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Upper Mississippi River System Hydrogeomorphic Change Conceptual Model and Hierarchical Classification

Open-File Report 2024–1051

U.S. Department of the Interior
U.S. Geological Survey

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U.S. Geological Survey, Reston, Virginia: 2024

Suggested citation:
Fitzpatrick, F.A., Rogala, J.T., Hendrickson, J.S., Sawyer, L., Stone, J., Erwin, S., Brauer, E.J., and Vaughan, A.A., 2024, Upper Mississippi River System hydrogeomorphic change conceptual model and hierarchical classification: U.S. Geological Survey Open-File Report 2024–1051, 24 p., https://doi.org/10.3133/ofr20241051.

ISSN 2331-1258 (online)

Acknowledgments

The authors would like to thank the participants of the 2018 workshop for their input and necessary guidance and expertise on factors affecting the geomorphology of the Upper Mississippi River System as well as the history and background on available datasets that could help define the river's hydrogeomorphic change based classification scheme. Special thanks go to Molly Van Appledorn who spent much time connecting the team to the Upper Mississippi River System floodplain inundation attributes. Jeff Houser provided needed connections to potential ecological applications and manuscript reviews. We would also like to thank the additional unnamed reviewers who helped improve and clarify the contents of this report.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)

Abbreviations

CES	cumulative effects study
GIS	geographic information system
HGM	hydrogeomorphic method
HGU	hydrogeomorphic unit
HNA	habitat needs assessment
HREP	habitat protection rehabilitation and enhancement
LFA	landform sediment assemblage
LTRM	long term resource monitoring
UMRR	Upper Mississippi River Restoration
UMRS	Upper Mississippi River System
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

Upper Mississippi River System Hydrogeomorphic Change Conceptual Model and Hierarchical Classification

By Faith A. Fitzpatrick,[1] James T. Rogala,[2] Jon S. Hendrickson,[3] Lucie Sawyer,[4] Jayme Stone,[5] Susannah Erwin,[6] Edward J. Brauer,[4] and Angus A. Vaughan[1]

Abstract

Understanding the geomorphic processes and causes for long-term hydrogeomorphic changes along the Upper Mississippi River System (UMRS) is necessary for scientific studies ranging from habitat needs assessments, sediment transport, and nutrient processing, and making sound management decisions and prioritizing ecological restoration activities. From 2018 through 2020 the U.S. Geological Survey and U.S. Army Corps of Engineers led a series of calls and meetings, and a workshop to develop a draft UMRS hydrogeomorphic change conceptual model and hierarchical classification scheme. This project was funded through an Upper Mississippi River Restoration 2018 science in support of restoration proposal entitled, “Conceptual Model and Hierarchical Classification of Hydrogeomorphic Settings in the Upper Mississippi River System.” This report documents the background leading up to and the major findings from the workshop. The resulting conceptual model focuses on the drivers and boundary conditions that affect the major hydrogeomorphic processes along the valley corridor using a continuum of spatial and temporal scales and resolutions. The draft hierarchical classification was based on three existing and three new nested geospatial datasets that ultimately can be used to characterize hydrogeomorphic settings that span the UMRS valley corridor. The conceptual model and hierarchical classification will help characterize recent (mid-1990s through mid-2010s) decadal-scale processes and sources for potential hydrogeomorphic change that span a range of spatial scales from watershed hydrology and sediment sources to channel hydraulics and sediment transport.

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Introduction

The Upper Mississippi River Restoration (UMRR) program covers 2.7 million acres across the Upper Mississippi River System (UMRS), including the Illinois River (fig. 1). The 1986 Water Resources Development Act (Public Law 99–662) recognized the importance of the UMRS for both aspects and authorized the U.S. Army Corps of Engineers (USACE) to implement the UMRR Program in consultation with the Secretary of Interior and the adjacent States. The program has two elements: monitoring, research, and analysis (long term resource monitoring [LTRM]), and habitat protection rehabilitation and enhancement (HREP).

The LTRM and HREP components of the UMRR acknowledged a need for more context of the river’s hydrogeomorphology across aquatic and terrestrial settings, especially regarding areas that are prone to hydrogeomorphic change. The LTRM is done annually in six study reaches and trend pools and includes water quality, aquatic vegetation, fish, standardized study design and methods, and centrally stored and publicly available data in a variety of formats. The six study reaches include pools 4, 8, and 13; La Grange Pool; pool 26; and open river Jackson, Missouri. Initially the program had a component for monitoring bathymetry, but this was disbanded. Long-term monitoring is needed in the UMRS because of its complex ecologic and navigational significance. In addition, a high-level synthesis of existing studies and more recent data collection and mapping efforts was needed to better design and prioritize future research and monitoring associated with the HREP element of UMRR.

In 2018, a core team of scientists was assembled to develop a conceptual model for hydrogeomorphic change and begin to outline a hierarchical classification scheme with the combined knowledge gained from a broad panel of expert geomorphologists, engineers, and physical scientists with regional expertise in a workshop setting (appendix 1). The workshop panel covered the background and history of geomorphic classification schemes and UMRR-related geographic information system (GIS) datasets available for possible use in the classification. The approach included incorporation of research results and restoration activities that had taken place after the completion of a cumulative

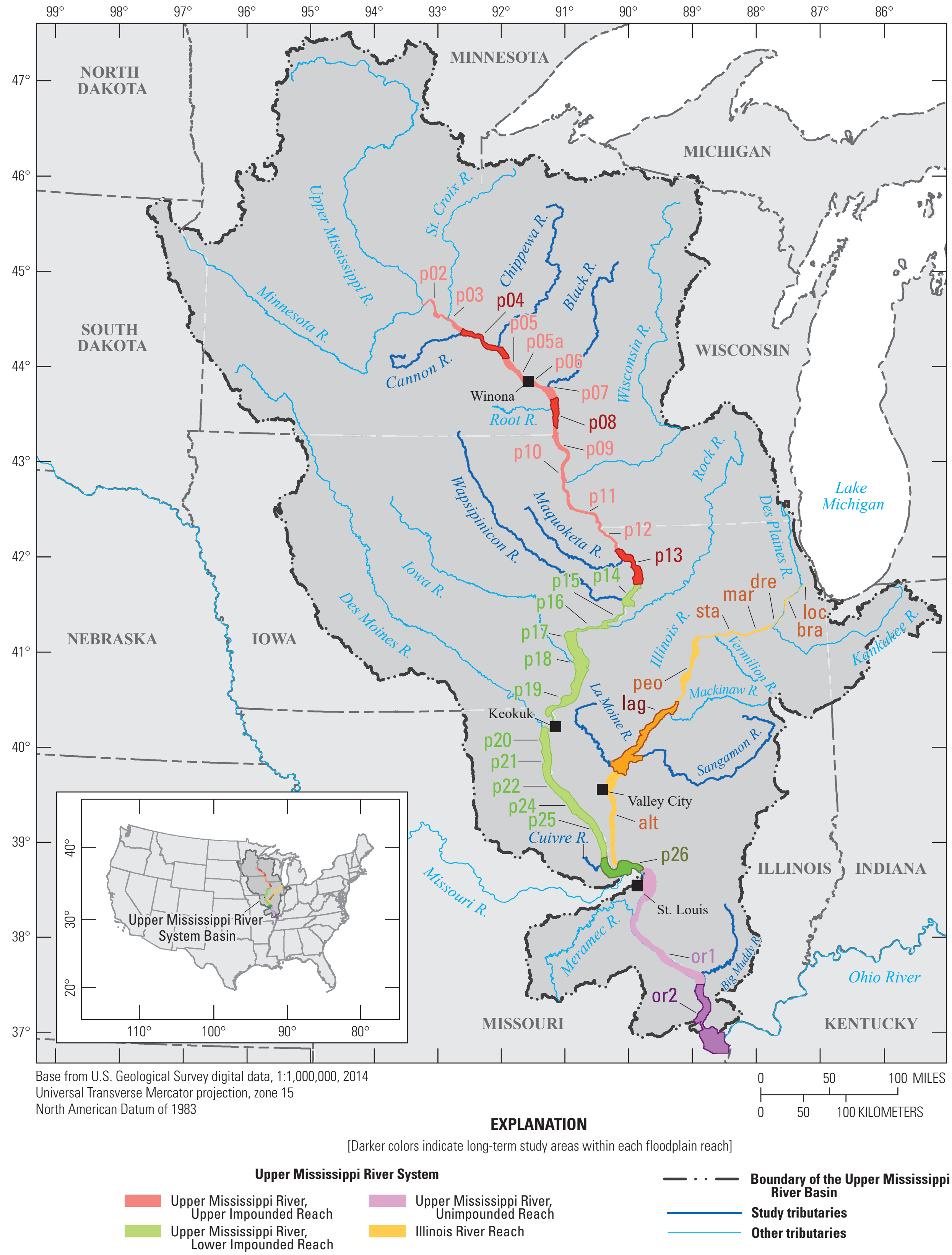


Figure 1. The Upper Mississippi River System as part of the Upper Mississippi River Restoration Program (from Houser and others, 2022).

effects study (CES) in 2000 (WEST Consultants, Inc., 2000). A feasibility investigation of hydrogeomorphic modeling and analyses for the UMRS had also been published with relevant information (Heitmeyer, 2007). The 2018 workshop included the following specific goals and outcomes:

- Development of a draft conceptual model for the UMRS, which included potential for hydrogeomorphic change relative to climate and land-use change, tributary inputs, lock and dam impoundment effects, and other infrastructure.
- Identification of the potential components of a hierarchical classification system of hydrogeomorphic change that potentially includes sedimentation and flow patterns, processes, and rates in the UMRS.
- Application of the draft conceptual model and hierarchical classification system to an example reach of the UMRS.
- Development of a plan for future classification, mapping, and visualization. A goal of the project was to define hydrogeomorphic units along the entire valley corridor of the UMRS to help inform managers regarding the type, location, and amount of restoration techniques, as well as evaluate the success of those restoration techniques.

The idea for the hydrogeomorphic change conceptual model and classification was introduced by Schumm (1977) to describe the river continuum of geomorphic processes and channel forms in relation to predictable zones of erosion, transport, and deposition in a stream network. During the last couple of decades, there have been several classifications developed for large rivers that describe geomorphic response potential; relative stability of channel types related to type and amount of sediment load, sediment size, flow velocity, and slope; and floodplain-river interactions (Nanson and Croke, 1992; Fryirs and Brierley, 2000; Church, 2002; Thorne, 2002; Fryirs, 2003; Buffington and Montgomery, 2013; Wheaton and others, 2015; Fryirs and Brierley, 2022). Integration of hydrogeomorphology with ecology has been a long-term priority for science and management actions at international levels for more than a decade (Vaughan and others, 2009).

A system-wide conceptual framework helps river managers and decision makers with a context-based understanding of how the current geomorphology of the river is potentially changing. Characterization of geomorphic forms with processes can be assessed relative to historical changes and how human alterations or climate change may affect future trajectories of change (Grabowski and others, 2014; Belletti and others, 2017). This understanding can facilitate future rehabilitation techniques and project selection, prioritization, and expected longevity regarding areas with the potential for erosion and sedimentation. For project implementation, challenges included predicting backwater sediment deposition, altered connectivity, shoreline erosion, and floodplain forest mortality. Opportunities included development of a qualitative baseline sediment deposition and erosion map and analysis of the experimental design of restoration features compared with geomorphic scale and how they interact to potentially accelerate deposition in backwaters and affect habitat resilience. The hydrogeomorphic change framework provides critical information for river managers and decision makers to prioritize restoration actions within the HREP. Key needs for restoration are identification of areas of habitat needs and habitat resilience. Key habitat questions include what habitats are most affected by hydrogeomorphic change, where are they, how are they changed, and were restoration efforts successful?

Of special interest for the UMRR is how historical (for example, lock and dam systems) and new structures (for example, constructed islands) affect flows and sedimentation patterns. Also, potentially changing tributary inputs of sediment and flow are of interest, with such inputs considered boundary conditions for studies focused on the UMRS main stem and its valley. Causes for and trajectories of sedimentation of pools in backwater lakes was also a major interest (Rogala and others, 2020b).

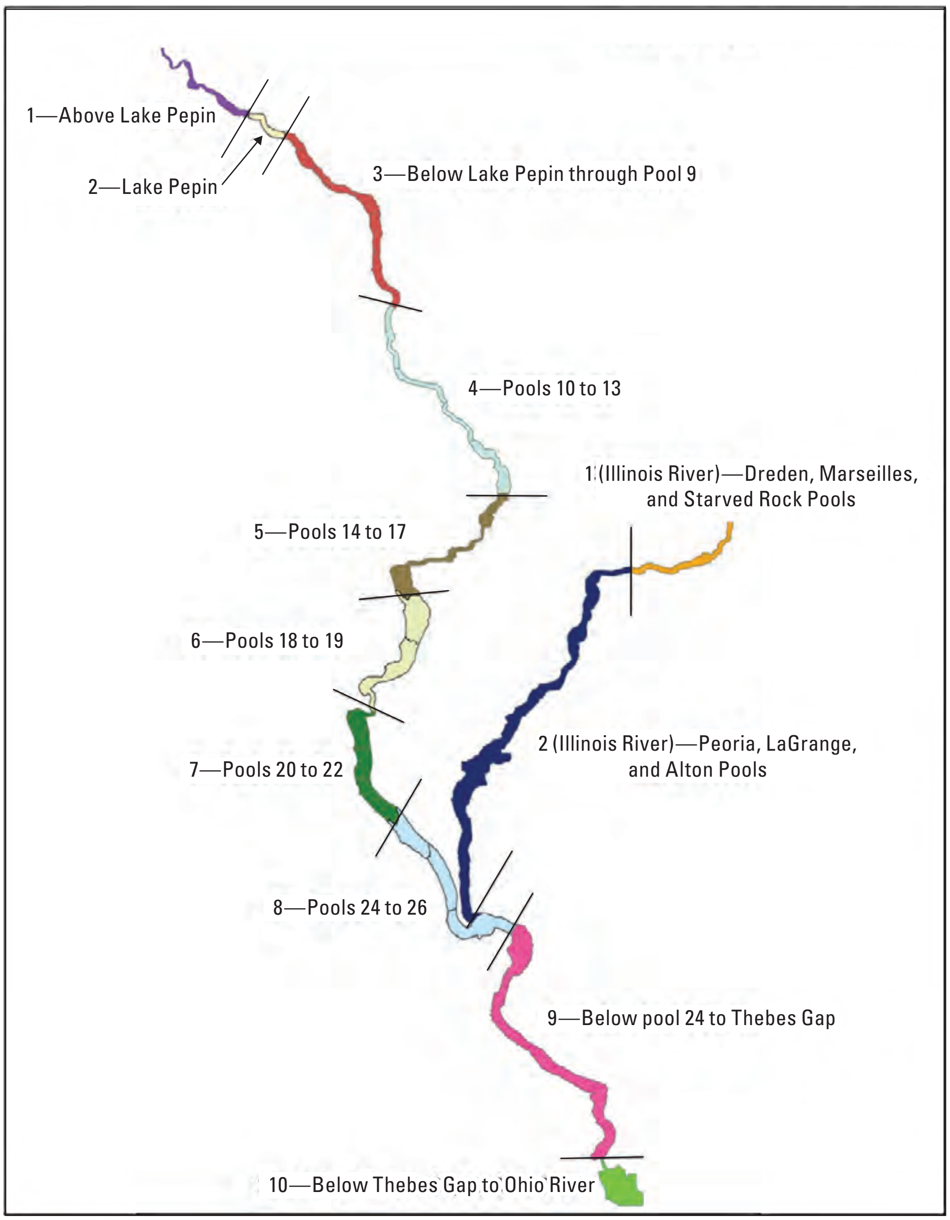
This report documents the approach and results from the development of a hydrogeomorphology-based conceptual model and hierarchical classification system for the UMRS. The report contains a summary of previous studies and existing geospatial data layers that were reviewed and considered for helping to build a classification system. Also included are a draft application of the conceptual model and classification, and future needs and next steps for full development. The resulting model and classification system were developed from the combined efforts of a core team of scientists and engineers from the U.S. Geological Survey (USGS) and USACE aided by a wider panel of workshop participants that helped to cover the large spatial extent and range of environmental settings along the UMRS, as well as connect with other related ongoing and past work. An important component of this project was to begin to explore and update the UMRS GIS database and query tools.

Previous Studies and Existing Geospatial Data

As part of the core meetings and 2018 workshop, existing studies and geospatial datasets were examined and summarized with the goal of potential use in a hydrogeomorphic change mapping system. The following descriptions of previous studies and existing datasets were extracted from core team and workshop meeting minutes. The descriptions are not all-inclusive but are focused on the potential application of the datasets to the development of the conceptual model and hierarchical classification.

Cumulative Effects Study

A CES (WEST Consultants, Inc., 2000) for the UMRS addressed how the navigation projects affected the river environment. In addition, one goal of the CES was to predict future conditions for the year of 2050, including potential changes related to tributaries, levees, land use, climate change, and floods. The first volume of the CES report contained the results of a broad geomorphic assessment compiled by a board of consultants and a USACE support team consisting of engineers, hydrologists, and geomorphologists familiar with the Upper Mississippi River. The CES identified UMRS geomorphic reaches by longitudinal profile and location of dams, including 10 reaches on the Mississippi River and two on the Illinois River (fig. 2). When identifying reaches, effects of tributaries and the associated deltas were considered. The longitudinal profile had not been updated since 2000 (fig. 3; WEST Consultants, Inc., 2000). The CES described the geologic background that informed the reach designations. These geomorphic reaches were slightly refined later with more information on geomorphic controls, including levees, for floodplain inundation studies (Theiling and Burant, 2013).



Data from WEST Consultants, Inc. (2000)

Figure 2. Geomorphic reaches (segments) of the Upper Mississippi River System (WEST Consultants, Inc., 2000).

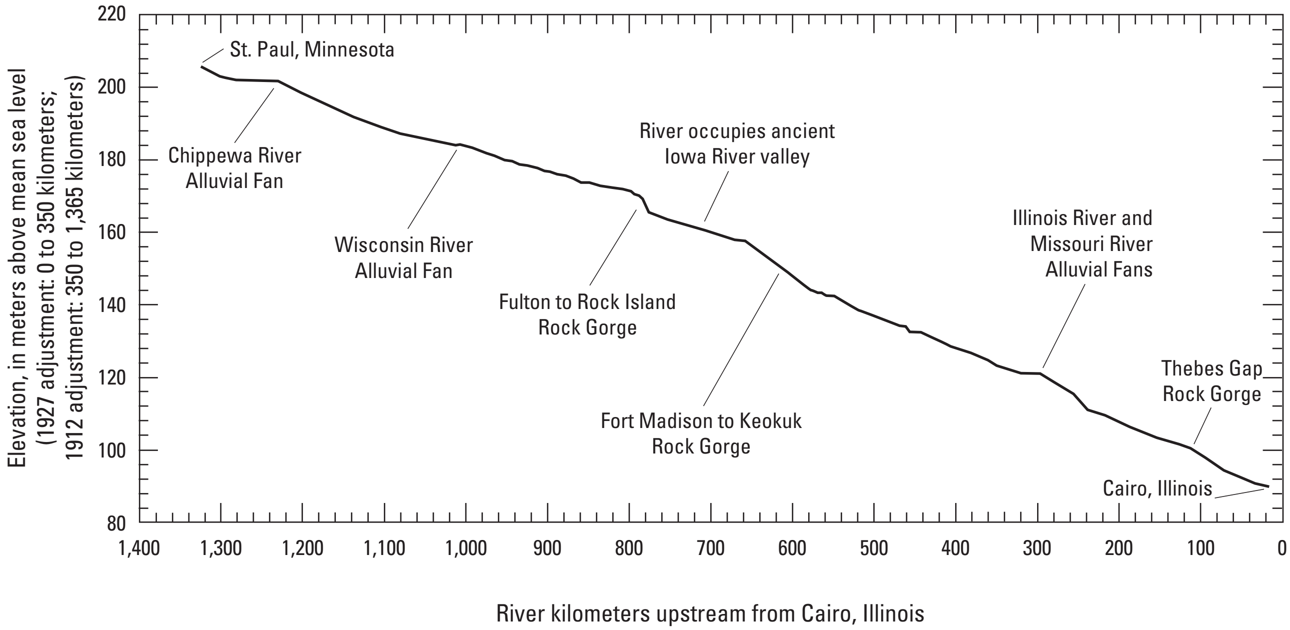


Figure 3. Longitudinal profile of the Upper Mississippi River (WEST Consultants, Inc., 2000).

The CES included sediment budgets for two-time periods, 1930s–1950s and 1950s–2000, for the main channel and pools 11 through 26. Unknowns in the sediment budget included off-channel sediment storage and changes in tributary loads over time. Bedload was measured for tributaries including the Chippewa, Black, and Wisconsin Rivers (Rose, 1992). If no other bedload data were available, tributary inputs were calculated assuming bedload was 10 percent of the total sediment load. Dredging records from USACE District Offices helped in completing the sediment budgets. Tributary and main-stem loads may have decreased over time because of storage in tributary reservoirs and improved watershed land use, including soil conservation practices.

Conclusions and recommendations from CES included the need for more research on the following topics:

- Effects of climate change and global warming on hydrology and sediment transport
- Sedimentation in backwater areas and possible loss of habitat diversity
- Loss of continuous and isolated backwaters
- Role of secondary channels in changing backwater habitats
- Several topics specific to sediment transport
    - o Contributions of suspended-sediment loads and bedload from gaged and ungaged tributaries
    - o Contributions from bank erosion
    - o Changes in reservoir trapping efficiency

During the 2018 workshop, attendees were able to re-examine the CES's 50-year projections for geomorphic conditions and to refine mechanisms driving the patterns in geomorphic change. The following considerations related to the CES were identified during the 2018 workshop:

- The 2050 CES predictions need to be reviewed and the CES's descriptions of the mechanisms driving the patterns in geomorphic change need to be refined. This could include a review of the forecasts for 1950–2000 and analysis of decadal based changes perhaps driven by climate change.
- Physiographic regions need to be grouped by their glacial geology to determine if there are geographic differences that were not apparent for physiographic regions.
- Available data for the 2000–20 period need to be examined to determine if overall floods and tributary sediment loads are decreasing as expected from land-use changes, with exceptions such as Lake Pepin owing to documented increasing sediment loads on the Minnesota River.
- Determine if isostatic rebound of glacial bulge areas (terminus of Wisconsin, Illinoian, and pre-Illinoian glacial margins) are evident in longitudinal profile deviations in tributaries and the main stem and need to be considered as a driver of geomorphic change.
- How hydraulic models and sediment data and models can be used for describing the potential for geomorphic change needs to be explored. There are

two-dimensional hydraulic models available for pools 5, 8, 13, 21, and 26 for the 2-year flood event. Pool areas were assigned velocity groupings of high (greater than 0.45 meter per second), medium (0.45 to 0.15 meter per second), and low (less than 0.15 meter per second) velocity. Sediment data are available for all pools from navigation dredging projects to describe particle size and sediment chemistry. Most of the navigation channel was medium-sized sand, coarsening upstream and fining downstream. Pools 4, 5, 6, and 8 had sediment transport models (River Resources Forum–Water Level Management Task Force, 2013; Nelson, 2020; Nelson and others, 2022).

- Causes for spatial heterogeneity in backwater sedimentation rates need to be investigated.
- How climate cycles and potential changes in flood characteristics have interacted with land-use changes need to be considered.
- The previous assumptions that reservoir trapping rates were constant, and that bank erosion was a small fraction of total sediment load and therefore was considered negligible need to be explored.
- Projections for geomorphic changes, mostly along the main channel, need to be described.

The 2018 workshop participants also identified more near-term followup actions for the CES, which included updating the longitudinal profile with available water-level datasets and overlaying the more detailed profile with existing reaches to see if any followup was needed for reach designations.

Aquatic Areas and Habitat Needs Assessments

The UMRS aquatic areas classification system was developed by Wilcox (1993) using systemic land-cover data for 1989 from photography as a baseline land/water coverage. Using rules developed by Wilcox (1993), linework was completed to delineate aquatic area types. Aquatic areas included channel, off-channel contiguous, off-channel isolated, and floodplain categories, with additional subclasses in a hierarchical system. This expanded the geomorphic classification scheme that had been started with the CES and offered additional information for the core team and 2018 workshop participants to review as a potential aid for mapping hydrogeomorphic units that might be more susceptible to geomorphic change based on their proximity to the main channel.

A GIS query tool was developed for the habitat needs assessments (HNAs) I (Theiling and others, 2000) and II (McCain and others, 2018). The HNA I relied on expert opinion for determining existing condition, forecasted future, and desired future conditions (hence habitat needs). Resource managers used existing spatial data for the HNA I, rather than specific input from geomorphology or engineering experts. Locations of projected change were mapped including loss of contiguous/isolated backwater, tributary delta formation, and island dissection.

The HNA II indicators report (De Jager and others, 2018) contains a re-analysis of the HNA I aquatic areas at three levels and was useful for the core team to further define the potential hydrogeomorphic classification levels and hydrogeomorphic units that could be included in the hierarchical classification. Level 1 HNA classification was simplified to develop categories that could be mapped with confidence; for example, off-channel classes were collapsed at this level. Level 2 further delineated Level 1 classes using bathymetry and land-cover data to distinguish different off-channel and side channel classes. Level 3 delineated structured and unstructured main channel borders and contained a wide variety of metrics calculated for each polygon region. Metrics included in the mapping were extent of different anthropogenic structure types, inundation depths, sill (measure of depression, depth, and connectivity), vegetation, forest perimeter, wind fetch, perimeter mapped as channel, shoreline development index, and position of connections (upstream compared with downstream location, which is a metric of flow going through the backwater).

Planform Change Mapping

Coincident with this study was a study focused on mapping planform changes through overlays of 1989, 2000, and 2010 land-cover/land-use maps (Rogala and others, 2020a; Rohweder, 2019). Changes in the vegetation classes in the land-cover/land-use maps were the basis for identifying new areas of land in the planform change mapping. Willow, and secondarily wet meadow, were especially important for reflecting new fluvial landforms. The dataset was determined to be important for developing the conceptual model because it described the location and mechanisms of hydrogeomorphic change in the UMRS. A particular focus of the study was depositional features common in large rivers, especially those with numerous impoundments.

Planform changes during two time periods (1989–2000 and 2000–10) were classified based on a combination of geomorphic form, origin of sediment, geomorphic process, and proximity to existing terrestrial land (Rogala and others, 2020a). Classes included tributary delta, crevasse splay/delta, impounded delta, and bar-tail limbs. The first three delta-related areas had lenticular forms arranged in fan shapes and were generally downstream from distributary channels. The bar-tail limbs were along the margins of a main or side channel and had more linear forms. Many new depositional features were not classified into one of the four main types. The amount of area of new fluvial landforms was similar between the two time periods, with about 350 hectares of depositional bars added across the UMRS in each period (fig. 4). These features illustrated areas of hydrogeomorphic change resulting from a potential combination of hydrologic drivers, hydraulics, and sediment inputs at multiple spatial scales. Important factors affecting the spatial distribution of change areas included location within the impoundments, tributary entrants along valley sides, and proximity to the main channel and levees.

Obstacles to overcome in the change mapping were georeferencing errors, water-level effects, effects of seasonality and age on new vegetation, and subjectivity in methods used to derive polygons. Areas with planform change were mapped if larger than 0.1 hectare. The adjacency of new landforms to existing terrestrial land was also tracked in this dataset.

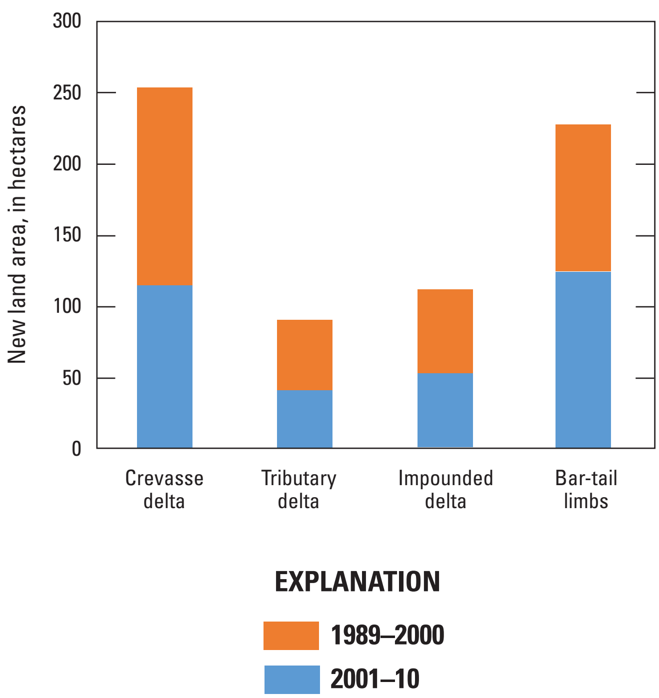


Figure 4. Area of new land masses in the Upper Mississippi River System for two time periods (Rogala and others, 2020a).

Landform Sediment Assemblages

Landform sediment assemblage (LSA) maps covered four terrestrial mapping extents of the UMRS: pools 1–10 (Madigan and Schirmer, 2001), pools 11–22 (Bettis and others, 1996), the Illinois River (Hajic, 2000), and the Middle Mississippi River (Hajic and others, 2006). Each of the four mapping efforts had different methods and classification systems with varying levels of resolution. A unified UMRS-wide layer was compiled and documented by Theiling and others (2012), but it was determined to have limited application for the conceptual model and hierarchical classification because it resulted in too much generalization after the unification. The purpose of the original LSA mapping was to describe surface or buried cultural resources and relied heavily on subsurface/core information. The UMRS-wide LSA layer of Theiling and others (2012) was created by collapsing the different classification systems and correlating them into a unifying classification system. The unified LSA maps had valley-bottom surfaces categorized into broad “floodplain” types. These types did not distinguish older point bars, backswamps, and recent chutes and bar features that are important for understanding how the hydraulics and sediment transport are manifested in geomorphic features.

Hydrogeomorphic Method

A hydrogeomorphic method (HGM) for hydrogeomorphic modeling and analyses of the UMRS floodplain was developed by Heitmeyer (2007) to help evaluate ecosystem and management options for the UMRS. The goals of the HGM were like the goals for this study except they were limited to the terrestrial portions of the UMRS. Additional goals of the HGM were to identify alterations following pre-Euro American settlement and construction of the lock and dam system.

The matrix style of the approach was feasible at the time because there was enough available historical and current geomorphic, hydrologic, and ecological data in a GIS to understand how historic conditions and physical setting likely affected floodplain vegetation and ecological communities. The study identified eight datasets needed to develop the HGM approach: (1) soils, (2) geomorphology, (3) topography/elevation, (4) hydrology and flood frequency, (5) aerial photographs and cartographic maps, (6) land cover and vegetation communities, (7) presence and distribution of key plant and animal species and habitats of concern, and (8) physical anthropogenic features. The geomorphology relied mainly on the LSA maps, as well as surficial geology maps, with the recognized limitation that the LSA maps lacked the mapping resolution needed for defining geomorphic mapping units within the floodplain. Maps that covered the middle and lower portions of the Mississippi River included a channel change map (Brauer and others, 2005), geomorphology and Quaternary history (Saucier, 1994; Woerner and others, 2003), and landform maps for river miles 855–614 of the Mississippi River. The recommendations from the study included that HGM evaluations be done on an ecoregion basis compiled by major river area within a systematic framework of data gathering and field verifications. It was recommended that the work take place in the UMRS from south to north to connect the HGM evaluations from the middle portion of the Mississippi River.

The HGM approach was later used for bottomland restoration and potential vegetation mapping in the UMRS (Theiling and others, 2012). This study recognized the importance of hydrology, hydraulics, and geomorphic setting as drivers for potential floodplain vegetation models. The

GIS-based methods included assembling the eight sets of data types listed in the previous paragraph. From these overlays, on a river-mile basis, nine vegetation types were mapped in the hydrogeomorphic classification: open water, bottomland lake, riverfront forest, floodplain forest (ridges/swales), bottomland hardwood forest, slope forest, savanna, bottomland prairie (wet/intermediate), and mesic prairie. Each of these vegetation types had a unique combination of geomorphic landforms, soil types, and flood frequencies. It was hoped that having site conditions better mapped would increase the success of the restoration efforts while also providing a means to test alternative approaches.

Floodplain Inundation Model

The UMRS floodplain inundation model, also called the surface water connectivity model, was developed by Van Appledorn and others (2018, 2021) to expand the range of modeled flood magnitudes to include more high frequency events than the existing USACE 1-dimensional hydraulic model (U.S. Army Corps of Engineers, 2004) that focused on large, infrequent floods. The goal of the UMRS floodplain inundation model was to systematically map the inundation regime across floodplain surfaces in a spatial gradient format that was relevant for ecological investigations and to provide a flexible framework for hydrologic inquiry. Model outputs included water depth on the floodplain at a daily time step that could be used to summarize the frequency, depth, duration, and timing of floodplain inundation. Considerations for use in hydrogeomorphic change mapping included potential sources of error and implications for terrain model, hydrologic data, and geospatial processing. Potential limitations include no hydraulic information, static terrain, and a terrestrial-only spatial extent.

Backwater Sedimentation Surveys

Repeat field-based transects of sedimentation rates in select backwaters of pools 4 and 8 were surveyed from 1997 through 2017 to assess loss of water depth and overwintering habitat for fish (Rogala and others, 2020b). The transects had varied resolution among pools but helped to document areas of hydrogeomorphic change associated with underwater sedimentation. The results can be used to validate aquatic areas prone to change and be overlaid with sensitive habitat types. In turn, future hydrogeomorphic change maps can be used to assist in understanding the broader spatial scale source and causes for sedimentation along transects. The repeat transect surveys confirmed backwater areas were filling, although at a slower rate than previously thought. Additionally, deeper areas were filling faster than those close to shore, further raising concerns about loss of pool habitat and overwintering refuge documented in other studies, such as Belby (2005). Sedimentation rates also varied spatially, with average backwater sedimentation rates in pool 8 almost double those in pool 4. Linking floodplain sedimentation and planform change maps with areas of high backwater sedimentation rates would be helpful for identifying the spatial continuity and sediment connectivity of geomorphic feature growth across terrestrial and aquatic environments. There are likely GIS-based methods that might make the transect-style of data more easily overlaid onto other aquatic mapping units.

Conceptual Model Development for Upper Mississippi River System Hydrogeomorphic Change

Conceptual models are constructed to help visualize, describe, and communicate the key components within a complex system of interest and how they interact (Jacobson and others, 2015). No studies with a specific focus on terrestrial and aquatic areas of the river system that are prone to hydrogeomorphic change from the combination of hydrology, flows, and sediment dynamics had been done for the UMRS. Geomorphology of the river is one of five major ecosystem descriptors for the UMRS and UMRR program with the other groupings of hydraulics and hydrology, biochemistry, habitat, and biota (De Jager and others, 2018). Existing conceptual models and classifications that were examined during the project included general hierarchical classification system for stream habitat (Frissell and others, 1986), river styles systems (Brierley and Fryirs, 2005), dam/interdam sequencing (Skalak and others, 2013), classifications of linearly connected geomorphic forms related to floodplain sedimentation (Lewin and others, 2017), and the lower Columbia River estuary classification system (Simenstad and others, 2011). Two other models of particular significance for identifying drivers of geomorphic processes include the model of drivers of flow and sediment in geomorphic responses and multiple feedback loops from Charlton (2008) and Newson and others (1998).

The wide range of expertise and disciplines of the 2018 workshop participants allowed for active discussion and inclusion of the major processes of hydrogeomorphic change in the UMRS that helped to construct the beginnings of a conceptual model (fig. 5). Extra attention was given to immediate needs for furthering interaction among USACE's restoration and management activities and the USGS's science in support of restoration. The brainstorming groups tallied important spatial scales, within-corridor drivers and controls, drivers and feedbacks of processes, river processes and rates, evolutionary pathways, hydrogeomorphic responses, outcomes of processes, and indicators of processes. Simplistic conceptual models of hydrogeomorphic change were aided in development by familiarization with other larger river conceptual models, such as the conceptual ecological model developed for pallid sturgeon (*Scaphirhynchus albus*) population dynamics in the Missouri River pallid sturgeon effects analysis (Jacobson and others, 2015).

This first attempt at a conceptual model for hydrogeomorphic change included recognition of the importance of sediment sources and interactions of flows in describing the dynamics of fluvial landforms (fig. 5). The ultimate focus of the conceptual model was on those geomorphic processes that produce dynamic and continually changing landforms, acknowledging that the processes reflect human and biological interactions that can change over time and understanding the processes of hydrogeomorphic change can better link science and research activities with restoration and management associated with the UMRR. The workgroup identified six scales of interest that spanned the three scales shown in figure 5 and acknowledged the importance of the dams—entire basin, subbasins (hydrologic unit code 4 level; Jones and others, 2022), the four major river reaches, the 12 geomorphic reaches, interdam sequences, and hydrogeomorphic complexes. These six nested spatial scales have elements of conceptual models and classifications of Frissell and others (1986), Brierley and Fryirs (2005), Skalak and others (2013), and Lewin and others (2017), and formed a starting point for the discussions on and the development of the UMRS hierarchical classification.

The relatively simple conceptual model that was developed illustrates drivers and boundaries at three major spatial scales: the basin, a segment of the stream network, and a section or reach of the Upper Mississippi River valley corridor (ascending order in fig. 5). The three spatial scales span the scales at work for altered hydrology, sediment budgets, and topography (Lord and others, 2009). Drivers of change at the basin scale include vegetation and land cover, topographic relief, climate, and human modifications that speed or inhibit the delivery of water and sediment to downstream areas and affect the hydrology at the segment scale. In turn, the processes may be controlled by boundary conditions of soil types, glacial landforms, and natural base-level features such as bedrock types and glacial end moraines. At the segment scale, tributary flow inputs, as well as valley or floodplain slopes and the interaction of slopes

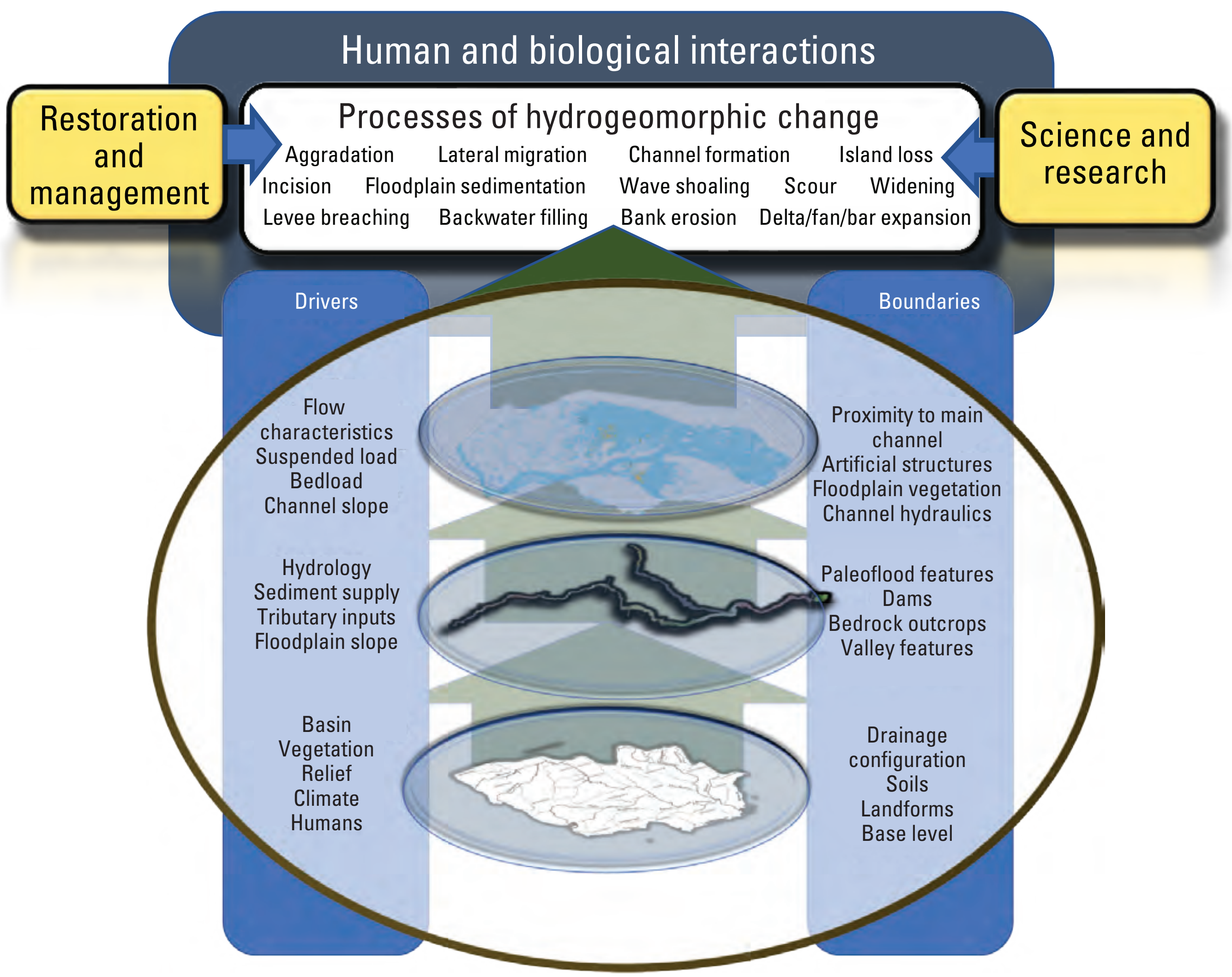


Figure 5. Draft conceptual model for hydrogeomorphic change in the Upper Mississippi River Basin.

with bedrock outcrops and valley features, and dams, can be quantified. It was thought that the subbasin level would be useful for looking at climate change scenarios and tributary inputs to the valley corridor.

The most granular valley corridor scale allows for accounting for how the hydrology and sediment inputs from the basin and segment scales locally affect flow characteristics, the distribution of suspended and bedload, and channel slopes. Those interactions depend on the proximity of the main channel and artificial structures, floodplain vegetation, and channel hydraulics. Thus, resulting landforms derived from hydrogeomorphic change reflect the local hydraulics and velocities and their interaction with sediment (for example, for a project location or a river reach) as well as broader scale hydrology and sediment inputs from the surrounding landscape and tributary watersheds. The type of, and potential for, hydrogeomorphic change is mediated by local variations in vegetative roughness, proximity to tributaries and dams, valley slope and width, and hardened structures added throughout the years for navigation and rehabilitation. Hydrogeomorphic changes reflect several time scales ranging from episodic, immediate changes from flood events to more multidecadal responses to interdam base-level rises associated with the 29 lock and dam structures constructed in the 1930s.

Hydrogeomorphic processes that produce depositional and erosional changes in fluvial landforms in the UMRS are related to the interaction of flows and sediment sources within a surrounding environment of alluvial sediment, vegetation, relict glacial meltwater landforms, and anthropogenic structures (fig. 5). In large mapping efforts based on remote sensing data sources, depositional forms are easier to distinguish in repeat mapping efforts than are erosional features, especially erosion in the vertical direction. However, even for depositional forms, it is difficult to link the form back to the process and a rate and source for a change because of the complexities involved in geomorphic complex-response mechanisms (Lane and Richards, 1997; Buffington, 2012).

Large lowland river systems tend to be dominated by depositional environments within and transcending channels onto floodplain surfaces (Lewin and others, 2017) and the UMRS is no exception. The lock and dam system adds further base-level control that continues to promote sediment deposition upstream from the dams. Depositional processes of hydrogeomorphic change include aggradation, lateral channel migration, floodplain sedimentation, levee building, backwater filling, delta and fan expansion, and bar growth, including downstream extension of islands. The presence of depositional landforms and their spatial heterogeneity lend evidence for determining the processes responsible for them. Notable erosional processes include lateral channel migration, new channel formation, island loss, incision, wave shoaling, scour, widening, levee breaching, and bank erosion. The distance and elevation of a landform relative to the nearest channel gives some indication of the potential processes involved in its formation (Fryirs and Brierley, 2022). In addition to physical changes, biological activity associated with beavers may also lead to erosion and sedimentation processes including the formation of new side or accessory channels and damming of old.

Indicators of hydrogeomorphic changes identified during the 2018 workshop included both measured (repeat surveys) and predictive (modeling). Examples of indicators included hydraulic geometry (width, depth, area) of the main channel, side channels, and connector channels; longitudinal profiles of the channels and aquatic and terrestrial overlays; areas that need frequent dredging; specific gage analyses (for example, Biedenharn and others, 2017); variations in fluvial landforms; cumulative distribution of elevations (topobathy diversity); velocity/depth combinations; lateral connectivity indices of main channel to side channel and backwaters; variations in aquatic and terrestrial vegetation; channel bedforms; and bed sediment texture. Losses, gains, or changes in geomorphic types can also be indicative of change. For example, sequences of bedforms, such as riffle-pool or dune-ripple, give indications of the hydraulics and type of sediment transport (Montgomery and Buffington, 1993; Wheaton and others, 2015).

Other geomorphic concepts that are difficult to show on the simplified conceptual diagram (fig. 5) included time scales involved in the outcomes of geomorphic change, such as the interplay of historical drivers and controls, evolutionary pathways, and geomorphic feedback mechanisms. Timescales of importance identified during the 2018 workshop included yearly to seasonal, 20 years in the past (for example, 2000–20), 30–50 years in the future (within 30-year epoch climate cycles and 50-year design life for HREP), and 100 years in the future (long-range climate predictions). Hydrogeomorphic changes at the reach scale might be abrupt or gradual, depending on the duration and frequency of hydraulic energy required to erode or deposit sediment. The changes may represent exceedance of a threshold (such as bank stability and tree toppling along banks) or be gradual or episodic (such as flood-related overbank sedimentation). An example of a geomorphic feedback mechanism might be bar formation and backwater sedimentation related to a levee breach and new side channel formation. The evolutionary trajectory associated with that side channel might be eventual channel filling (from main channel sedimentation) and building of a delta in the backwater that eventually becomes a relict feature once the side channel fills with sediment. Mechanisms associated with a longer time scale would be the decadal and long-term geomorphic response to the construction of the dams in the 1930s, which changed the valley slope and backwater sedimentation and likely resulted in new connector channel formation, splays, deltas, sand filling, and transport of silts and clays downstream. Geomorphic responses to the rise in base level associated with the dam construction may continue for centuries and affect responses to decadal changes in hydrology and sediment inputs. The location of the dams may alter tributary channel migration through the valley bottoms and delta formation. Wing dams, constructed for easier navigation, cause main channel narrowing and floodplain building.

Not shown on this diagram (fig. 5) are important steps of conceptual model building that require more ecological details that could be related to habitat needs and biological functions and endpoints (Jacobson and others, 2015; De Jager and others, 2018). These include development of indicators of change and disturbance, trajectories of recovery, and restoration potential. The past and future trajectories and probabilities of the processes and their effects on ecosystems and biogeochemical processes could be developed. Science topics of immediate interest are aquatic vegetation and sedimentation, island forests and bank erosion, the role of large wood in geomorphic function and habitat, mussel distribution relative to sedimentation, and prolonged flooding effects on floodplain sedimentation and channels connecting backwaters.

Uses and products of the conceptual model linked to geomorphic change include the following:

- Identification of sedimentation and erosion processes and rates in sensitive backwater habitat areas or navigation channels. Sedimentation in backwaters could be related to location within interdam sequences and proximity to areas prone to cutoff channels and crevasse splays.

- Probability of change maps for erosion and growth of islands and bars. The drivers and boundary conditions identified by the conceptual model provide direction for targeting the development of metrics to quantify probability of change in a GIS.

- Positive and negative feedbacks of biological communities and nutrient distributions, especially as related to properties of substrates. For example, multiple previous studies have shown substrate stability to be an important factor in the presence, density, and survival of native mussels in the UMRS (Zigler and others, 2008; Newton and others, 2020); therefore, application of the conceptual model to identify geomorphic settings likely to maintain stable substrate may be an important tool for predicting quality mussel habitat and prioritizing habitat restoration projects. The hierarchical nature of the conceptual model should allow predictions to be made and tested at multiple spatial scales, such as along the UMRS at the geomorphic reach or navigation pool scale, as well as within navigation pools at the longitudinal process zone (interdam sequence) and finer scales.

- Links of hydrologic and sediment changes from system-wide to local scales. Applications could link to fluvial landforms and effects on terrestrial and aquatic vegetation, navigation channel maintenance, and how water levels and inundation are affected by deposition over time relative to proximity to impoundments.

- Linking geomorphic processes with habitat restoration to inform HREP features and monitoring. Additional information on the possible trajectory of change of geomorphic processes, and whether that change is from basin-wide changes or valley corridor alterations, could help with design alternatives, expected longevity, and monitoring designs.

Components of a Hydrogeomorphic Change Hierarchical Classification System

Large river systems require a systematic and organizational approach for mapping geomorphic features that will be useful for application in scientific studies and restoration activities (Thorne, 2002). An initial hierarchical classification system for hydrogeomorphic change in the UMRS was developed based the conceptual model and its associated spatial scales of interest (fig. 6). During the workshop, the core team provided overviews of the existing datasets that could be useful in developing a classification system for mapping fluvial landforms in the UMRS with a high potential to change. The classification builds off the matrix style HGM floodplain hydrogeomorphology approach (Heitmeyer, 2007; Theiling and others, 2012).

The following six hierarchical classes were included, listed from broadest to finest spatial and temporal scale: (1) physiographic province, (2) floodplain reach, (3) geomorphic segment, (4) longitudinal process zone, (5) hydrogeomorphic catenae, and (6) hydrogeomorphic unit (fig. 6). The first three classes are from existing GIS-based datasets (Fenneman and Johnson, 1946; U.S. Army Corps of Engineers, 2011; WEST Consultants, Inc., 2000, respectively) and the last three classes are proposed as new data sets. The fourth class, an initial longitudinal process zone, was constructed after the 2018 workshop and is included in this report for the first time, adapting the interdam sequences of Skalak and others (2013) for UMRS impounded sections. The details of an approach for development of the hydrogeomorphic catenae and hydrogeomorphic units are proposed for a followup study. The hydrogeomorphic unit forms the basic mapping unit of the classification with a goal of being able to add attributes related to sensitivity to hydrogeomorphic change, mainly erosion and deposition, that would span terrestrial and aquatic settings across the valley corridor. Once areas of potential geomorphic change are identified, the hierarchical classification can potentially help to identify basin-wide

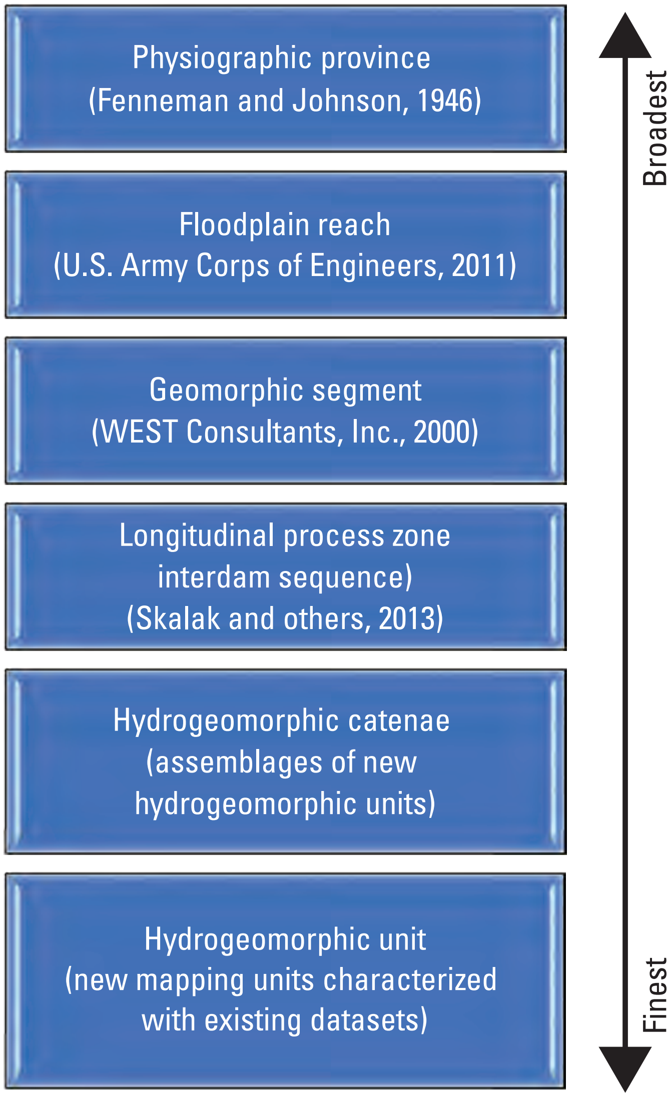


Figure 6. Initial hierarchical classification system for hydrogeomorphic change mapping in the Upper Mississippi River Basin.

changes that happen synchronously, possibly owing to a climatic shift, or long-term continuous change, such as from dam construction. In addition, risk-related changes can be identified at a reach scale, such as shifts in side channel flow and associated sedimentation near bridges or critical habitats (Sear and Newson, 2003).

Physiographic Provinces

The physiographic provinces for the UMRS cover large geographic areas (Fenneman and Johnson, 1946) (fig. 7). The use of the provinces as the highest level of the classification stemmed from its inclusion in defining the geomorphic reaches of the CES (WEST Consultants, Inc., 2000) and reflect overall differences in natural landscape features and glacial/post-glacial history affecting the physical characteristics of the river basin (Knox, 2007). Patterns in land cover/land use, drainage density, basin slope, soils, glacial history, and related tributary hydrology and sediment inputs associated with the provinces may affect valley corridor-scale hydrogeomorphic processes. The UMRS overlaps with mainly the Central Lowland of the Interior Plains, with subdivisions in the Western Lake, Wisconsin Driftless, Till Plains, and Dissected Till Plains sections.

Floodplain Reaches

Four floodplain reaches for the UMRS were mainly determined by anthropogenic factors, physiographic setting, navigation dams, and major basins (Lubinski, 1999; U.S. Army Corps of Engineers, 2011; Theiling and others, 2012). They are the Upper Impounded (pools 1–13), Lower Impounded (pools 14–26), Unimpounded, and the Illinois River (fig. 1). The Upper Impounded Reach extends from Minneapolis and St. Paul, Minnesota, to Rock Island, Illinois, and has a relatively narrow floodplain but abundant off-channel aquatic areas and less well-developed levees than the Lower Impounded Reach that extends to St. Louis. The Unimpounded Reach, which extends to Cairo, Ill., includes flows from the Missouri River, contains few off-channel aquatic areas, and levees are well developed. The Illinois River reach also has well-developed levees for agriculture and abundant off-channel aquatic areas.

The USACE developed hydraulic models for each of the four reaches, with the last completed in 2022 (U.S. Army Corps of Engineers, 2018, 2020a, 2020b, 2022a). Outputs from the mainly 1-dimensional models, such shear stress and velocity, may be useful to provide validation in areas of interest identified in future hydrogeomorphic change mapping.

Geomorphic Segments

Nested in the four floodplain reaches are 12 geomorphic segments or reaches defined further by tributary confluences, geologic controls, valley features, longitudinal profile, and sediment transport characteristics (WEST Consultants, Inc., 2000) (fig. 2). The geomorphic segments were notable as being helpful to group floodplain vegetation characteristics and define ecological restoration objectives by Theiling and others (2012). The geomorphic segments are at a spatial scale similar to river reaches in the River Ecosystem Synthesis approach in Thorp and others (2006, 2008). The segments can be used to further group characteristic assemblages of geomorphic units such as the river reach or river style in Brierley and Fryirs (2005) approach. During the 2018 workshop the adjustment of boundaries for these geomorphic segments was discussed but no changes were made. For

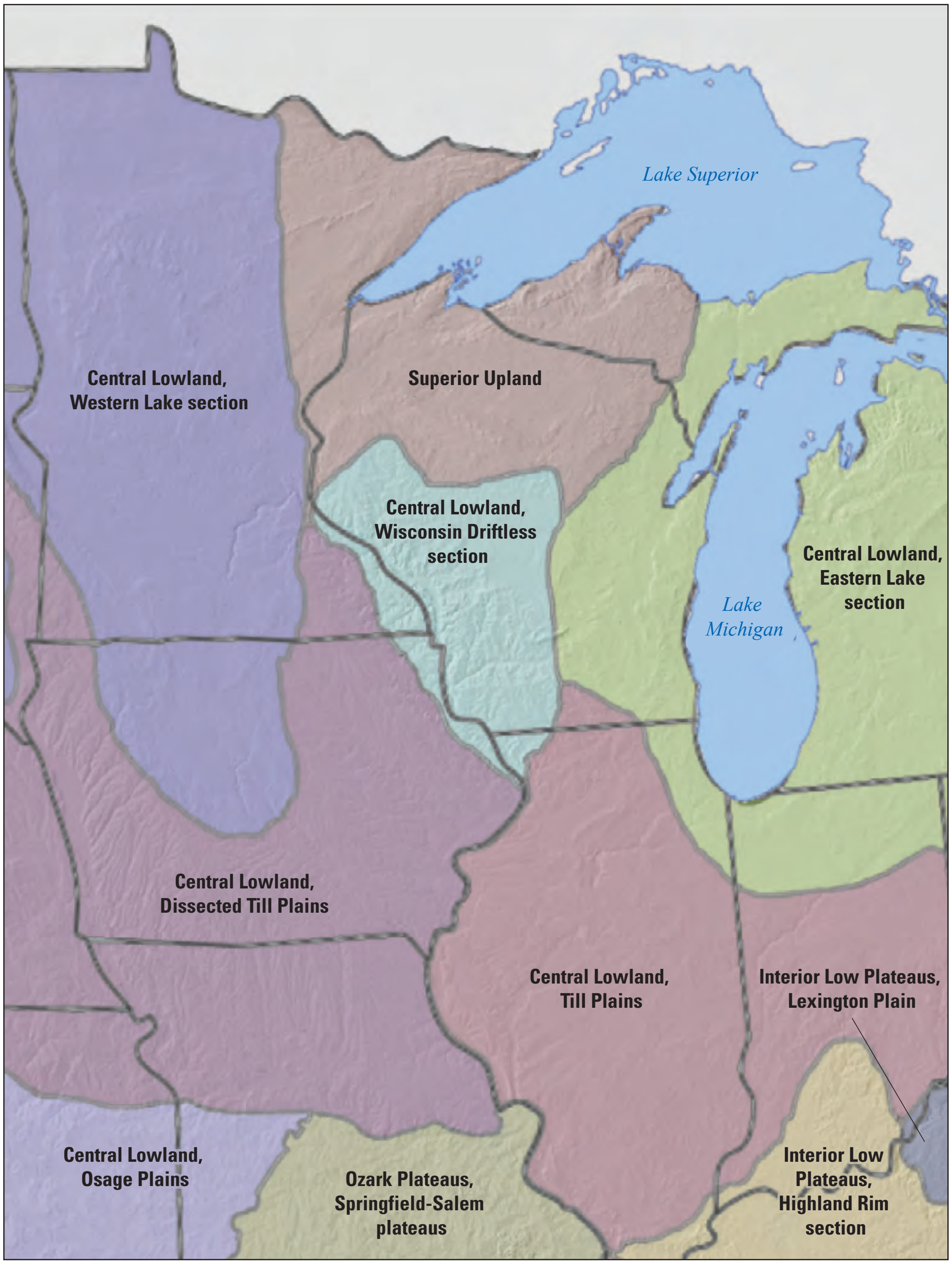


Figure 7. Physiographic regions in the vicinity of the Upper Mississippi River System (Fenneman and Johnson, 1946).

example, there was a proposal to split segment 1 into 1a, which is referred to as the gorge through the Twin Cities, and 1b, which is the reach from St. Paul to Lake Pepin.

Segments 1 and 2 have a relatively gentle slope and flow through the Dissected Till Plains. Segments 3 and 4 are in the Driftless Area in the Upper Impounded Reach and contain the Chippewa River alluvial fan. Segments 5 through 8 are in the Central Lowlands and Lower Impounded Reach. Two segments make up the Illinois River portion and are also in the Central Lowlands. Segments 9 and 10 are downstream from the Illinois River confluence in the Unimpounded Reach and separate the Ozark Plateau on the west side of the river from the Central Lowlands on the east side. Thebes gap, a bedrock gorge, separates segments 9 and 10.

Longitudinal Process Zones (Interdam Sequences)

For geomorphic segments 1–8 in the upper and lower impounded sections of the UMRS, an interdam sequencing of longitudinal flow and sediment interactions was adopted based on the river corridor study of two dams on the Upper Missouri River (Skalak and others, 2013). The Upper Missouri River study described zones of river geomorphic conditions between dams based on their erosion and depositional tendencies and geomorphic forms, although the Missouri River model is based on a system of reservoirs that have more regulated water-level fluctuations and flows than the UMRS. The major river zones in the Upper Missouri River include dam proximal, attenuating, river-dominated transitional, reservoir dominated transitional, and reservoir, which are all organized along a continuum of sediment supply-limited to transport limited conditions. A first attempt at a longitudinal process zone diagram for the UMRS was done near the end of the study and was adapted from the Upper Missouri River using pool 8 as an example (fig. 8).

Following the Upper Missouri River model, the flow and sediment dynamics associated with the river zones can be described in terms of their possible effects on the spatial distribution of hydrogeomorphic units that have a potential to change (table 1). Proceeding downstream from a dam, the sequences move through potentially erosional or unchanging to depositional until the portion of the river becomes dominated by impounded water, where most of the pre-dam fluvial features have been submerged or perhaps eroded by wave action associated with a longer fetch across the open water sections. Most of the hydrogeomorphic change likely happens in the river-dominated transitional zone, where there is enough sediment contributed from upstream erosion or from tributaries, the amplitude of the water-level hydrograph is increasing, and the number of hydraulic connections is high to drive erosion and deposition within the channel and floodplain. Lateral floodplain slopes are steep enough to cause erosion of existing side channels with sediment deposition in the receiving backwater. The effects of sediment from tributaries depend on the proximity of their mouths to the main channel. If the tributaries connect directly to the main navigation channel, it is likely that sediment contributions will be transported downstream or dredged. If they connect to a backwater environment, then most of the sediment may be deposited and form new land (Rogala and others, 2020a). It is important to note that these longitudinal zones will likely have different lengths and not all zones may be present, depending on the lock and dam configuration and the geologic setting.

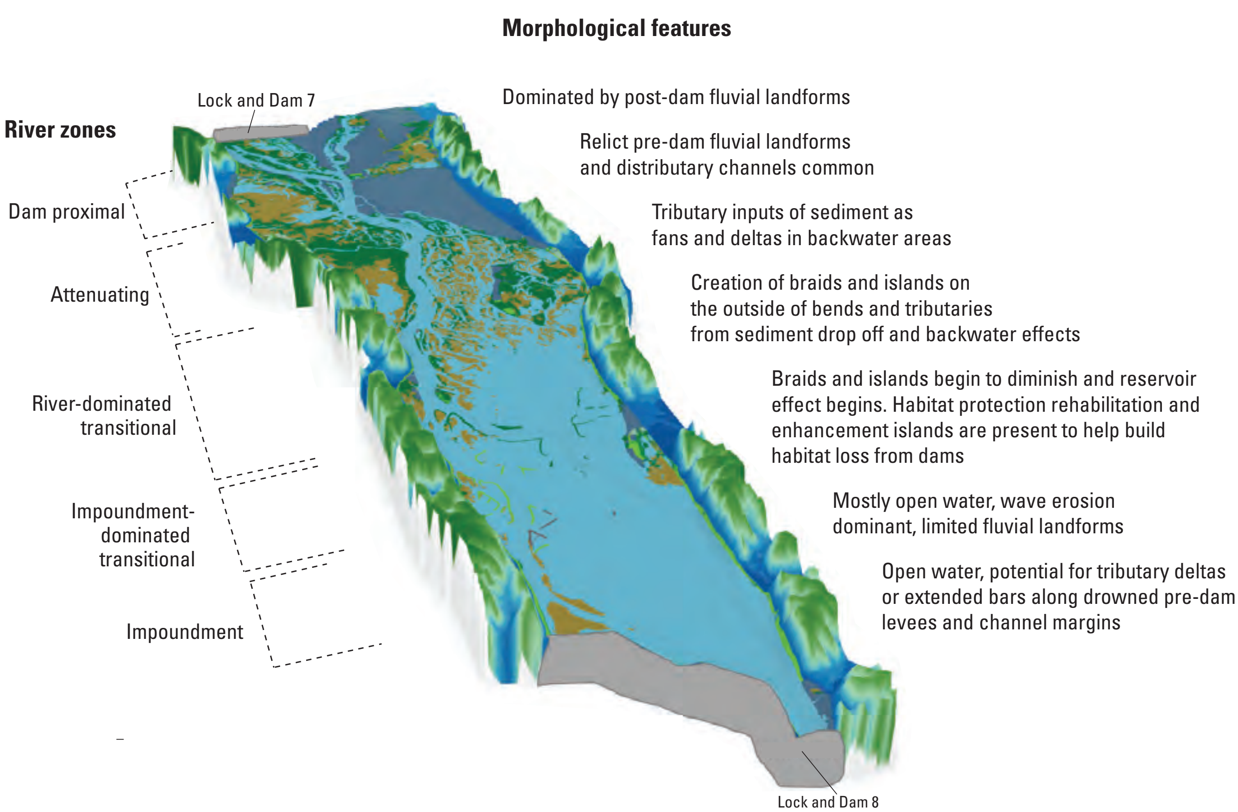


Figure 8. Longitudinal process zones associated with geomorphic segments with dams. Longitudinal process zones are based on Skalak and others (2013).

Table 1. River zones descriptions related to interdam sequences of river zones along geomorphic segments 1–8 in the Upper Mississippi River System, in comparison to those developed for the Upper Missouri River (Skalak and others, 2013).

River zone	Geomorphic indicators (Skalak and others, 2013)	Hydrogeomorphic change characteristics for (adaption for this study)
Dam proximal	Removal of islands in channel, new vegetation growth and stabilization of point bars.	Flow inputs across valley bottom controlled by location of lock and dam structures, sediment starved, lack of new depositional features.
Attenuating	Sand bar islands remain but island movement is steady in managed flows	Intact pre-dam floodplain landforms, distributary flows and side channels, sediment inputs from tributaries variable but potentially large and cause of deposition in backwaters. Proportion of sand to fines from tributaries varies.
River dominated transitional	Creation of large islands on outside of bends from sediment drop off and backwater effects	Transitional between pre-dam floodplain landforms and backwater effects from next downstream dam. Depositional bars common in highly diverse floodplain environments. Tributary deltas common in backwater and cause of backwater sedimentation. Levee breaches and side channels to backwaters common.
Reservoir/impoundment dominated transitional	Inundated scroll bars, large tree die-off from changing reservoir levels, submerged delta front	Limited distributary pre-dam landforms. Depositional bars in more open water settings. Potential for more submerged deposition from main channel and tributaries. Wave erosion more common. Subsurface erosion possible.
Reservoir/impoundment	Minor deposition	Limited to no pre-dam landforms visible. Depositional landforms from tributary deltas may be present. Submerged deposition possible from tributaries. Subsurface erosion possible.

Hydrogeomorphic Units and Hydrogeomorphic Change Catenae

Hydrogeomorphic units (HGUs) form the basic building block and mapping unit of the classification scheme and collectively represent a new combination of terrestrial and aquatic geomorphic forms that are informed by existing mapping sets of topobathy (U.S. Army Corps of Engineers' Upper Mississippi River Restoration Program Long Term Resource Monitoring element, 2016) aquatic areas (Wilcox, 1993), planform change (Rogala and others, 2020a), and floodplain inundation (Van Appledorn and others, 2021). Geomorphic mapping of fluvial landforms in a GIS has been developed using high resolution bathymetry datasets (Wheaton and others, 2015; Bangen and others, 2017; Kramer and others, 2017). The Wheaton and others (2015) geomorphic unit technique approach has a four-tiered framework that differentiates forms within a channel based on their ties to water levels (tier 1), shape (tier 2), additional key shape attributes (tier 3), and roughness or vegetation modifiers (tier 4). For terrestrial areas the geomorphon approach (automated mapping of shapes with similar morphometrics) was developed by Jasiewicz and Stepinski (2013). Both approaches would use the existing UMRS valley-wide topobathy data. Classifications based on form alone are difficult to associate with geomorphic processes or sensitivity to geomorphic change unless the features include evidence of flow energy and sediment particle size. Other horizontal and vertical associations are also needed, such as proximity of the features to the main channel or tributary mouths, how often they are flooded, and where they are located within the interdam longitudinal process zones.

The individual HGUs can be grouped into catenae, or assemblages of units linked by related hydrogeomorphic processes, based on commonalities in flow and sediment dynamics as well as pre-impounded geomorphology. The HGUs defined by forms in fluvial environments have been successfully grouped into zones of similar geomorphic processes for other large rivers (Lewin and others, 2017; Fryirs and Brierley, 2022). Assemblages of geomorphic units have been created based on river character, behavior, condition, and recovery in the River Styles approach linked by morphology and sediment type, which can be related to available hydraulic energy associated with locations (Fryirs and Brierley, 2022).

The approach for the hydrogeomorphic change catena or process assemblage is different for this UMRR application because it attempts to connect HGUs based on their common origin and formation from the interaction of flows and sediment. The combination of flow direction and inundation relative to the main channel or tributaries, coupled with potential sediment sources, helps to define units more sensitive to erosion and depositional processes. An example catena is the crevasse channel and splay that are common in levee breaches (Lewin and others, 2017). Erosive flows originating from the main or side channel cause crevasse channel formation and subsequent deposition of a delta or fan on the floodplain or backwaters (delta or splay bars) (fig. 9). The crevasse splay deposits which form on floodplains or in backwaters are linked with accessory channels connected to the main stem from which the sediment originated. The splay HGUs are thus linked with the crevasse channel HGU by their common flow and sediment origin (the main or side channel) and by the crevasse channel serving as a conduit and potential additional source for the sediment forming the splay. Crevasse splays and the side channels that feed them are dynamic features that can change after a single flood, and new side channels can form or old channels be filled over time. The linkage of the splay to the source of the flows and sediment help to characterize how fast they might build or where they might form.

Application of Draft Conceptual Model and Hierarchical Classification System to Pool 8

A simple example for crevasse splays (fig. 9) shows how the hierarchical classification system can be applied using available data and pre-existing maps (fig. 10). Crevasse delta bars were one of four types of new land masses identified in Rogala and others (2020a) (Rohweder, 2019). These above-water features are growing and changing shape over time, indicating a hydrogeomorphic setting sensitive to change. The availability of sediment for the bar deposition is linked to proximity of an accessory or side channel. These channel features have been mapped in the UMRR aquatic areas dataset (De Jager and others, 2018; U.S. Army Corps of Engineers' Upper Mississippi River Restoration Program Long Term Resource Monitoring element, 2018) but not specifically linked to the crevasse delta bars in a mapping system. The combination of the accessory channel linked to the bars forms the assemblage or catena. These usually originate from the main channel as a source for flows to transport sediment from the main channel or to erode additional sediment from a side channel. If the hydraulics of the flows change from either natural or anthropogenic causes, a new side channel may form, grow larger, or fill with sediment. The geomorphic process zone, where the side channels and crevasse splays are most likely to form, is in the river dominated transitional zone (mid-pool; fig. 10). In pool 8, the abundance of crevasse splays is in the river dominated transitional zone coincident with where the valley widens.

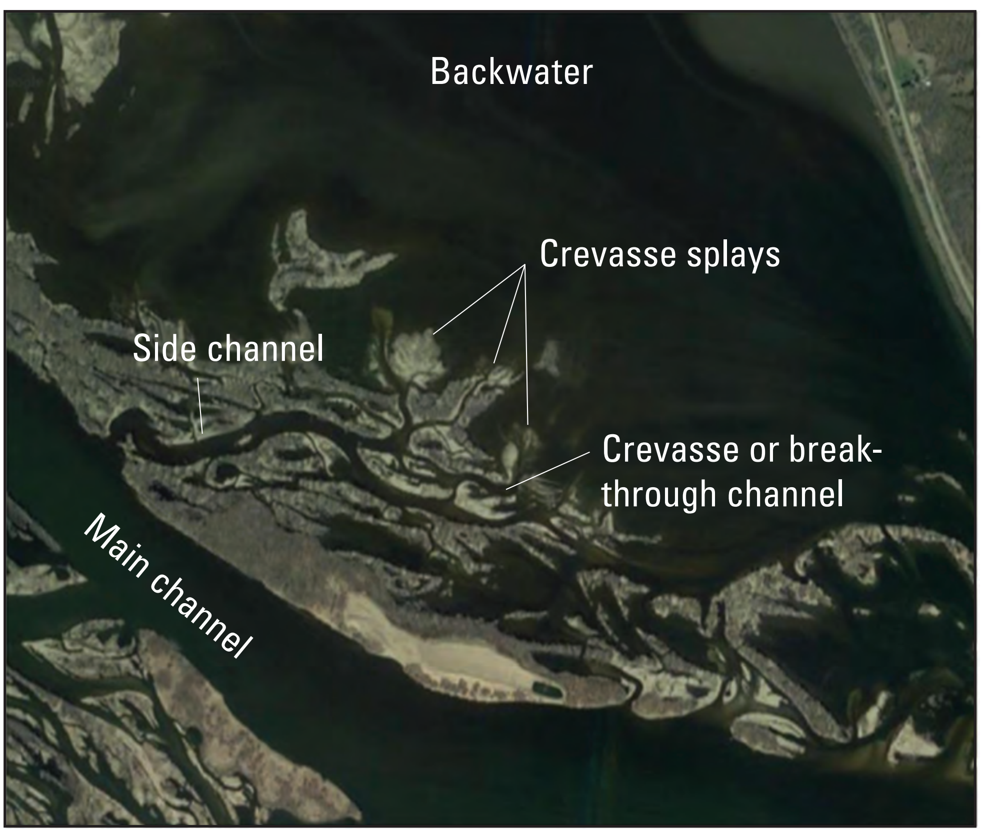
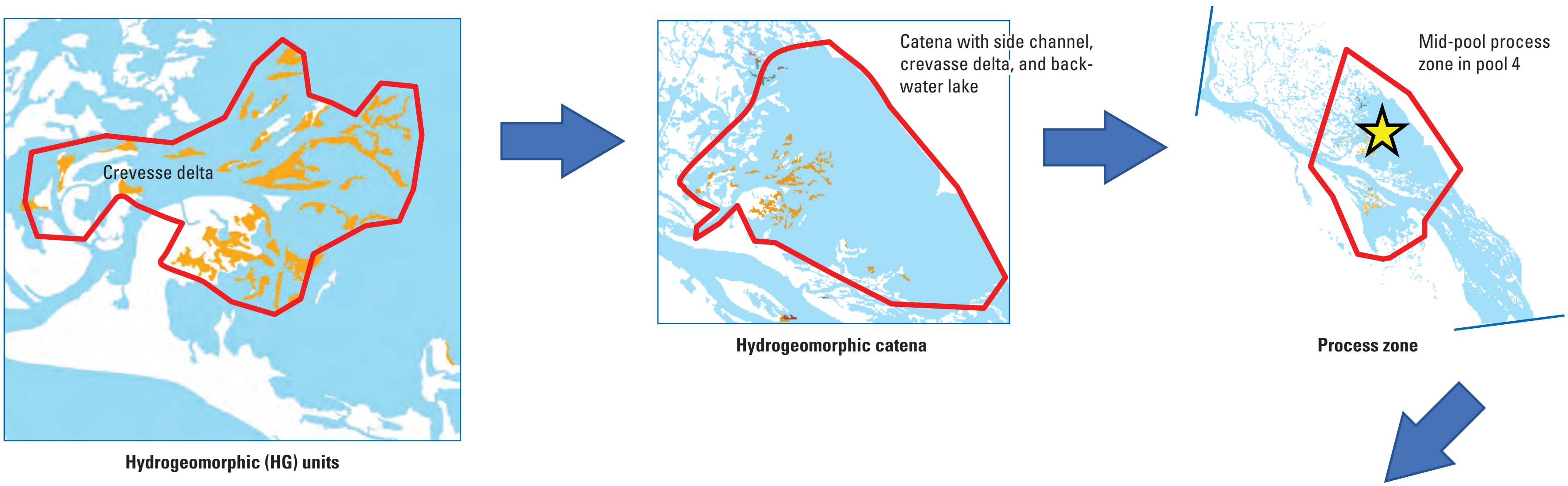


Figure 9. Example of crevasse splays from an aerial image in pool 4.



Scale	Example attribute
HG unit	Crevasse delta
HG cantena	Channel/delta/lake
Process zone	Mid-pool
Geomorphic segment	3
Floodplain reach	1
Geologic province	Dissected till plains

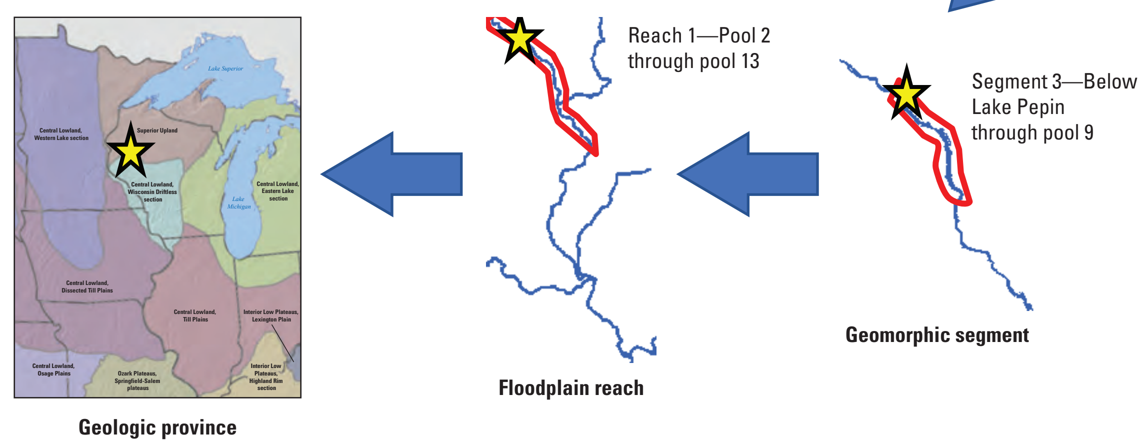


Figure 10. Example of hierarchical classification approach for a hydrogeomorphic unit of crevasse delta bar and related catena of crevasse splay that includes the side channel, crevasse delta bars, and the backwater lake that it formed in for pool 8.

Future Needs for Classification, Mapping, and Visualization

As part of the 2018 workshop, panelists identified short- and long-term needs for future classification, mapping, and visualization of hydrogeomorphic change in the UMRS. The exact method to quantify sensitivity to hydrogeomorphic change for the newly mapped HGUs was not determined during the workshop but was proposed to be explored once the HGUs were mapped and overlaid with other geospatial data like the planform change maps.

A summary of the 2018 workshop findings was presented to the larger group of scientists involved in Focal Area 1 planning group, HREP, and LTRM studies in 2020. As part of the 2020 round of UMRR science in support of restoration proposals, an experimental GIS database and query tool was proposed and funded to explore innovative visualization tools for mapping temporal variability in dynamic geomorphic features. Immediate potential applications included floodplain forest dynamics and health, mussel habitat, and fish survival by mapping areas prone to high erosion and sedimentation rates that may cause tree die-off, bury mussel beds, and fill overwintering pools for fish. Possible long-term studies included applications of mapping hydrogeomorphic units and their sensitivity to geomorphic change in terms of sediment source and sink variability from watershed sources, water-level variations, and climate change. In addition, the hydrogeomorphic change classification system should give context to locally derived water chemistry and biological monitoring data. Remotely sensed datasets and models that cover large geographic areas continue to grow. These additions will add granularity to characterizing the drivers, boundary conditions, and temporal context of hydrogeomorphic change in the UMRS.

Below is a list that summarized the workshop findings into short-term and long-term needs to help build the process toward hydrogeomorphic change mapping.

Short-Term Needs

- Update the longitudinal profiles for the riverbed, valley bottom, and water surfaces at different flows.
- Identify the origin of any previously classified geomorphic units identified by their form. For example, connect the crevasse splay bars of the planform change maps (Rogala and others, 2020a) with side channels and the main channel mapped for aquatic areas (De Jager and others, 2018). If possible, identify crevasse splays on floodplains, which typically form where natural levees are breached.
- List other commonly expected HGU catenae and how they might be identified and mapped.
- Identify the relative contributions of flow and sediment from tributaries and where they enter the valley bottom relative to backwaters and the main channel. Add cumulative drainage area to longitudinal profile. Consider use of USGS SPAtially Referenced Regressions On Watershed attributes mappers for estimates of tributary suspended sediment loads (Robertson and Saad, 2019).
- Map common HGUs and catenae by hand to start visualizing how the automation process of generating them might work. Use Swan Lake in pool 26, which contains significant backwater habitat but has sedimentation problems and altered hydrology, as an example.
- Consider how HGUs and catenae and their potential for geomorphic change can be linked and incorporated into terrestrial and aquatic habitat characterization.
- Link HGUs, catenae, and their potential for hydrogeomorphic change to their proximity to the main channel and backwater lakes in a GIS.

Long-Term Needs

Below is a list of sediment-related long-term needs:

- Inventory sediment data that have been collected on the main stem and tributaries.
- Assemble relevant sediment budget updates from the last 20 years including Minnesota tributaries like the Root and Zumbro Rivers.
- Identify and prioritize streamflow and (or) sediment gages to re-initiate. Include why the location and density of sites are important and identify the main data needs.
- Consult with those conducting water-quality monitoring on relations between total suspended solids and suspended-sediment concentration data.
- Construct a sediment budget for an example backwater, accounting for sediment entering and leaving. Select a backwater with adequate bathymetry change and sedimentation rate data. Consider approach of Gaugush (2004).
- Monitor bedload in pre-identified reaches with navigation problems and where dredging and sand fill is frequent.
- Strategize and recommend locations and types of sediment data that need to be collected, and how it is going to be made available across agencies and the public.

Climate change variability related:

- Examine streamflow trends from the 1970s–1980s to the present. Identify changes in the magnitude of peak flows and “change points” in location (central tendency) or scale (spread) of annual flow peaks. Verify presence of strong increase in peak flow in 1970 as indicated in the literature.

- Consider results from the existing USACE ECB–2018–14 climate change analyses (U.S. Army Corps of Engineers, 2022b) that evaluate change points and trends in future hydrology for USGS main-stem streamgages. Discuss possible effects on HGUs and their sensitivity to hydrogeomorphic change.

- Distinguish differences in geomorphic change rates between high-, medium-, and low-energy environments and predict potential changes to those environments, including flow velocity and sediment texture differences, expected from climate change.

- Investigate effects of wind-fetch changes on bank and shoreline erosion rates over time.

Below is a list of changes in tools:

- Increase familiarity with the availability of new tools for systematic evaluation of rivers, including incorporation of more types of measurements and remote sensing data, while at the same time being able to continue incorporation of historical data.

- Inventory the amount of geomorphic change by 0.1-mile increments spaced longitudinally along the river, which may help alleviate any biases in pre-existing boundaries.

Summary

From 2018 through 2020 the U.S. Geological Survey and U.S. Army Corps of Engineers led a series of calls and meetings, and a workshop to develop an Upper Mississippi River System hydrogeomorphic change conceptual model and hierarchical classification scheme. This report contains a summary of the process used to develop the conceptual model and a description of how the hierarchical classification was assembled. Three of the six datasets used in the hierarchical classification are new. A longitudinal process zone related to interdam sequences was proposed as a fourth level. Hydrogeomorphic catenae and the basic building block of hydrogeomorphic units were proposed to be developed during a follow-on study. The catenae are hydrogeomorphic units linked by flows and sediment sources that resulted in relatively recent (mid-1990s to mid-2010s) changes in fluvial landforms of the valley bottomlands. These landforms are most likely different types of depositional bars but also include erosional features such as side channels and crevasse splays. Short-term and long-term data needs for mapping and classification identified during the 2018 workshop were included in the report for future reference as the mapping process associated with the hierarchical classification and possible applications continue to be of interest to the for the habitat protection rehabilitation and enhancement and long term resource monitoring studies.

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Appendix 1. Participants of the Upper Mississippi River Restoration Geomorphic Characterization Workshop, November 14–15, 2018

Table 1.1. Participants of the Upper Mississippi River Restoration geomorphic characterization workshop, November 14–15, 2018.

[USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey; ERDC, Engineering Research and Development Center; UMESC, Upper Midwest Environmental Science Center; UCLA, University of California, Los Angeles]

Name	Agency	Role
Eddie Brauer	USACE, St. Louis	Core team
Susannah Erwin	USGS Columbia Environmental Science Center	Core team
Faith Fitzpatrick	USGS Upper Midwest Water Science Center, Middleton, Wisconsin	Core team
Jon Hendrickson	USACE, St. Paul District	Core team
Jim Rogala	USGS Upper Midwest Environmental Science Center, La Crosse, Wisconsin	Core team
Lucie Sawyer	USACE, Rock Island District	Core team
Jayme Stone	USGS Upper Midwest Environmental Science Center, La Crosse, Wisconsin	Core team
Adam Benthem	USGS, Water Mission Area, Branch of Hydrodynamics, Reston, Virginia	Panel member
Travis Dahl	USACE ERDC, Vicksburg, Mississippi	Panel member
Karen Gran	University of Minnesota, Duluth	Panel member
Robb Jacobson	USGS Columbia Environmental Science Center	Panel member
Laura Keefer	Illinois Water State Water Survey	Panel member
Kevin Landwehr	USACE, Rock Island District	Panel member
Nate Young	University of Iowa	Panel member
Molly Van Appledorn	USGS UMESC	Local resource
Kristen Bouska	USGS UMESC	Local resource
Nate De Jager	USGS UMESC	Local resource
Jeff Houser	USGS UMESC	Local resource
Kathi Jo Jankowski	USGS UMESC	Local resource
Jess LeRoy	USGS Central Midwest Water Science Center	Remote resource
Stan Trimble	UCLA, Department of Geography	Remote resource

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Publishing support provided by the
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Fitzpatrick and others—**Upper Mississippi River System Hydrogeomorphic Change Conceptual Model and Hierarchical Classification**—OFR 2024–1051

ISSN 2331-1258 (online)
https://doi.org/10.3133/ofr20241051