago, and they occur as independent, quasi-political entities that have taxation and other authority for residents within their boundaries (Thompson., 2002). They have been hugely successful in preventing inundation during high frequency flood events with only a few significant disasters (Belt, 1975; Interagency Floodplain Management Review Committee, 1993; Galloway 2008). Levees and the development they protect have greatly altered hydro-ecological drivers and land cover in the floodplain.

### 3.3 Hydrogeomorphic methodology

Our HGM maps are relatively simple deterministic models that select various combinations of hydrology, geomorphology, and soil to map individual community distribution (Figure 9) which are integrated to produce potential vegetation estimates (Figure 9). Potential vegetation (HGM) maps (Figure 10) have been produced for several Mississippi River Reaches (Heitmeyer, 2008a; 2010) and many individual refuges or restoration sites

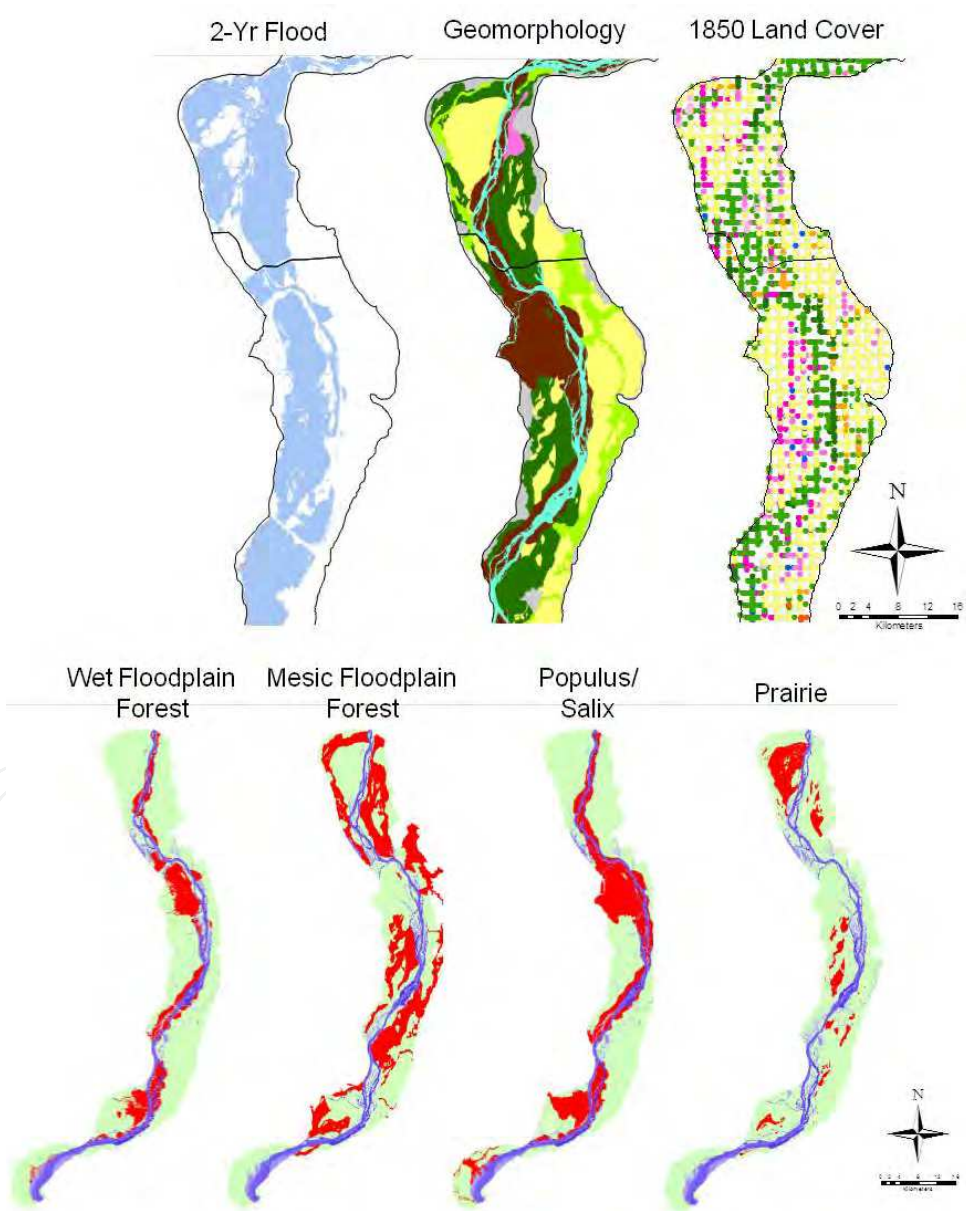


Fig. 9. Hydrogeomorphic Data layers and examples of deterministic model results.

(Heitmeyer and Westphal, 2007; Heitmeyer, 2008b). Each HGM evaluation is much more than simply combining GIS layers. An HGM evaluation reviews the physical setting, climate and hydrology, and the distribution and characteristics of presettlement habitats to establish a potential natural landscape. The HGM then reviews changes due to development and succession to make restoration and management decisions based on the likelihood of natural communities to recover from disturbance and in light of future disturbances. Potential vegetation maps assembled from hydrologic, geomorphic, and soils data are simply tools to visualize and quantify landscape response to management actions.

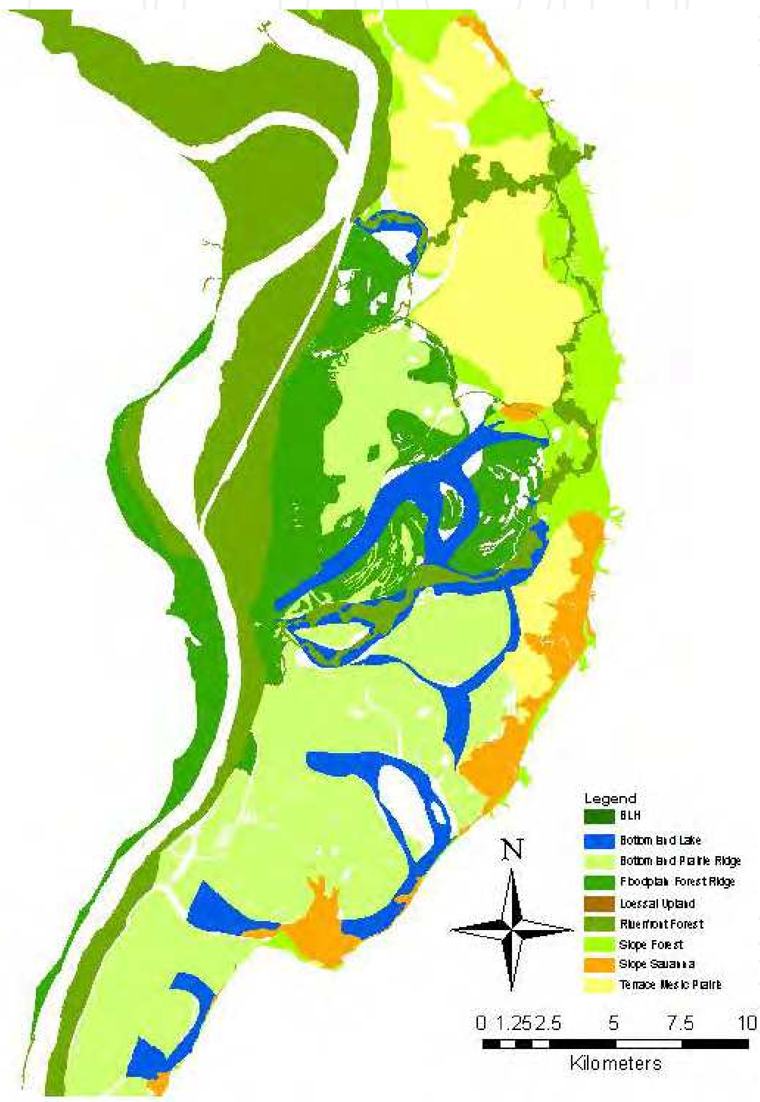


Fig. 10. A portion of a HGM map for the St. Louis region.

The near term intent is to complete an initial set of potential natural vegetation maps to help inform forest and land management plans for the entire UMRS (National Great Rivers Research and Education Center, 2010). The hydrology and geomorphology base layers described above were an important precursor to the rapid completion of the project. When the initial potential vegetation maps are complete, or as project needs dictate, potential vegetation maps for alternative floodplain management plans can be modeled to estimate environmental benefits that may accrue from restoration and management actions. Ultimately, these plant community models may be used in more comprehensive ecosystem services models that incorporate dynamic hydrology and ecosystem feedback loops that simulate complex functional processes of riverscapes (Thorp et al., 2006, 2008).

## 4. Discussion

There are many environmental and economic management needs that can be addressed with ecosystem modeling. Hydraulic models have become so precise that their results are routinely used for engineering design to simulate alternative design features (Silberstein, 2006). We believe the HGM approach for potential vegetation community assessment can achieve a similar standard for ecosystem restoration alternative analysis. The methods are not precise to species levels, nor very small spatial scale, at this stage of development but they do match well with the scale of most wildlife refuges and management areas that are the focus of most natural resource management and restoration activity. They also scale nicely for landscape ecology metrics and regional ecosystem management (USACE, 2011). HGM models have been developed for many floodplain systems (Klimas et al. 2009; U.S. Army Corps of Engineers, 2010), and they gain wide agency acceptance when developed collaboratively between managers and scientists.

These HGM methods for the UMRS are still quite simple in their statistical capacity and ability to model land cover occurrence. Future work will explore more rigorous landscape metrics that examine adjacency of land cover classes and associations with physical landscape features. The fundamental premise of the Hydrogeomorphic Method (HGM) is that vegetative communities segregate according to a single, or some combination of landscape features (e.g. geomorphology, hydrology, soil type). Indeed floodplain topography influences the frequency and duration flooding, which both directly influences plants via control over the length of oxic and anoxic phases, and indirectly influences plant communities by changing the physical properties of the soil (e.g. texture, pH, fertility). However, few studies have quantified the degree to which different plant communities segregate along key environmental gradients. By quantifying nonrandom associations among hydrology, soils and vegetation, land managers can increase their odds of successfully matching species and community types to suitable site conditions, thereby improving the odds of successful restoration.

To test the hypothesis that various plant communities segregate according to a given landscape feature or some combination of landscape features, an electivity index can be used (Jacobs, 1974; Jenkins, 1979; Pastor and Broschart, 1990). An electivity index calculates the juxtaposition of one cover type from one GIS data layer with some other landscape feature in a separate data layer.

These methods allow one to empirically test the hypothesis that a particular vegetation cover class 'elects' for a given landscape feature. If a particular cover class indeed elects for a given landscape feature, then it provides land managers with a prescription of broad-scale conditions that may be required for successful establishment of a given plant community under a given set of environmental conditions (Dr. Nathan DeJager, U.S. Geological Survey, Upper Midwest Environmental Sciences Center, La Crosse, Wisconsin, contributed text).

A multiple reference condition analysis has been proposed for UMRS ecosystem restoration planning (Nestler and Theiling, 2010). Sufficient data exist to evaluate hydrologic and geomorphic ecosystem drivers and land cover in presettlement, several historic snapshots, and contemporary conditions for nearly the entire 2.8 million acres. The virtual reference condition (i.e., simulated hydrology, potential vegetation, or geomorphic features), or plausible alternative future condition, is an important tool to estimate future without project condition and the response to alternative restoration plans (Figure 11; USACE, 2000). It is possible to simulate alternative floodplain management scenarios and extrapolate benefits as simple acreage estimates (Figure 11, bottom), potential vegetation (Heitmeyer, 2008; 2010), or any range of habitat suitability (USFWS, 1980) or ecosystem services metrics that can be attributed to potential land cover estimates.

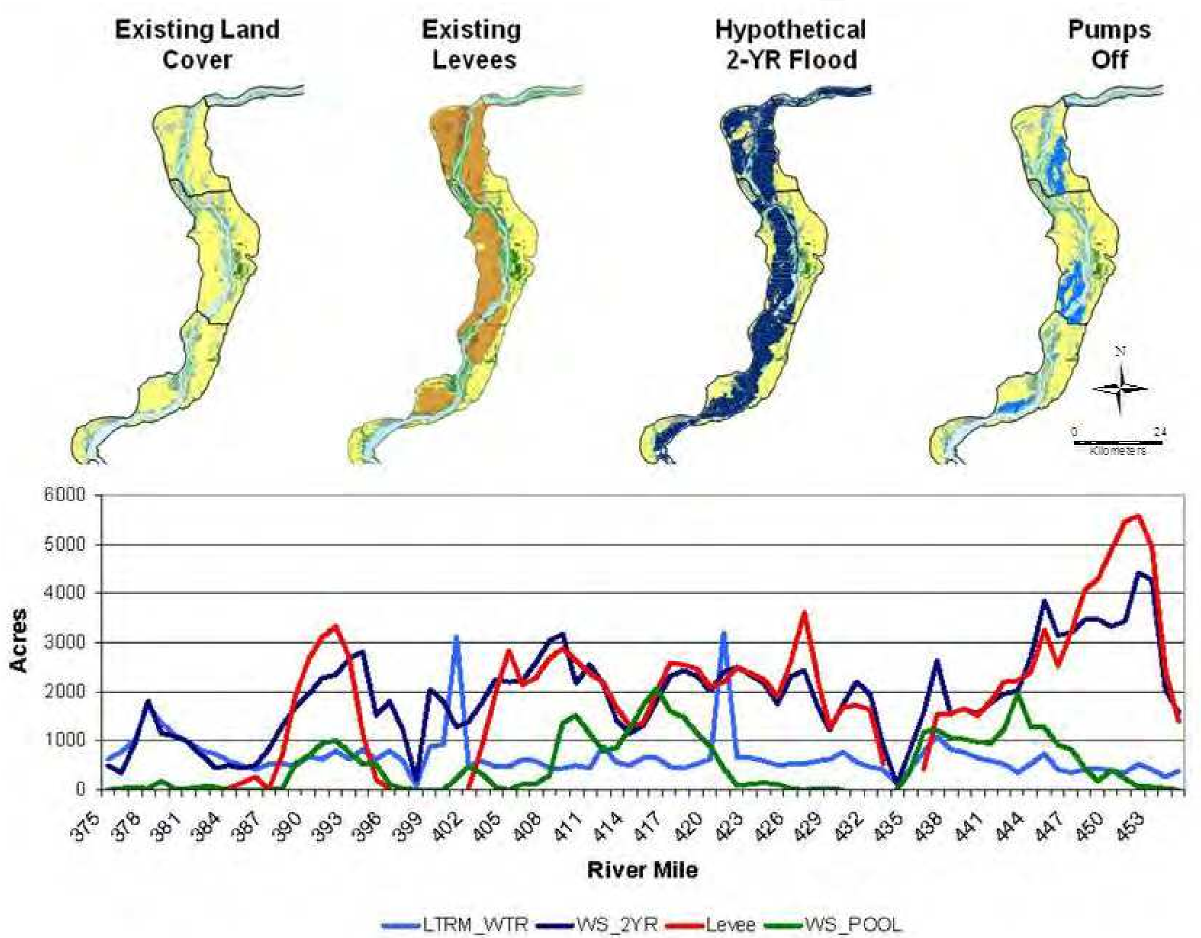


Fig. 11. Examples for UMRS benefits that may be attained by alternative floodplain management plans. LTRM_WTR = low flow surface water, WS_2YR = 50 percent exceedence/2-year flood, Levee = leveed area, WS_Pool = potential inundation under Pumps Off scenario.

## 5. Acknowledgements

An Army Corps of Engineers, Long Term Training Program grant from the Rock Island District and Headquarters supported much of Dr. Theiling's effort. The U.S. Army Corps of Engineers, St. Paul, Rock Island, and St. Louis Districts collaborated on archaeological investigations, flow frequency analyses, and flood risk assessments that provided data that were adapted for this study. The Upper Mississippi River Environmental Management Program administered by the U.S. Army Corps of Engineers and U.S. Geological Survey supported land cover mapping, future landscape analysis recommendations, and technical assistance. The U.S. Army Corps of Engineers, Navigation and Ecosystem Sustainability Program provided support to Dr. Theiling and Dr. Heitmeyer. Finally, The Nature Conservancy Great Rivers Partnership graciously supported development of the system-wide presettlement land cover data through a grant to the University of Wisconsin Department of Forest Ecology and Management.

Many individuals supported data development and analysis: John Burant – U.S. Army Corps of Engineers, Nathan DeJager – U.S. Geological Survey, Tim Fox – U.S. Geological Survey, Edwin Hajic – Illinois State Museum, Ken Lubinski – U.S. Geological Survey, David Mladenoff – University of Wisconsin - Madison, J.C. Nelson – U.S. Geological Survey, John Nelson – Illinois Nature Preserves Commission, Jim Ross – U.S. Army Corps of Engineers, Michael Reuter – The Nature Conservancy, Ted Sickley – University of Wisconsin - Madison, Paul West – The Nature Conservancy.

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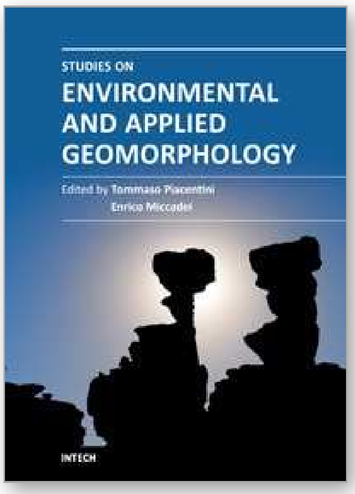


**Studies on Environmental and Applied Geomorphology**
Edited by Dr. Tommaso Piacentini

ISBN 978-953-51-0361-5
Hard cover, 294 pages
**Publisher** InTech
**Published online** 21, March, 2012
**Published in print edition** March, 2012

This book includes several geomorphological studies up-to-date, incorporating different disciplines and methodologies, always focused on methods, tools and general issues of environmental and applied geomorphology. In designing the book the integration of multiple methodological fields (geomorphological mapping, remote sensing, meteorological and climate analysis, vegetation and biogeomorphological investigations, geographic information systems GIS, land management methods), study areas, countries and continents (Europe, America, Asia, Africa) are considered.