A Hydrogeomorphic Classification of Connectivity of Large Rivers of the Upper Midwest, United States

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

Cover. Landsat 8 composite multispectral image of the Mississippi and Ohio Rivers, August 20, 2019, over southern Illinois, eastern Missouri, western Kentucky..

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as

$$°F=(1.8×°C)+32.$$

The International System of Units and U.S. customary units are used for hydrologic statistics to facilitate communication with river management agencies.

Abbreviations

ATTZ aquatic-terrestrial transition zone

NHD National Hydrography Dataset

NID National Inventory of Dams

PCA principal components analysis

TN total nitrogen

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Abstract

River connectivity is defined as the water-mediated exchange of matter, energy, and biota between different elements of the riverine landscape. Connectivity is an especially important concept in large-river corridors (channel plus floodplain) because large rivers integrate fluxes of water, sediment, nutrients, contaminants, and other transported constituents emanating from large contributing drainage basins, and thereby contribute to the complexity of large-river ecosystems. Large rivers are also highly valued for socioeconomic goods and services, which has led to historical fragmentation, lack of connectivity, and contentiousness about best policies for managing large-river corridors. The classification is intended to serve as a template for understanding geographic variation in large rivers within the Midwest, to aid in designing scientific studies of large river ecological processes, and to match specific river-management and restoration objectives to specific river reaches. The focus of the classification is on measuring river connectivity from available hydrological and geomorphic data.

We provide a multiscale assessment and classification for segments of 15 rivers that meet various criteria for largeness. All rivers are tributaries to the Mississippi River system. The 11,600 kilometers (km) that qualified as large were classified by major alterations (unimpounded, navigation pools, storage reservoir) and additionally assessed for their network continuity as a function of numbers and heights of dams. Among the 15 rivers, 55 percent of segment length was unimpounded, 30 percent was in navigation pools, and 15 percent was under storage reservoirs. Assessment of network longitudinal connectivity among river segments documented the contrast between river segments with low-head navigation dams (Upper Mississippi, Illinois, Ohio, Green, and Cumberland Rivers) and those segments with high-head dams (mostly in the Upper Missouri River). The longest unimpounded river pathways exist in the Lower Missouri River and connected tributaries where nearly 1,300 km of the Missouri River connect to an additional 1,800 km of the Middle and Lower Mississippi Rivers.

At our finest scale, we present a statistically based, component classification based on 10-km segments. Cluster analysis of hydrologic variables from 66 streamflow-gaging stations yielded 5 clusters calculated from 5 ecohydrological metrics related to lateral connectivity with the floodplain. A separate cluster analysis of 5 geomorphologic variables associated with each of the 1,172 river segments also yielded 5 clusters. When the hydrologic variables were associated with corresponding segments, the cluster analysis yielded 8 hydrogeomorphic clusters that could be explained in terms of their contribution to floodplain connectivity. Although the clusters overlap considerably in principal component space, the resulting hydrogeomorphic classification leads to a physically reasonable distribution of classes. The resulting classification is intended to increase geographic awareness of the range of variation of connectivity potential among large rivers of the Upper Midwest, to increase understanding of the extent of alteration of these rivers, and potentially to serve as a template for stratifying study designs of large-river corridor ecological processes.

Introduction

Large rivers provide a multitude of ecosystem services to humans and are among the most used of all ecosystems (Tockner and Stanford, 2002). In the Midwest United States, large rivers are used for transportation, waste treatment, water supply, power generation, fisheries, and recreation, among other purposes. Control of flood waters allows society to use extensive alluvial floodplains of large rivers for agriculture and development. Some of these uses are mutually compatible, but in other cases there are incompatibilities among uses and society is challenged to select some uses over others or to seek compatibilities. Large rivers also provide substantial ecosystem services, including some that are currently poorly understood but that may be highly valuable (Thorp and others, 2010).

Human uses of large midwestern rivers have had direct effects on physical processes (for example, dams that alter flow regimes and restrict fish migrations, levees that isolate rivers from their floodplains, point sources of pollution, and channelization). In addition, large midwestern rivers have been indirectly altered by cumulative land-use changes and hydroclimatic events in their watersheds. Increased sediment and nutrient loads from agricultural sources have been linked to declines in river habitat quality (Waters, 1995) and hypoxia in the Gulf of Mexico (Alexander and others, 2008). Aquatic invasive species like Asian carps (black carp [*Mylopharyngodon piceus*], bighead carp [*Hypophthalmichthys nobilis*], grass carp [*Ctenopharyngodon idella*], and silver carp [*Hypophthalmichthys molitrix*]) and zebra mussels (*Dreissena polymorpha*) have taken advantage of large rivers as invasion corridors. Many river agencies are now anticipating increased hydroclimatic uncertainties (droughts as well as floods) associated with future climate change (Milly and others, 2008; Gu and others, 2010). Informed decision making about managing large-river resources can be improved with fundamental understanding about how these resources vary over time and across the Midwest, especially in context of increasing uncertainties.

Background

This report is a product of the Large River Initiative, a science effort hosted by the Midwestern region of the U.S. Geological Survey. The Large River Initiative was designed to increase the information basis needed to manage and restore large rivers of the Upper Midwest United States (fig. 1). We selected the concept of connectivity to frame this effort because of the concept's importance to river ecosystem science and socioeconomic goods and services.

Connectivity is defined in aquatic ecological literature as water-mediated exchange of matter, energy, and biota between different elements of the riverine landscape (Pringle, 2001). Connectivity is considered one of the primary drivers of river productivity, biological diversity, and riverine ecosystem health (Junk and others, 1989; Bayley, 1995; Ward, 1998; Tockner and others, 2000). Moreover, the broad ecological definition of connectivity includes socioeconomic characteristics that matter to humans, such as inundation hazards, depositional and erosional hazards to floodplain infrastructure, nutrient processing (especially denitrification) on floodplains, and water supply. Dimensions of connectivity may be lateral to floodplains, vertical to shallow groundwater, and longitudinal to additional river, lake, estuary, wetland, and coastal water bodies (Amoros and Bornette, 2002; Ward and others, 2002). Because magnitude, duration, and timing of connectivity are likely to be important to ecological functions, connectivity also has temporal attributes.

Large rivers and their floodplains provide fertile soils, level land, and abundant water resources that have driven agricultural, urban, and industrial development. To maximize development, connectivity has often been minimized through construction of dams, weirs, bank stabilization, floodwalls, and levees. Dams alter water flows, sediment and nutrient loads, river temperatures, ecological processes, and fish migration patterns, which all contribute to diminished longitudinal connectivity. Interruptions to lateral and vertical transfers of water, sediment, nutrients, and biota by levees, floodwalls, and bank stabilization are another form of discontinuity in riverine connectivity (Ward and Stanford, 1995). Other important mechanisms that alter the connectivity conditions of large rivers include water diversions that may de-water a channel or geomorphic channel adjustments that change river-floodplain connections. For example, channel incision may result in perched, hydrologically disconnected riparian areas, whereas channel aggradation may result in increased hydrologic connections to floodplains and floodplain aquifers and wetlands (Jacobson and others, 2011).

All these mechanisms play out in different combinations across the rivers of the Midwest United States, and many may accumulate through the channel network, resulting in cumulative effects and interactions that require a landscape approach for understanding. How variability in connectivity affects ecological patterns and processes may differ among major river segments, given regional to local differences in ecological attributes; however, the purpose of this report is to develop a basic understanding of differences and commonalities in the physical patterns and processes that define connectivity among these rivers. Because of the underlying geologic and climatic variation in the Midwest, patterns of natural connectivity, and the degree to which they have been altered, are expected to vary geographically. The purpose of this report is to develop an understanding of differences and commonalities among these rivers.

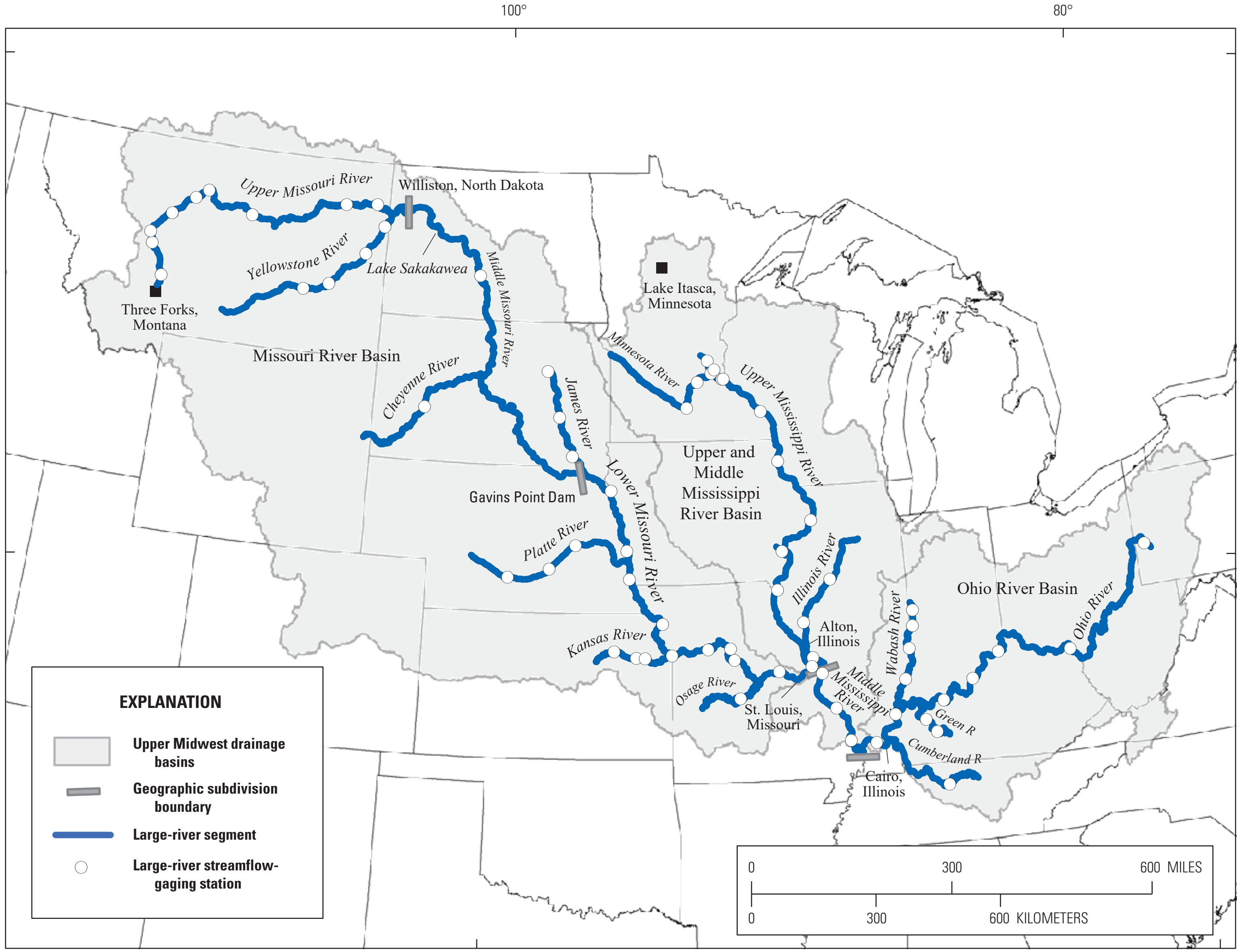
River Classifications and Definitions

Classification is a fundamental step in organizing scientific understanding of complex and dynamic systems. Rivers can be described and classified in a variety of ways and at a variety of scales of resolution. Classification serves to identify rivers or parts of rivers that are similar, to discriminate among parts that are different, and to organize understanding about river processes. For scientific inquiries into riverine ecology, classification based on physical characteristics serves to partition variability into parts of the river that are inherently similar, thereby increasing the ability to resolve differences because of other causes, such as stresses related to altered water quality or flow regime (Thoms and Parsons, 2002; Thorp and others, 2006). Physical classification of a river indicates where processes, resources, stresses, and hazards are similar and require similar management policies (Montgomery, 1999; Thorp and others, 2010).

River science is inherently interdisciplinary, and opportunities arise for confusion about fundamental concepts and terms. We therefore offer this set of definitions for this report:

- "Transect" is used to measure cross-sectional attributes of rivers, such as floodplain width, topographic roughness, and leveed area.

- "Segment" is used to indicate longitudinal parts of a stream system between substantial tributaries and with relatively uniform properties of bedrock and valley physiography (Frissell and others, 1986).



Base from U.S. Geological Survey digital data, 2012
Albers Equal-Area Conic projection

Figure 1. Large-river segments and selected streamflow-gaging stations of the Upper Midwest.

- "Reach" is used to indicate longitudinal subdivisions of stream segments between breaks in channel slope and characterized by channel patterns that contrast with those upstream and downstream. This definition differs somewhat from Frissell and others (1986) because it does not use riparian vegetation or valley-floor width as criteria. Reaches typically include multiple riffle/pool or bend/crossover sequences.

- "Riparian" is used to indicate areas of banks, bars, and the valley bottom subject to frequent flooding, erosion, and deposition because of interactions with the channel; riparian areas are frequently identified by characteristic vegetation communities. This definition is used to include a strict definition of riparian (that is, limited only to streambank area) and the operational definition used by many land and stream managers (that is, alluvial bottomland, frequently including the entire valley bottom).

- "Floodplain" is the flat area adjacent to the river channel constructed by the present river in the present climate and frequently subject to overflow (Leopold, 1994). "Frequent" means about once every 1.5 years or exceeded two times in 3 years. Operationally, the floodplain is often identified by the presence of recently deposited sediment.

- "Valley bottom" is the nearly flat or terraced land surface adjacent to a river channel and within a valley. It has been formed by fluvial processes of erosion and deposition. The valley bottom includes the floodplain but also includes terraces that are not flooded as frequently.

- "River corridor" consists of the river channel, valley-bottom surface, valley-bottom water bodies, and underlying alluvial sediments and bedrock that are hydrologically connected to the river channel. The river corridor can be defined as main-stem segments of arbitrary length, or it can include branches into tributary rivers.

River Names

Official domestic river names are maintained by the U.S. Board on Geographic Names in the Geographic Names Information System (GNIS, https://www.usgs.gov/core-science-systems/ngp/board-on-geographic-names/domestic-names). The official river names generally do not recognize geographic modifiers that are widely used by scientists, resources managers, and the public to apply additional specificity (Domestic Names Committee, 2016). For example, the GNIS does not recognize Upper Mississippi, Middle Mississippi, and Lower Mississippi river subdivisions (with capitalized geographic modifiers), despite the very common usage and understanding of these subdivisions (Schramm and others, 2015; Remo, 2016). Similar geographic subdivisions have been proposed and are widely used in the Missouri River, wherein "Upper," "Middle," and "Lower" designations relate to well-defined changes in hydrology, physiography, and management (Jacobson and others, 2010). The GNIS governing document allows for usage of geographic modifiers in cases where it is consistently used by the public, and, in such cases, the policies allow the modifier to be capitalized (Domestic Names Committee, 2016, p. 37). We adopt the convention of using capitalized geographic modifiers throughout this document to maintain geographic clarity and consistency (fig. 1).

Geographic modifiers applied to the Missouri River follow Jacobson and others (2010):

- The Lower Missouri River extends from the confluence with the Mississippi River near St. Louis, Missouri, to the lowermost main-stem dam at Gavins Point, South Dakota (Gavins Point Dam). The abrupt change in hydrology, water quality, and channel morphology at this point justify the geographic break.

- The Middle Missouri River refers to the reservoir-dominated segments of the Missouri River from Gavins Point Dam to the headwaters of Lake Sakakawea, near Williston, North Dakota.

- The Upper Missouri River refers to the segments of the Missouri River upstream from Lake Sakakawea that are characterized by substantial inter-reservoir segments, upstream to Three Forks, Montana, where the Missouri River begins at the confluence of the Jefferson, Gallatin, and Madison Rivers.

On the Mississippi River, geographic modifiers follow Remo (2016):

- The Lower Mississippi River (not shown) extends from the Gulf of Mexico upstream to the Ohio River confluence. These segments of the Mississippi River differ substantially from those upstream because of the large volume of discharge added by the Ohio River, and they differ geomorphically in that the river flows in the broad alluvial valley of the Mississippi embayment.

- The Middle Mississippi River extends from the confluence with the Ohio River, near Cairo, Illinois, upstream to the confluence with the Missouri River near St. Louis, Mo. These segments of the Mississippi River differ markedly from those upstream in that navigation is maintained through river-training structures rather than locks and dams, and the valley is relatively narrow.

- The Upper Mississippi River extends from Melvin Price Locks and Dam at Alton, Ill., to the origin of the Mississippi River at Lake Itasca, Minnesota.

Scope and Objectives

The geographic scope of this report is large rivers of the Upper Midwest United States (fig. 1). Because most large rivers within the Midwest drain to the Mississippi River, the geographic scope is consistent with the rivers within the Upper and Middle Mississippi River drainage basins. Large rivers are defined in the “What Is a Large River?” section of this report.

The objective of this report is to develop an understanding of differences and commonalities among these rivers, with an emphasis on how river connectivity varies over space and time. We document the geography of these large rivers using a hierarchy of description, leading to a segment-scale classification. The classification is intended to serve as a template for understanding geographic variation in large rivers within the Midwest, to aid in designing scientific studies of large-river ecological processes, and to match specific river management and restoration objectives to specific river reaches. The focus of the classification is on measuring river connectivity from available hydrological and geomorphic data.

Approach

Our approach to this classification process involved multiple components. The first component was to define what makes a river large. Based on that definition we identified rivers that met the criteria defining largeness and described them as to extent of alteration and longitudinal connectivity. We then classified segments by statistical analysis of streamflow-gaging station records for these rivers, and by statistical analyses of geomorphic characteristics of river-corridor segments. Finally, we merged these two classifications to develop a hydrogeomorphic classification of reaches based on a statistical cluster analysis that combined geomorphic and hydrologic characteristics at the segment scale.

What Is a Large River?

The first step in our classification was to define what constitutes a large river. Largeness can be defined in various ways, including operational approaches to measurements, metrics of physical dimensions, measures of ecological functions and processes, and importance to socioeconomic systems. An operational definition could be based on the need to use specific techniques to measure important features of rivers (for example, the inability to rely on wading measurements, the need to use boat-mounted sensors, and the ability to use a wide range of satellite and remote-sensing data). For example, the U.S. Environmental Protection Agency (EPA) uses “non-wadable” and “large river” interchangeably (Flotermersch and others, 2006) to mean lotic systems more effectively and safely sampled with boat-based methods.

Definitions based on physical size that include a threshold drainage area or flow quantile, a threshold stream order, or a main-stem length have been used (Potter, 1978; Gupta, 2007). These metrics are readily calculated, but the threshold of size above which a river achieves largeness is unclear. Kammerer (1987) defined the 20 largest rivers of the United States and ranked them based on three characteristics: total length, basin area, and average annual discharge. Notably, different rivers had different ranks for the three criteria. One aspect of largeness in rivers relates to their size and diversity of climate, geology, land use, and ecoregions encompassed by their drainage basins: a critical characteristic of large rivers is their aggregation of runoff, sediment, nutrients, and pollutants from broad and variable areas. In previous work, large rivers have been defined as having unregulated mean annual discharge greater than 356 cubic meters per second (or 12,600 cubic feet per second; Dynesius and Nilsson, 1994), a threshold that would include many river segments in the Midwest. The U.S. Environmental Protection Agency differentiated large rivers from “great rivers,” defining great rivers as having at least 400,000 square kilometers of drainage area and discharge at the mouth of at least 3,000 cubic meters per second (or 106,000 cubic feet per second); only 14 rivers in North America are thought to meet these criteria (Angradi, 2006).

Large rivers have been noted for having distinct ecological functions and processes. Large rivers tend to have lower gradients, finer sediments, and longer residence time for water in transit compared to smaller rivers. These conditions can affect habitat availability and productivity. In particular, large rivers tend to have greater turbidity than smaller rivers because of substantial suspended-sediment transport, and turbidity tends to create conditions suitable for a narrow range of aquatic species. Large rivers frequently have large floodplains that were naturally inundated by long seasonal flood pulses, one of the attributes that has been associated with their great productivity (Junk and others, 1989; Bayley, 1995). Importantly, large rivers connect broad sections of the landscape, providing migration corridors that are essential for reproduction and survival of some aquatic, avian, and terrestrial species. Although these ecological functions and processes are characteristic of large rivers, there is no clear, strictly ecological threshold that would identify when a river becomes large. Some potential thresholds may be derived from factors such as depths required by large-river obligate fish species or widths that accommodate sight distances required by migratory birds like sandhill and whooping cranes (*Grus canadensis* and *Grus americana*, respectively); these definitions would depend, in part, on the species that inhabit the rivers and not on physical river features that would be comparable across rivers with different biota.

Compared to smaller rivers, large rivers also provide an abundance of socioeconomic resources, including hydropower, municipal and industrial water supply, navigation, and recreation. Engineering of large-river corridors has provided additional socioeconomic benefits in floodplains by providing flood control, bank stabilization, and flood-protection structures that allow for agriculture, urban, and industrial development of floodplains. As a result, one characteristic shared by almost all large rivers is extensive alteration from their natural condition. Some scientists and managers have recognized that there is potential for many of these large rivers to be restored to more natural conditions to increase net benefits (Tockner and Stanford, 2002; Pahl-Wostl, 2006; Bouska and others, 2016); however, there is no clear threshold of socioeconomic development or ecological floodplain functions that can be used to delineate large rivers from small.

For the purposes of this initiative we will define large rivers broadly as those rivers that have all or most of the characteristics listed above. To include rivers that are large based on drainage area, average annual discharge, and length, we ranked rivers of the Midwest according to each criterion. Data were compiled from Kammerer (1987) and verified using the National Hydrography Dataset (NHD) version 2 (McKay and others, 2014). Among all rivers compiled by name, we selected the top 10 under each category and then combined those that qualified based on one or more criteria. This resulted in 15 total rivers that were included in at least 1 of the lists (table 1). Within this group of large rivers, our classification considered main-stem channels extended upstream to include all segments of Strahler order 7 and greater (Strahler, 1957), as indicated in the NHD.

Identifying these 15 large rivers is somewhat dependent on the names historically assigned to specific lengths of river as well as the physical criteria used. As a result, some river segments that meet the physical criteria are not represented in the top 15. An example is the North Platte and the South Platte Rivers. Segments of each of these tributaries to the Platte River would qualify under the physical criteria if they were considered extensions of the Platte River; however, because a new name begins at the confluence, our filtering excludes them. Similarly, segments of the Allegheny and Monongahela Rivers upstream from their confluence (to form the Ohio River) are large but excluded. The reliance on the historically assigned names of large rivers introduces a bias in river selection but does not alter the classification trends. A classification that is independent of historical river names may be warranted in future work.

Table 1. Top 10 rivers of the Upper Midwest ranked by length, mean annual discharge, and drainage area.

[Data from Kammerer (1987)]

Rank	Length	Mean discharge	Drainage area
1	Missouri River	Ohio River	Mississippi River
2	Mississippi River	Mississippi River	Missouri River
3	Ohio River	Missouri River	Ohio River
4	North Platte River	Cumberland River	Kansas River
5	Yellowstone River	Wabash River	Platte River
6	Cheyenne River	Illinois River	Yellowstone River
7	Minnesota River	Osage River	Wabash River
8	Platte River	Green River	Illinois River
9	Cumberland River	Yellowstone River	Cheyenne River
10	James River	Iowa River	South Platte River*

*Although the South Platte River qualifies as large based on drainage area, it was excluded from the statistical analysis because it did not have segments with Strahler order 7 or higher.

Classification Concepts

Classifications of natural phenomena are most useful when they satisfy several criteria (Driscoll and others, 1984). Desired characteristics of a classification system are as follows:

1. it is hierarchical (that is, the classification is amenable to aggregation and disaggregation to resolve differences at various levels);
2. it is based on quantifiable, physical features or processes; and
3. it is structured to support its intended use.

Many types of classification systems have been devised for rivers; the variety of classifications arises from the variety of questions and uses that classifications are intended to address. The structure and type of classification are heavily influenced by its intended use. As Rowe (1962, p. 420) stated, "…purpose is implicit in all classifications and different purposes lead to different classifications." Hence, the optimum classification of a river system for understanding water quality may differ from one intended to categorize flood hazard or biodiversity. The applicability of a classification will increase to the extent that the system is based on quantifiable characteristics that are fundamental determinants of system functions. In most cases, classification of a natural system attempts to create logical, discrete divisions in systems that are characterized by continua or gradients. A central challenge of classification is to develop objective criteria for defining useful breaks along these continua.

In a discussion of ecosystem classification, Driscoll and others (1984) identified two types of classifications: integrated and component. An integrated classification presents a system in which the total effect of interacting factors is known or understood sufficiently to define useful classes. The widely used stream classification system proposed by Rosgen (1994) is an example of an integrated classification system; the Rosgen system is based on the premise that measures of channel morphology provide a useful integration of the various factors that affect characteristics of a river reach.

In contrast, a component classification initially presents classifications of individual factors, and the user is allowed to choose the factors and levels that are appropriate for the intended use. Component classifications often proceed through statistical ordination, classification, or cluster analyses of factors associated with river reaches, thereby providing an inductive and objective classification (Elliott and Jacobson, 2006; Jacobson and others, 2010; Kondolf and others, 2016). The component approach is readily applicable in environments where nearly continuous measurements of classification variables (such as channel sinuosity, width, slope, or valley width) are available through remote sensing or other geographic information system (GIS) datasets. Component systems evaluated through cluster analysis or regression-tree type methods are also amenable to hierarchical organization (Elliott and Jacobson, 2006).

For component classifications that are defined by characteristics along the channel, by reach, or by segment, there are two spatial scales of effect relevant to associating classification variables with a river location: those based on characteristics of the contributing drainage-basin area (watershed) and those that are based on physical characteristics within the river corridor (including the channel and adjacent valley bottom). Watershed-based classifications include landscape-scale factors that are thought to affect runoff, sediment supply, water quality, or anthropogenic stressors within the basin that propagate to the river. Watershed-based classifications have been used to group hydrologically similar rivers as a basis for assessments of water quality and ecological alteration (Wolock and others, 2004; Carlisle and others, 2011).

Corridor-based classifications are based on morphologies or processes within the river corridor. Prominent examples of integrated corridor classifications are presented by Rosgen (1994), Frissell and others (1986), and Montgomery and Buffington (1997). Examples of component corridor-based systems are presented by Elliott and Jacobson (2006) and Jacobson and others (2010). The Ecological Limits to Hydrologic Alteration approach to environmental flow assessments includes both watershed-based approaches to quantifying hydrologic effects and corridor-based classification to assess local factors that mediate flow regime by altering hydraulics, flow resistance, substrate, riparian shading, or other conditions (Poff and others, 2010).

The choice of emphasis on a watershed-based or corridor-based classification clearly depends on the type of heterogeneity that exists in a river system and the intended applications of the classification. In smaller drainage areas, watershed characteristics are likely to have direct effects on channel form and process. As rivers grow larger and incorporate more varied land use, geology, physiography, and climate, watershed-based classifications tend to lose predictive capability, with the exception of drainage area, which is almost always relevant. Larger rivers also tend to have more impoundments, which act to disconnect corridor hydrology and water quality from the contributing basin; furthermore, bank stabilization and navigation structures common in larger rivers may exert strong controls on channel form and process at the corridor scale.

We present three levels of resolution to explore differences and commonalities among these rivers with respect to connectivity. At the coarsest level, we document the general classification of alteration of river segments. At the next level of resolution, we present a simplified analysis of longitudinal connectivity based on density and types of dams on the large river segments in the dataset. At our finest level of resolution, we assess potential for lateral connectivity between surface water in the channel and the floodplain at the segment scale. Lateral connectivity can be measured with two broadly defined types of information: hydrologic characteristics of the rivers and geomorphic factors that determine whether surface water inundates—or connects with—floodplain lands.

Our classification approach was to assemble hydrologic data and physical data related to connectivity and then analyze the data for statistically occurring clusters. We completed the cluster analyses separately for hydrologic data (by streamflow-gaging station) and for geomorphic factors (by segment). We then attributed each segment with the nearest upstream hydrologic record and completed a cluster analysis for merged hydrologic and geomorphic data.

General Classification of River Alteration

We classified the segments in the larger-river dataset into three broad, descriptive categories indicative of degree of alteration and related to connectivity:

- Navigation pools, which are segments impounded by low-head (2–12 meters high) navigation dams and locks and act as run-of-the-river reservoirs with little flood storage capacity;
- Storage reservoirs, which are segments that are impounded and mostly inundated by high-head, multi-purpose reservoirs; and
- Unimpounded, which are segments not directly affected by impounded dams. It should be noted that all segments of large rivers of the Upper Midwest are affected to some extent by hydrologic alteration from upstream reservoirs. In addition, those classified here as unimpounded include variable degrees of channelization and bank stabilization.

These classes are used for descriptive statistics; segments that were identified as storage-reservoir segments were subsequently excluded from the segment-scale cluster analyses.

Longitudinal Connectivity Assessment

Longitudinal connectivity refers to continuity of movement of constituents along the channel network. For water, sediment, nutrients, and contaminants, downstream connectivity is most relevant. For aquatic biota, upstream and downstream connectivity are both important. Lack of connectivity because of dams or natural lakes can result in accumulation of sediment and perhaps sequestering of nutrients, carbon, and contaminants. Reservoirs also increase residence time of water that may drive nutrient processing or other transformations that are important to water quality. For fish species, dams may decrease or prevent fish passage and consequently interrupt life cycles of native species. Dams may slow the spread of some invasive species but at the same time create habitats suitable for non-native species. Conversely, some changes to channel networks may serve to increase connectivity in the sense that they increase downstream advection of constituents. For example, channelization and navigation structures simplify channel complexity, resulting in faster advection and extended downstream transport of water, sediment, and transported constituents—including fish and invertebrate larvae and plant propagules.

Although a detailed consideration of longitudinal connectivity is beyond the scope of this report, we performed a reconnaissance evaluation of dams along the large river segments covered in our analyses to illustrate the potential extent. Using the U.S. Army Corps of Engineers National Dam Inventory (U.S. Army Corps of Engineers, 2013), we evaluated the distribution of dams that were likely to serve as an impediment to transport of constituents and upstream and downstream movements of biota based on height classes.

Hydrologic Classification

Hydrologic classifications typically concentrate on the point locations where streamflow-gaging stations exist (Richter and others, 1996; The Nature Conservancy, 2005; Henriksen and others, 2006; Kennen and others, 2007) or on extrapolation of statistics from gaging stations to the surrounding landscape based on drainage-basin characteristics (flow regionalization; Ries and others, 2004; Yadav and others, 2007). A classification framework introduced by Olden and others (2012) differentiates among three deductive approaches based on inference from basin characteristics and the inductive approach based on scaling up from the observed streamflow gage information. The approach used in this report is inductive as it is based on analysis of streamflow records.

We identified streamflow-gaging stations for large rivers of the Midwest (table 1) for statistical analysis based on criteria that the gages were on the main stem of the qualifying large rivers and had at least 10 years of recent record (table 2; fig. 1). Because our classification is intended to illustrate current conditions of these rivers, we were not concerned about history of alteration, only that streamflow-gaging station records were recent and of sufficient length to calculate statistics.

Although a very large number of variables can be calculated from hydrologic time series (Richter and others, 1996; Olden and Poff, 2003; Henriksen and others, 2006), our focus is on variables related to lateral connectivity between channel and floodplain. Determining connectivity requires first an estimate of the threshold discharge that overtops the bank, or bankfull flow. Bankfull flows are best determined on-site as the discharge that just starts to inundate the floodplain, but for this extensive regional assessment we use the simplifying assumption that, on average, river floodplains in quasi-equilibrium with their channels are inundated every 1.5 to 2 years (Leopold, 1994). Of course, actual extent of inundation of the floodplain is affected by factors such as levees and channel incision or aggradation that can disrupt equilibrium and alter the average return interval for floodplain inundation (Jacobson and others, 2011; Jacobson and Faust, 2014). To represent a more conservative threshold of floodplain inundation of bankfull flow we have used the 50-percent annual exceedance probability flood (or 2-year recurrence interval), calculated from the partial duration series of peak flows using the U.S. Geological Survey PeakFQ program (Flynn and others, 2006). The statistically determined bankfull discharge should be interpreted as a potential for floodplain inundation; the potential is mediated by site-specific conditions like levees, natural topographic variability, and channel incision.

We then created custom scripts in the Practical extraction and reporting language (called “Perl;” http://www.perl.org/) to process the hydrologic time series at each streamflow-gaging station to calculate average total days per year (duration) and average number of events per year (frequency) that discharges were greater than the bankfull threshold. We added additional metrics as indicated in table 3. The flood index is the ratio of the difference between the 1-percent annual exceedance probability flood (that is, the 100-year recurrence-interval flood) and the 50-percent annual exceedance probability flood (that is, the 2-year recurrence-interval flood) divided by the magnitude of the 50-percent annual exceedance probability flood. It is meant as a simple measure of the variance of the flood frequency distribution, similar to the upper-tail ratio of Smith and others (2018), but with less emphasis on the extreme flooding of record. We retained the 50-percent annual exceedance probability flood magnitude (or bankfull flood) as a measure of river size and the unit bankfull flood (bankfull flood divided by upstream drainage area) as a measure of hydroclimatology.

Statistical Analysis

We statistically explored hydrologic variables using scripts written in R (R Development Core Team, 2013). The steps include the following:

1. Normalizing data by centering around the mean and scaling by the standard deviation.
2. Performing K-means cluster analysis with the number of clusters ranging from 1 to 15.
3. Evaluating the optimum number of clusters by creating a scree-plot of within-cluster sum of squares by number of clusters, to help in selection of number of k-means clusters that adequately describe the data, as well as other measures.
4. Completing a principal components analysis (PCA) to evaluate which variables vary in similar or dissimilar ways.
5. Creating boxplots of scaled variables by clusters to visualize how clusters differ.
6. Attributing reaches with cluster numbers to map clusters in a GIS (Jacobson and Rohweder, 2019).

Table 2. Hydrologic characteristics of U.S. Geological Survey streamflow-gaging stations for large rivers of the Upper Midwest.

[ID, identifier; km^2, square kilometer; ft^3/s, cubic foot per second; (ft^3/s)/mi^2, cubic foot per second per square mile; Q, discharge magnitude at return interval indicated by subscript]

Station ID	Streamflow-gaging station	Hydrologic record			Drainage area (km^2)	Bankfull[1] (2-year) discharge (ft^3/s)	Unit bankfull discharge ([ft^3/s]/mi^2)	Mean annual days above bankfull discharge days	Mean annual duration of events above bankfull discharge days	Number of mean annual events above bankfull stage per year	Flood connectivity index $(Q_{100}-Q_2)/Q_2$
		Begin year	End year	Number of years							
03086000	Ohio River at Sewickley, Pennsylvania	1970	2014	44	49,982	169,000	8.75	8.67	0.55	0.705	1.28
03216600	Ohio River at Greenup Dam near Greenup, Kentucky	1970	2014	44	158,918	393,000	6.40	6.34	1.41	0.952	0.45
03277200	Ohio River at Markland Dam near Warsaw, Kentucky	1970	2014	44	213,181	432,000	5.25	5.19	2.61	0.929	0.39
03294500	Ohio River at Louisville, Kentucky	1970	2014	44	233,687	480,000	5.32	5.26	1.95	0.773	0.45
03303280	Ohio River at Cannelton Dam at Cannelton	1975	2014	39	248,630	489,000	5.09	5.04	3.26	0.784	0.47
03316500	Green River at Paradise, Kentucky	1970	2014	44	15,848	43,800	7.15	7.08	2.46	0.676	0.89
03320000	Green River at Lock 2 at Calhoun, Kentucky	1970	2014	44	19,393	46,500	6.21	6.15	3.55	0.659	0.94
03340500	Wabash River at Montezuma, Indiana	1970	2014	44	28,498	64,800	5.89	5.83	2.36	0.614	1.24
03341500	Wabash River at Terre Haute, Indiana	1970	2014	44	31,433	63,700	5.25	5.19	2.20	0.614	1.15
03342000	Wabash River at Riverton, Indiana	1970	2014	44	33,734	65,400	5.02	4.97	3.20	0.500	0.94
03377500	Wabash River at Mount Carmel, Illinois	1970	2014	44	73,397	145,000	5.11	5.06	3.81	0.545	1.06
03381700	Ohio River at Old Shawneetown, Illinois-Kentucky	2002	2014	12	361,411	662,000	4.74	4.70	3.09	0.364	1.16
03431500	Cumberland River at Nashville, Tennessee	1970	2014	44	32,953	98,500	7.74	7.66	1.00	0.714	1.04
03611500	Ohio River at Metropolis, Illinois	1970	2014	44	520,330	891,000	4.43	4.39	6.21	0.690	0.49
05288500	Mississippi River at Highway 610 in Brooklyn Park	1970	2014	44	48,957	32,300	1.71	1.69	5.24	0.605	1.25
05325000	Minnesota River at Mankato, Minnesota	1970	2014	44	38,192	22,600	1.53	1.52	6.11	0.955	3.25
05330000	Minnesota River near Jordan, Minnesota	1970	2014	44	41,524	23,900	1.49	1.48	6.90	0.932	3.39
05330920	Minnesota River at Fort Snelling State Park	2004	2014	10	43,318	35,700	2.13	2.11	6.08	0.625	1.70
05331000	Mississippi River at St. Paul, Minnesota	1970	2014	44	94,326	51,900	1.42	1.41	5.98	0.833	1.72
05331580	Mississippi River below L&D #2 at Hastings	1995	2014	19	95,095	64,300	1.75	1.73	6.00	0.571	1.81
05344500	Mississippi River at Prescott, Wisconsin	1970	2014	44	114,831	72,700	1.64	1.62	5.01	0.738	1.32
05378500	Mississippi River at WInona, Minnesota	1970	2014	44	151,741	105,000	1.79	1.77	5.43	0.659	1.10
05389500	Mississippi River at McGregor, Iowa	1970	2013	43	173,016	117,000	1.75	1.73	6.04	0.564	0.99
05420500	Mississippi River at Clinton, Iowa	1970	2014	44	219,410	154,000	1.82	1.80	4.79	0.698	0.73
05465500	Iowa River at Wapello, Iowa	1970	2014	44	32,040	41,600	3.36	3.33	2.78	1.023	2.87
05474500	Mississippi River at Keokuk, Iowa	1970	2014	44	305,021	214,000	1.82	1.80	5.03	1.045	1.13
05586100	Illinois River at Kingston Mines, Illinois	1970	2014	44	40,545	55,600	3.55	3.51	3.24	0.791	1.00
05586100	Illinois River at Valley City, Illinois	1970	2014	44	68,550	75,300	2.84	2.82	6.27	0.929	0.93
05587450	Mississippi River at Grafton, Illinois	1970	2014	44	439,076	321,000	1.89	1.87	6.31	1.000	0.79
06054500	Missouri River at Toston, Montana	1970	2014	44	37,600	17,400	1.20	1.19	5.71	0.864	1.40
06065500	Missouri River below Hauser Dam near Helena, Montana	1994	2014	20	43,257	9,650	0.58	0.57	12.90	0.550	3.42

Table 2. Hydrologic characteristics of US Geological Survey streamflow gaging stations for large rivers of the Upper Midwest.—Continued

[ID, identifier; km², square kilometer; ft³/s, cubic foot per second; (ft³/s)/mi², cubic foot per second per square mile; *Q*, discharge magnitude at return interval indicated by subscript]

Station ID	Streamflow-gaging station	Hydrologic record			Drainage area (km²)	Bankfull[1] (2-year) discharge (ft³/s)	Unit bankfull discharge ([ft³/s]/mi²)	Mean annual days above bankfull discharge days	Mean annual duration of events above bankfull discharge days	Number of mean annual events above bankfull stage per year	Flood connectivity index $(Q_{100}-Q_2)/Q_2$
		Begin year	End year	Number of years							
06066500	Missouri River below Holter Dam near Wolf Creek, Montana	1970	2014	44	43,956	11,000	0.65	0.64	10.62	0.750	2.58
06078200	Missouri River near Ulm, Montana	1970	2014	44	53,676	13,500	0.65	0.64	10.16	0.810	2.16
06090800	Missouri River at Fort Benton ,Montana	1970	2014	44	63,437	20,100	0.82	0.81	8.96	0.591	2.19
06109500	Missouri River at Virgelle, Montana	1970	2014	44	88,120	21,300	0.63	0.62	8.03	0.773	2.21
06115200	Missouri River near Landusky, Montana	1970	2014	44	105,058	24,600	0.61	0.60	6.96	0.750	3.15
06177000	Missouri River near Wolf Point, Montana	1970	2014	44	210,926	15,900	0.20	0.19	5.03	1.364	2.21
06185500	Missouri River near Culbertson, Montana	1970	2014	44	234,679	17,300	0.19	0.19	7.16	0.860	2.71
06295000	Yellowstone River at Forsyth, Montana	1977	2014	37	102,902	43,900	1.10	1.09	4.43	0.784	1.41
06309000	Yellowstone River at Miles City, Montana	1970	2014	44	123,682	46,700	0.98	0.97	4.30	0.744	1.16
06327500	Yellowstone River at Glendive, Montana	2002	2014	12	171,191	54,000	0.82	0.81	3.58	0.545	1.30
06329500	Yellowstone River near Sidney, Montana	1970	2014	44	177,074	49,200	0.72	0.71	3.93	0.841	1.32
06342500	Missouri River at Bismarck, North Dakota	1970	2014	44	477,781	33,500	0.18	0.18	14.09	1.364	1.72
06423500	Cheyenne River near Wasta, South Dakota	1970	2014	44	32,809	8,990	0.71	0.70	0.49	0.349	3.08
06475000	James River near Redfield, South Dakota	1970	2014	44	35,657	1,410	0.10	0.10	11.38	0.444	15.24
06477000	James River near Forestburg, South Dakota	1970	2014	44	45,087	2,320	0.13	0.13	25.26	0.568	18.18
06478500	James River near Scotland, South Dakota	1970	2014	44	52,938	3,730	0.18	0.18	15.07	0.523	16.00
06486000	Missouri River at Sioux City, Iowa	1970	2014	44	816,531	52,300	0.17	0.16	11.23	0.795	1.70
06610000	Missouri River at Omaha, Nebraska	1970	2014	44	837,549	69,000	0.21	0.21	6.51	1.045	1.45
06768000	Platte River near Overton, Nebraska	1970	2014	44	144,308	5,600	0.10	0.10	6.97	0.860	4.38
06770500	Platte River near Grand Island, Nebraska	1970	2014	44	147,769	6,620	0.12	0.11	3.41	0.517	2.97
06774000	Platte River near Duncan, Nebraska	1970	2014	44	151,998	8,550	0.15	0.14	4.59	0.886	2.39
06807000	Missouri River at Nebraska City, Nebraska	1970	2014	44	1,061,060	92,900	0.23	0.22	3.88	1.182	1.48
06818000	Missouri River at St. Joseph, Missouri	1970	2014	44	1,076,801	129,000	0.31	0.31	4.05	1.023	1.33
06887500	Kansas River at Wamego, Kansas	1970	2014	44	141,694	28,100	0.51	0.51	2.95	1.045	2.88
06889000	Kansas River at Topeka, Kansas	1970	2014	44	145,385	42,000	0.75	0.74	0.81	0.909	2.69
06891000	Kansas River at Lecompton, Kansas	1970	2014	44	149,845	51,200	0.88	0.88	0.79	0.955	2.50
06893000	Missouri River at Kansas City, Missouri	1970	2014	44	1,240,846	161,000	0.34	0.33	3.11	1.250	1.60
06895500	Missouri River at Waverly, Missouri	1970	2014	44	1,245,459	168,000	0.35	0.35	3.62	1.167	1.70
06906500	Missouri River at Glasgow, Missouri	2000	2014	14	1,278,781	212,000	0.43	0.42	3.77	0.929	1.00
06909000	Missouri River at Boonville, Missouri	1970	2014	44	1,283,395	236,000	0.48	0.47	2.85	1.091	1.34
06926000	Osage River near Bagnell, Missouri	1970	2014	44	35,885	49,700	3.59	3.55	3.94	1.045	1.68
06934500	Missouri River at Hermann, Missouri	1970	2014	44	1,339,273	292,000	0.56	0.56	2.89	0.705	1.36
06935965	Missouri River at St. Charles, Missouri	2000	2014	14	1,343,117	268,000	0.52	0.51	2.61	0.929	0.83
07010000	Mississippi River at St. Louis, Missouri	1970	2014	44	1,786,551	544,000	0.79	0.78	5.63	0.932	0.86
07020500	Mississippi River at Chester, Illinois	1982	2014	32	1,816,284	560,000	0.80	0.79	5.76	0.955	0.84
07022000	Mississippi River at Thebes, Illinois	1970	2014	44	1,828,075	584,000	0.83	0.82	5.70	0.818	0.83

Table 3. Hydrologic metrics used to statistically classify connectivity in large rivers of the Upper Midwest.

Metric	Abbreviation	Explanation
Bankfull flood magnitude	BF_Q	Magnitude of the bankfull flood, approximated as the 2-return flow, or 50-percent annual exceedance probability flood; indicates size of river.
Unit bankfull flood magnitude	BF_QU	Bankfull flood magnitude divided by contributing drainage area; indicates hydroclimatology of river.
Flood index	INDEX	Magnitude of 100-year recurrence-interval flood divided by magnitude of 2-year recurrence-interval flood; indicates variance in flood-frequency distribution.
Average number of bankfull floods per year	BF_NUM	Average number of bankfull floods (and greater) per year; indicates frequency of connectivity events.
Average annual duration of bankfull floods	BF_DUR	Average total days per year with floods greater than bankfull; indicates duration of connectivity events.

Geomorphic Classification

Geomorphic classification followed the same main steps as those for hydrologic classification but was based on segments rather than gage sites. River segments were derived by arbitrarily dividing rivers into 10-kilometer (km) sections, beginning at the downstream-most location of each river (some shorter segments exist at ends of the large-river sections). This resulted in 1,172 river segments along rivers with Strahler stream orders greater than 6 as calculated by NHD Plus (McKay and others, 2014). Floodplain width and percentage of leveed attributes were summarized by using the mean and standard deviation (or coefficient variation) of metrics calculated along cross-sectional river transects. To create transects, the valley-bottom centerline was delineated along each river (see example in fig. 2). The centerline was smoothed using the ArcGIS tool “Smooth Line” using the PAEK smoothing algorithm and a tolerance of 2 km. Transects were then generated perpendicular to the valley-bottom centerline using the “Perpendicular Transects Tool” (Ferreira, 2014). The tool was parameterized to create transects every mile, and overlapping transects were edited so that they did not cross one another (Rohweder, 2019). Five variables were used to assess geomorphic connectivity potential: channel sinuosity, average floodplain width, standard deviation of floodplain width, average percentage of length of transects behind (landward of) levees, coefficient of variation of transect length behind levees (table 4).

The lateral width of floodplains was delineated using a method that incorporated interpolating a water-surface elevation. The intersection of the water surface and land elevation at the outermost edge of the floodplain was used to delineate the extent of the floodplain. Water-surface elevations approximating the 0.2-percent annual exceedance probability flood were used when available; and where that information was not available, we used elevations approximating the 0.2-percent annual exceedance probability flood under the assumption that such floods would completely over-top water-control structures within the valley such as levees, floodwalls, and roadways. The water-surface elevations were documented at least every 20 miles along the river reach being analyzed and more often where it was deemed necessary, including areas of rapid longitudinal elevation change. These elevations were attributed to the corresponding 1-mile transect, and interpolation of water-surface elevations between each 1-mile transect was completed using the ArcGIS (ESRI, Redlands, CA) tool “topo to Raster.” Within the tool, parameters were chosen to create an interpolated surface using the transects as the input feature layer, the elevation values generated within that layer as the input field, and an input type of contour. Then areas of the 1/3-arc second National Elevation Dataset that were less than the interpolated water surface were identified using the ArcGIS tool “Greater Than.” These areas represent the lateral extent of the floodplain valley bottom for further analyses. This raster dataset was then converted to the vector boundary dataset labeled “Derived valley-bottom outline” (fig. 2)

Table 4. Geomorphic metrics for 10-kilometer segments used in statistical classification of connectivity, large rivers of the Upper Midwest.

Metric	Abbreviation	Explanation
Channel sinuosity	SIN	Total sinuosity for the 10-kilometer segment calculated by dividing segment length by the straight-line distance between the segment end points.
Average floodplain width	FPW	Average floodplain width calculated as average transect length across valley bottom.
Standard deviation of floodplain width	FPW_SD	Variation of floodplain width calculated as standard deviation of transect length across valley bottom.
Average percentage of transects landward of levees	LEV	Average percentage of valley-bottom transects on landward side of levees.
Coefficient of variation of percent transects landward of levee	LEV_CV	Variation in leveed condition calculated as variation of percentage of valley-bottom transects on landward side of levees.

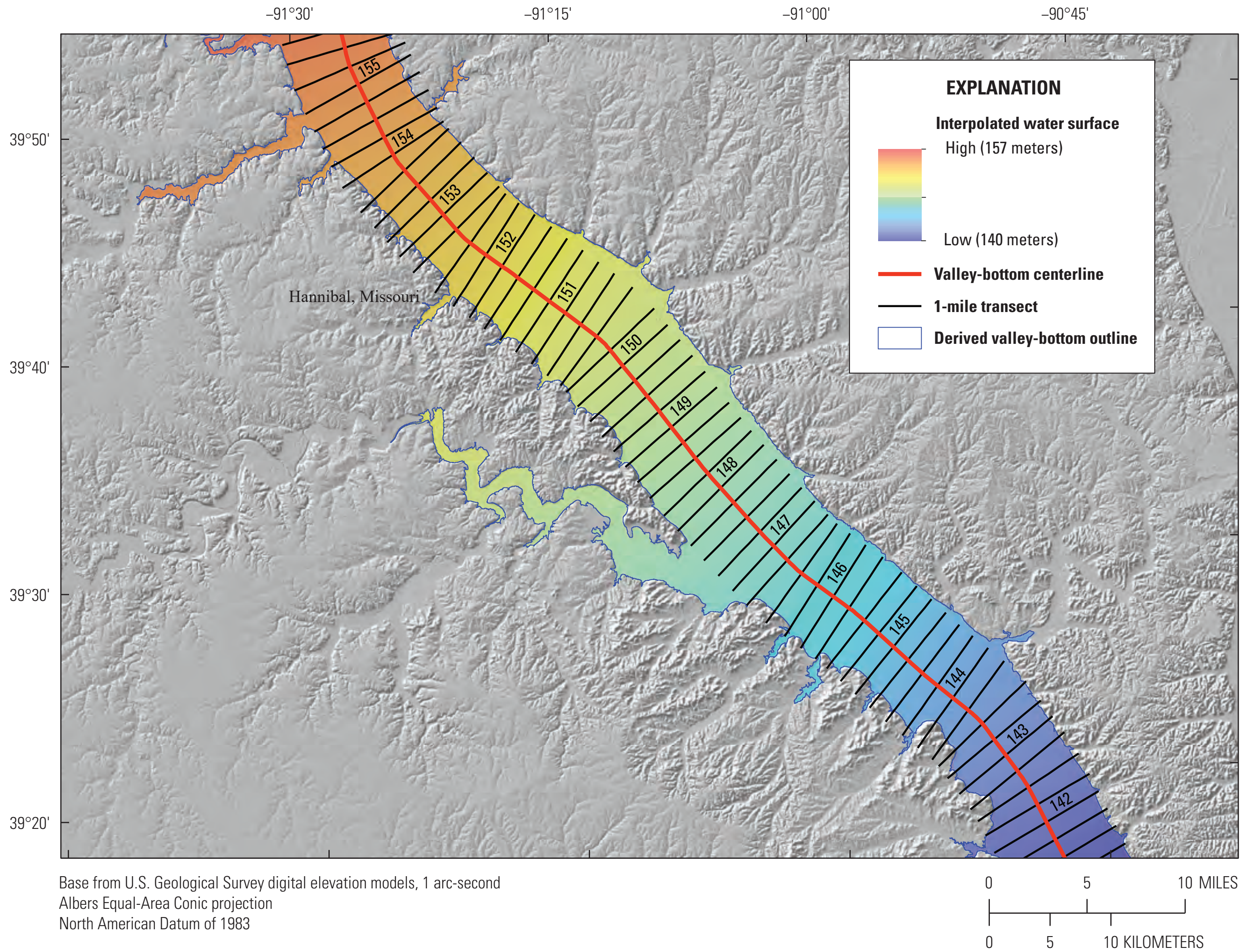


Figure 2. An example of the valley-bottom centerline used to derive perpendicular river transects. Also shown is an interpolated water surface, which was used in combination with river transects and the underlying digital elevation model to delineate the extent of the valley bottom. Data source: Rohweder (2019).

Once the valley bottom was derived, transects at 1-mile spacing (see example in fig. 3) were extended until they intersected the derived valley bottom outline using the "Extend tool" in ArcGIS. Transects that extended up into the valleys of connecting tributaries were not included because the resulting values were very large and a source of spatial bias. Inclusive features within the derived valley-bottom outline, such as raised plateaus, were removed. The total length of these extended transects was then calculated. Figure 3 shows transects extended to the valley-bottom outline. The average and standard deviation of the length of transects that intersected each 10-km river segment were then calculated and used as estimates of average and standard deviation of floodplain width. Finally, we merged the leveed areas from the U.S. Army Corps of Engineers National Levee Database (U.S. Army Corps of Engineers, 2014, 2015) with the floodplain-width transects. The average percentage of transects on the landward side of levees and coefficient of variation of the length of the transects that were landward of the leveed area polygons were then calculated (fig. 3).

Sinuosity was measured as the deviation of a line from the shortest possible path between the two endpoints of that line. The sinuosity index is calculated by dividing the length of the river segment by the shortest possible distance between the endpoints of that line and was calculated for each individual segment using an ArcGIS python toolbox. The linear representation of rivers in our study was taken from the NHD Plus version 2 NHDFlowline data source (McKay and others, 2014). These stream network segments extend uninterrupted from the mouth of the stream, upstream to the point it becomes less than stream order 7. Sinuosity is an index that ranges from 1 (perfectly straight line) to 2 or higher (highest sinuosity).

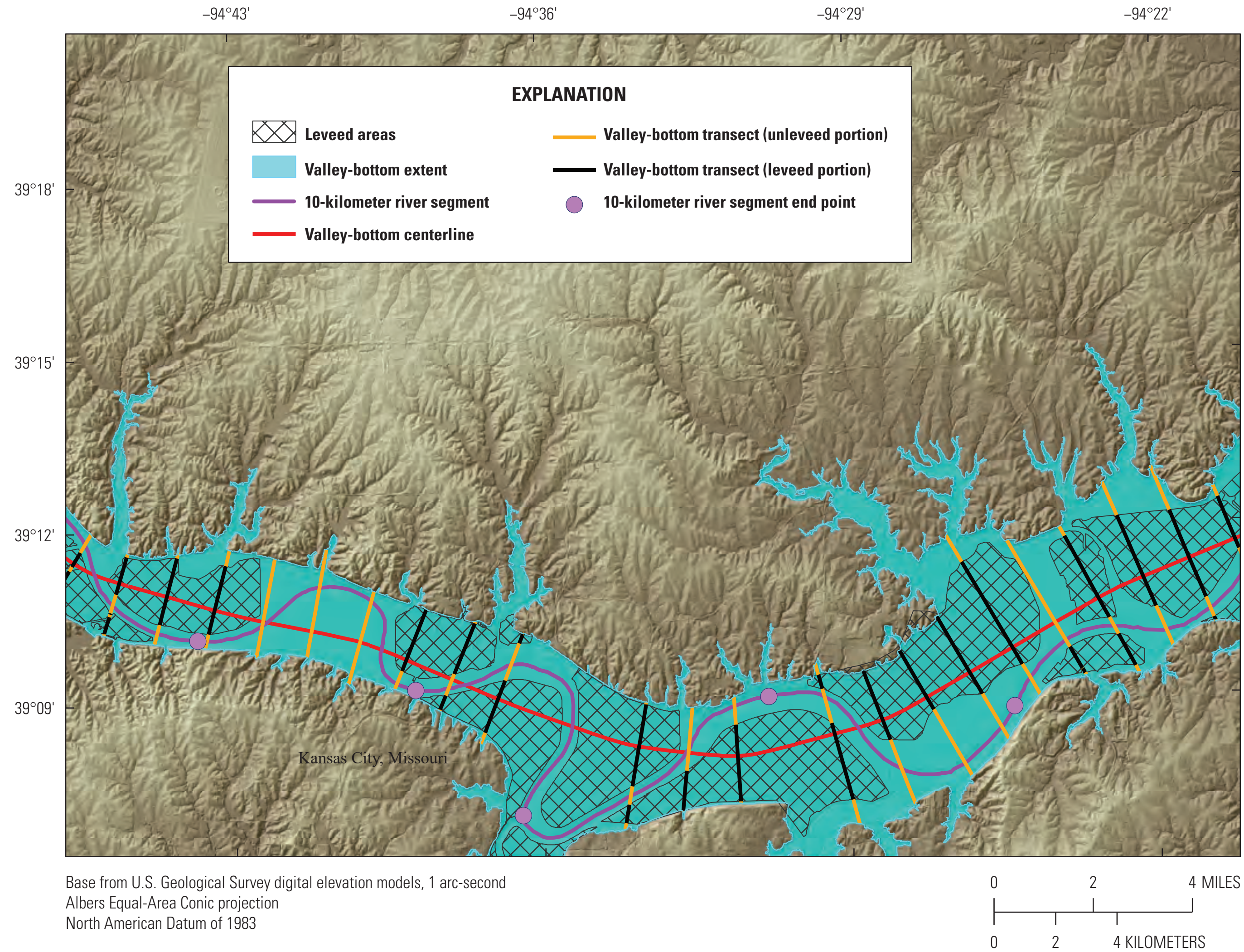


Figure 3. An example of using transects to measure valley-bottom width, length of transect behind levees, and sinuosity between river segment end points. Data source: Rohweder (2019).

Statistical Analysis

The 5 variables described above were measured for 1,172 10-km river segments and used in multivariate analyses similar to the hydrologic analysis. We explored geomorphic variables statistically using scripts written in R (R Development Core Team, 2013). The steps include the following:

1. Normalizing data by centering around the mean and scaling by the standard deviation.
2. Evaluating optimum number of clusters by creating a scree-plot of within-cluster sum of squares by number of clusters, to help select the number of *k*-means clusters that adequately describe the data, as well as other measures.
3. Completing a PCA of the scaled data to illustrate degree of separation of clusters.
4. Creating boxplots of scaled data by clusters to visualize how clusters differ.
5. Attributing reaches with cluster numbers to map clusters.

Hydrogeomorphic Classification

The separate hydrologic and geomorphic classifications provide some insights into connectivity differences among rivers using two separate datasets. However, a combined classification that uses both sources of data would provide a more integrated understanding of connectivity. To do this, we assigned 10-km segments to representative streamgages so hydrologic characteristics could also be associated with each segment. Assignment of segments to streamgages is not an exact process and depends on judgement about how much effect changing drainage area may have on segment-scale hydrology between streamgages. Generally, downstream segments were assigned to streamgages until a new streamgage location was encountered. If a large tributary entered the main stem between streamgages, the segments downstream of the tributary were assigned to the upstream or downstream gage, depending on judgement about relative influence. We used the same sequence of statistical analysis steps for the hydrogeomorphic database that we used for the separate hydrologic and geomorphic classifications.

Results—Potential for Hydrologic Connectivity of Large Rivers of the Upper Midwest

General Categorical Classification of Rivers

Large rivers of the Upper Midwest United States have been highly altered for socioeconomic benefits (fig. 4). Of 11,654 km of river channel that qualify by our definition of large river, 45.3 percent have either been altered by a navigation pool (30.0 percent) or storage reservoir (15.3 percent). Somewhat more than half (54.6 percent) remains free flowing in the sense that they are not directly impeded by a reservoir, although all are affected to some extent by upstream reservoirs. The unimpounded reach type does not differentiate between segments that have been channelized, stabilized, or both, and those that have minimal channel alterations. By major river basin (Missouri, Upper Mississippi, and Ohio), the Missouri River Basin large rivers are notable for the lack of navigation pools, substantial proportion of storage reservoirs, and high percentage of unimpounded reaches (table 5). In contrast, large rivers of the Ohio and Upper Mississippi River basins have substantial proportion in navigation pools maintained by low-head dams and relatively low proportion in storage reservoirs.

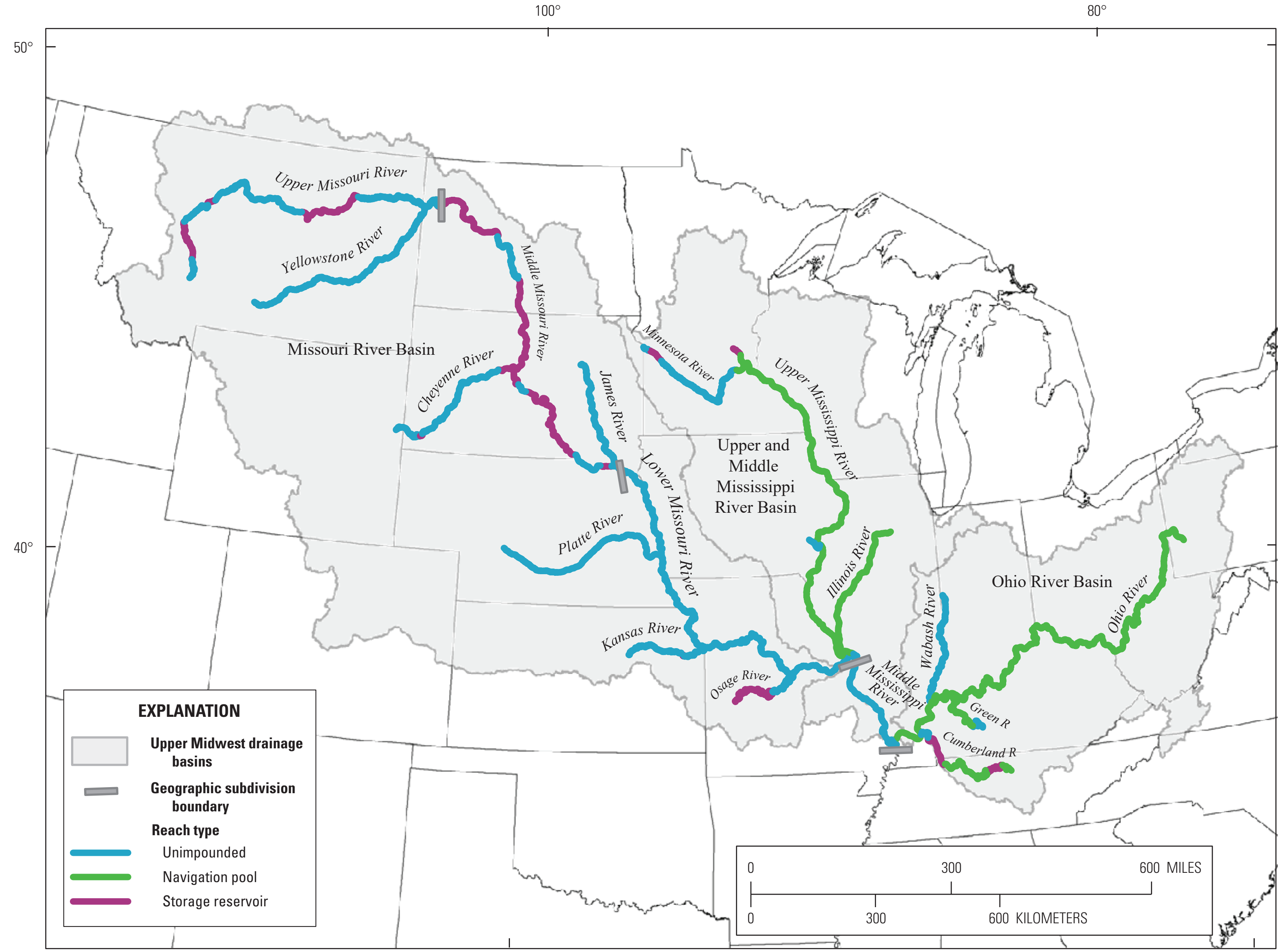
Each of the three major river basins has substantial reservoir storage, when summed by total storage area in the entire basin (table 5). Reservoir storage is highest in the Missouri River Basin, due in large part to the five main-stem reservoirs of the Missouri River Reservoir System, which accounts for 90 of the 168 cubic kilometers in the Missouri River Basin (fig. 5); however, reservoir storage is substantial throughout the Midwest.

Longitudinal Assessment of Connectivity

Longitudinal connectivity, as measured by spatial density of dams in the National Inventory of Dams (NID), varied among the rivers of the Upper Midwest. It is important to note that connectivity measures based on dams in the NID are contingent on how complete the NID is and on the assumption that dams are the major impediment to network connectivity. For our simplified analysis we looked at total number of dams in the three main river systems (Missouri, Upper and Middle Mississippi, and Ohio), and number of dams along the large rivers in the classification dataset (table 6). Connectivity potential of these dams may vary by construction characteristics, including height and overall area of the impoundment, which would affect ability of the impoundment to transmit sediment and other transported constituents through the reservoir. Connectivity for fish migrations—an important ecological aspect for large rivers—will vary as well by height, hydrology, and construction, and whether or not passage is possible through fish-passage structures or navigation locks.

If areal density of dams in the NID is assumed to be a surrogate metric for diminished total longitudinal connectivity, the Missouri River basin has the most at 0.015 dams per square kilometer, followed by the Upper Mississippi and the Ohio Rivers (table 6). If assessment of diminished connectivity is limited to dams on the main stems of the river segments that we have classified as large, the linear dam density of the Upper and Middle Mississippi River is greatest at 0.016 dams per kilometer (dams/km), followed by the Ohio River (at 0.01 dams/km) and the Missouri at 0.005 dams/km. Although the Missouri River large-river segments have the lowest density, they have the highest median height, followed by the Ohio and Upper Mississippi Rivers (fig. 6; table 6).

The navigation pools of the Upper Mississippi and Ohio Rivers contribute to the high spatial density, but the navigation dams are relatively low, are frequently opened to allow free flow of water at high flows, and allow some transport through the lock chambers at low flows—including upstream migration of native and invasive fishes (O'Connell and others, 2011). The dams in the Missouri River drainage basin lack locks for navigation and are generally higher, presenting more persistent and formidable impediments to longitudinal connectivity. The high dams on the Missouri River main stem have prevented (so far) invasion by Asian carps upstream from the lowest dam at Gavins Point, S. Dak. (Nico and others, 2018a, b). Although dams in the Missouri River large-river segments tend to be higher and therefore act to diminish connectivity, the lack of navigation dams and locks on 1,300 km of the Lower Missouri River contributes to the most connected river sections among the Upper Midwest large rivers (fig. 7). This is due to the historical decision to develop navigation on the Missouri River using channel-training structures instead of dams and locks (Ferrell, 1996). Because the Middle Mississippi River is also free flowing, connectivity of the Missouri and Mississippi results in as much as 3,080 km of connected large-river habitats.



Base from U.S. Geological Survey digital data, 2012
Albers Equal-Area Conic projection

Figure 4. Distribution of unimpounded, navigation-pool, and storage-reservoir segments of large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).

Table 5. Percentages and lengths of segment types by major large rivers of the Upper Midwest.

Segment type	Unit	Cheyenne River	Cumberland River	Green River	Illinois River	Iowa River	James River	Kansas River	Minnesota River
Unimpounded	Percent	92.7	8.2	29.4	0.0	100.0	100.0	100.0	94.4
	Kilometer	507	40	71	-	47	475	290	501
Navigation pool	Percent	0.0	50.9	70.6	100.0	0.0	0.0	0.0	5.6
	Kilometer	-	249	170	388	-	-	-	30
Storage reservoir	Percent	7.3	40.9	0.0	0.0	0.0	0.0	0.0	0.0
	Kilometer	40	200	-	-	-	-	-	-

Segment type	Unit	Mississippi River	Missouri River	Ohio River	Osage River	Platte River	Wabash River	Yellowstone River	All Rivers
Unimpounded	Percent	23.1	66.1	0.0	35.9	100.0	100.0	100.0	55.1
	Kilometer	330	2,457	-	130	518	393	664	6,422
Navigation pool	Percent	75.0	0.0	100.0	0.0	0.0	0.0	0.0	29.8
	Kilometer	1,070	-	1,567	-	-	-	-	3,474
Storage reservoir	Percent	1.9	33.9	0.0	64.1	0.0	0.0	0.0	15.1
	Kilometer	26	1,260	-	232	-	-	-	1,758

Segment-Scale Classification of Lateral Connectivity

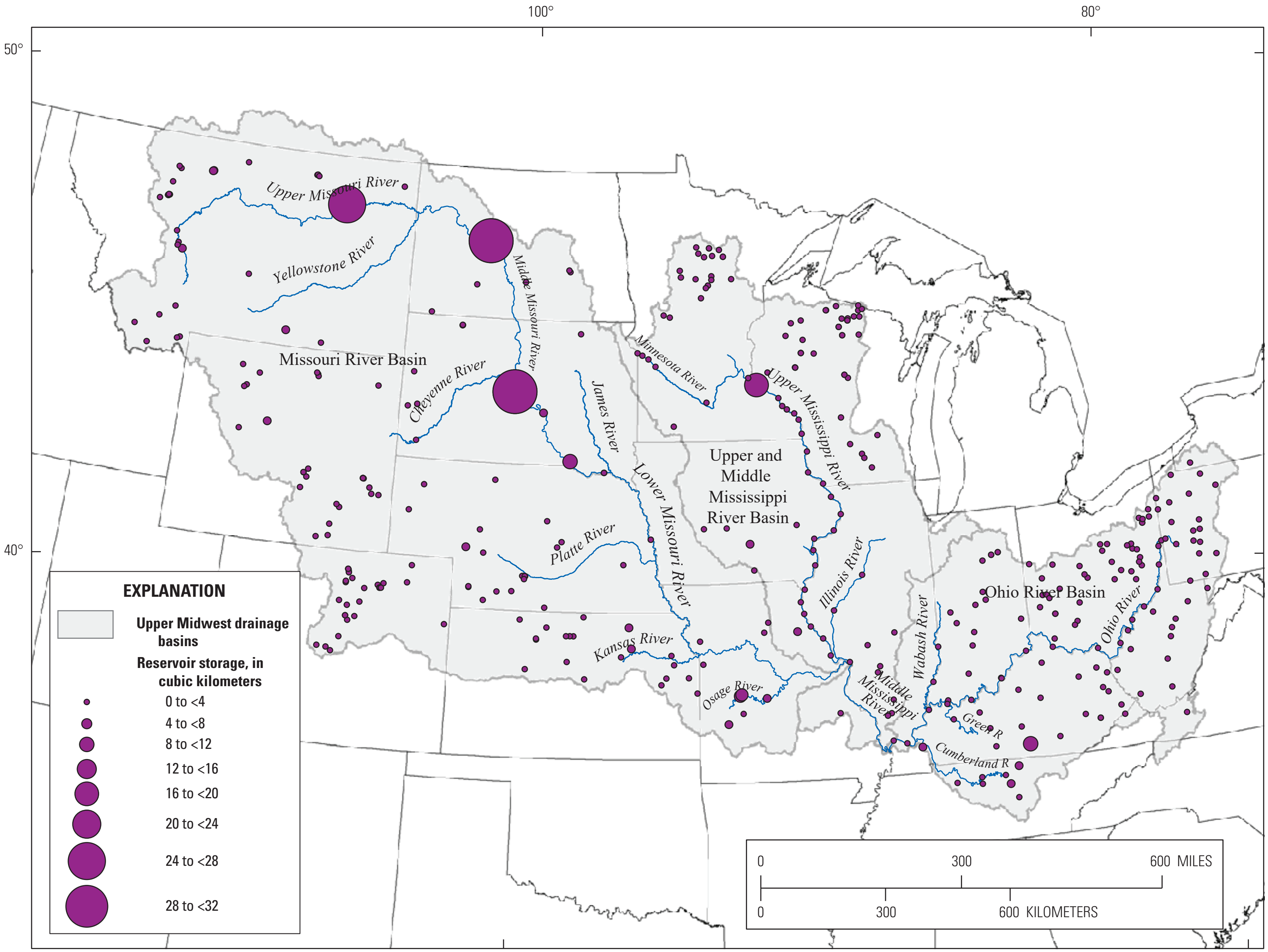
Hydrologic Analysis of Lateral Connectivity

The spatial distributions of hydrologic measures of connectivity indicate strong east-west differences, as would be expected from the existing precipitation gradients (fig. 8). When normalized by drainage area, bankfull discharge variation documents the increased discharge by unit drainage area in the Ohio and Upper Mississippi River Basins compared to the Missouri River Basin (fig. 9).

The average duration of floods that are greater than the bankfull threshold are noticeably higher in the west and north of the study area, presumably reflecting the effect of annual snowmelt flooding. (fig. 10). Regardless of the number of qualifying events, the average duration of floods was calculated as the average consecutive days of flow above the threshold. The James River stands out as an anomaly with very high durations. The flood index is a measure of relative influence of large (1-percent annual exceedance probability floods) relative to smaller (50-percent annual exceedance probability floods; fig. 11). As such it measures the skewness and breadth of the flood-frequency distribution. The large values of flood index on the James River again stand out as anomalies, followed by high values on the Platte River. In contrast, the number of bankfull events per year at or above the bankfull flow, is anomalously small on the James River compared to other rivers (fig. 12). The statistically expected number of bankfull events per year is 0.5, based on the flood-frequency calculation; hence, smaller numbers indicate a distribution with fewer small floods per year and a larger number indicates more frequent floods over the bankfull threshold each year. The cluster of values greater than one on the Kansas and Lower Missouri Rivers indicate a tendency for these rivers to experience multiple floodplain-connecting floods greater than the bankfull threshold each year.

The hydrologic data were analyzed to identify naturally occurring clusters using the *k*-means R statistical function (R Development Core Team, 2013). First, the data were scaled by dividing by the mean. Next, an optimal number of clusters was evaluated using the R NbClust function (Charrad and others, 2014). NbClust runs 30 indices—including scree plots—to determine the optimum number of clusters designated by most of the indices. Of the 30 indices, 7 indices (the majority) indicated 3 was the optimum number. The three-cluster class was not considered to be particularly informative, so we proceeded to the next-ranked number of clusters (five) that was supported by five indices. Five hydrologic clusters were retained for further analysis although useful information could also be extracted using other numbers of clusters.

The data were analyzed subsequently by a k-means cluster for five clusters using the R k-means function. The separation of clusters in multivariate space is illustrated by bivariate plots of the first two components of a PCA (fig. 13); this was accomplished using the clusplot function in R. The cluster numbers were added back to the dataset and boxplots of the nonscaled values of each variable were developed to illustrate and interpret what each cluster represents (fig. 14). Cluster numbers were also added back as attributes to the reach shapefile to illustrate the geographic distribution of clusters (fig. 15).



Base from U.S. Geological Survey digital data, 2012
Albers Equal Area-Conic projection

Figure 5. The distribution of reservoir storage associated with dams in the Upper Midwest. Note that only reservoirs with greater than 0.05 cubic kilometer (40,000 acre-feet) of storage are shown. Data source: Jacobson and Rohweder (2019).

Table 6. Number of dams, dam areal density in the three main drainage basins, and number, linear density, and median height of dams in the large rivers of the Upper Midwest.

[Data are from U.S. Army Corps of Engineers (2013). km³, cubic kilometer; km², square kilometer; m, meter]

Rivers	Number	Drainage area (km²)	Minimum reservoir storage in basin (km³)	Dam density (number per km²)	Number of dams on large rivers	Large-river dam density (number per km²)	Large-river dam median height (m)
Missouri River	19,627	1,349,283	168.3	0.015	30	0.005	20.1
Upper and Middle Mississippi Rivers	5,273	492,027	45.4	0.011	39	0.016	12.8
Ohio River	3,782	421,962	53.8	0.009	26	0.010	18.1
Total	28,682	2,263,271	268	0.013	95	0.008	13.4

Geomorphic Analysis of Lateral Connectivity

The spatial distributions of geomorphic variables that we hypothesize affect lateral connectivity show variable geographic patterns. Floodplain width is a metric for how much area is potentially available for lateral connectivity; as indicated in the previous section describing calculation of the variables, floodplain width has been identified nominally as the valley bottom delineated by bluffs or clearly demarcated valley walls. Although floodplain width generally increases downstream with larger river size, there are also some instances of geologically influenced floodplain width (fig. 16). Wide floodplain widths on the Platte River are reflective of a wide, braided floodplain deposited within sandy, highly erodible surficial deposits. The wide floodplain of the Lower Missouri River upstream from the Platte River confluence results from deposition of proglacial outwash during multiple episodes of Pleistocene glaciations. The Missouri River floodplain varies substantially between the Platte and the Mississippi River confluence because of variation in erodibility of bedrock and the history of channel changes during the Pleistocene. Variations in floodplain width along the Mississippi River relate to confluences, generally increasing where rivers come together (for example, the Missouri, Mississippi, and Illinois rivers confluence). Although most of the upper Ohio River has a relatively narrow floodplain, areas of increased floodplain width are apparent near the Wabash River confluence and upstream on the Wabash, which was affected by extensive glacial outwash deposits. The standard deviation of floodplain widths (within a segment) reflects some of the broad geologic controls as well as more local variations (fig. 17).

Levees directly diminish connectivity potential. Leveed segments are concentrated in the wide, dominantly agricultural floodplains of the Kansas, Missouri, Mississippi, Illinois, and Wabash Rivers (fig. 18), although small areas of levees and floodwalls also exist at local scale, and some agricultural levees with low protection may not be well represented in the National Levee Database (U.S. Army Corps of Engineers, 2014, 2015). We used the coefficient of variation of percentage of leveed area to indicate segments where levee protection was more or less variable (fig. 19).

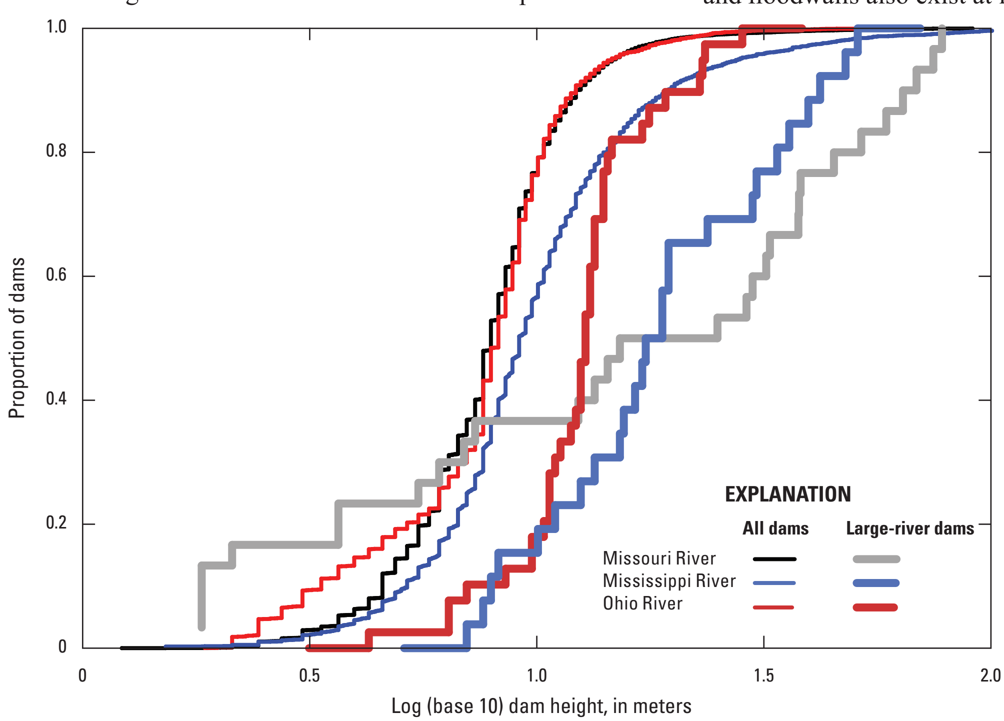
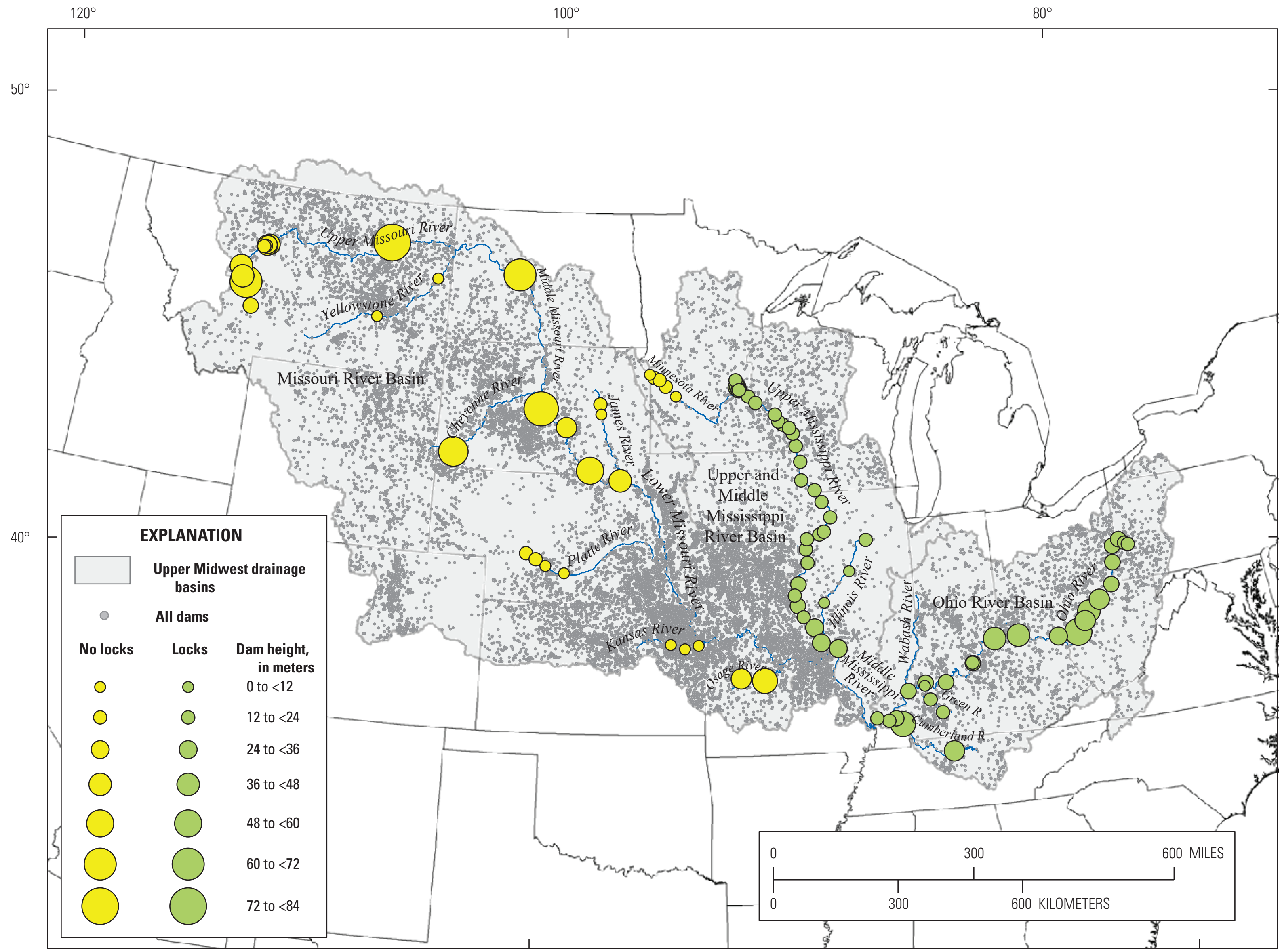
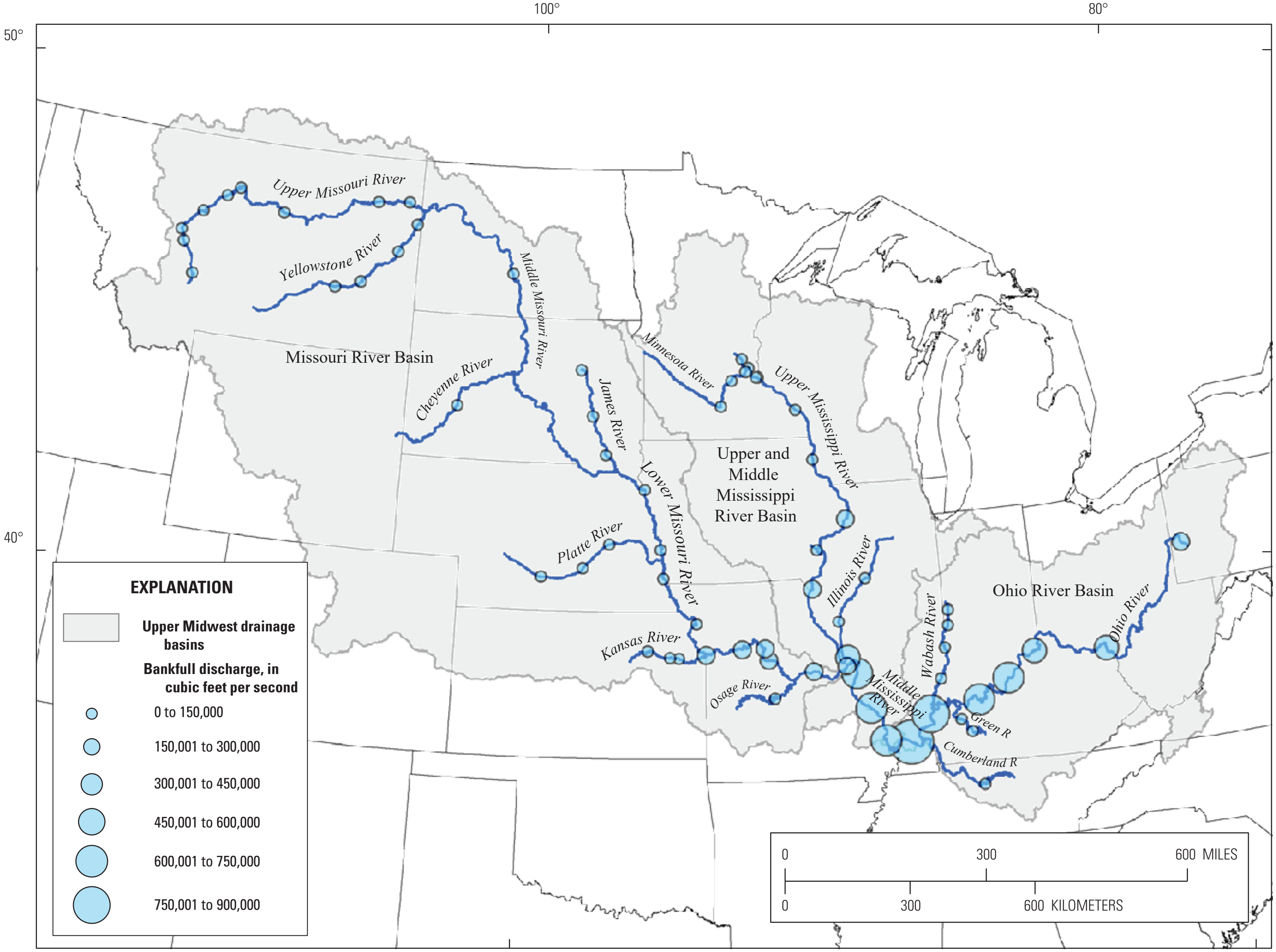


Figure 6. The cumulative distribution functions of dam heights (transformed by log base 10) of all dams from the National Inventory of Dams in the Missouri, Upper Mississippi, and Ohio River drainage basins, and for the dams on the large-river segments of the three drainage basins.



Base from U.S. Geological Survey digital data, 2012
Albers Equal-Area Conic projection

Figure 7. All dams from the National Inventory of Dams (NID), and NID dams on large-river segments, with and without navigation locks, symbolized in proportion to dam height, Upper Midwest. Data source: Jacobson and Rohweder (2019).



Base from U.S. Geological Survey digital data, 2012
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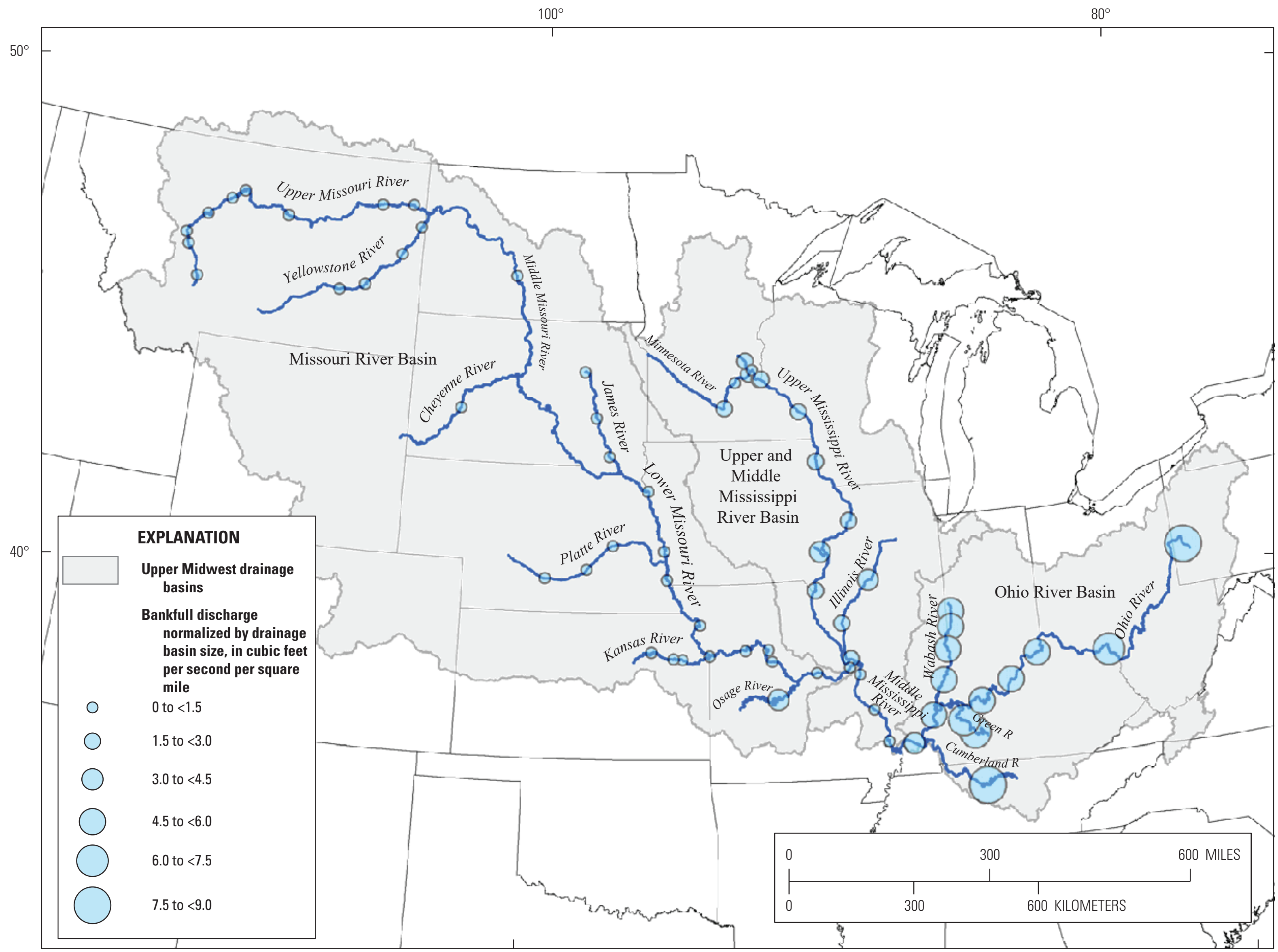
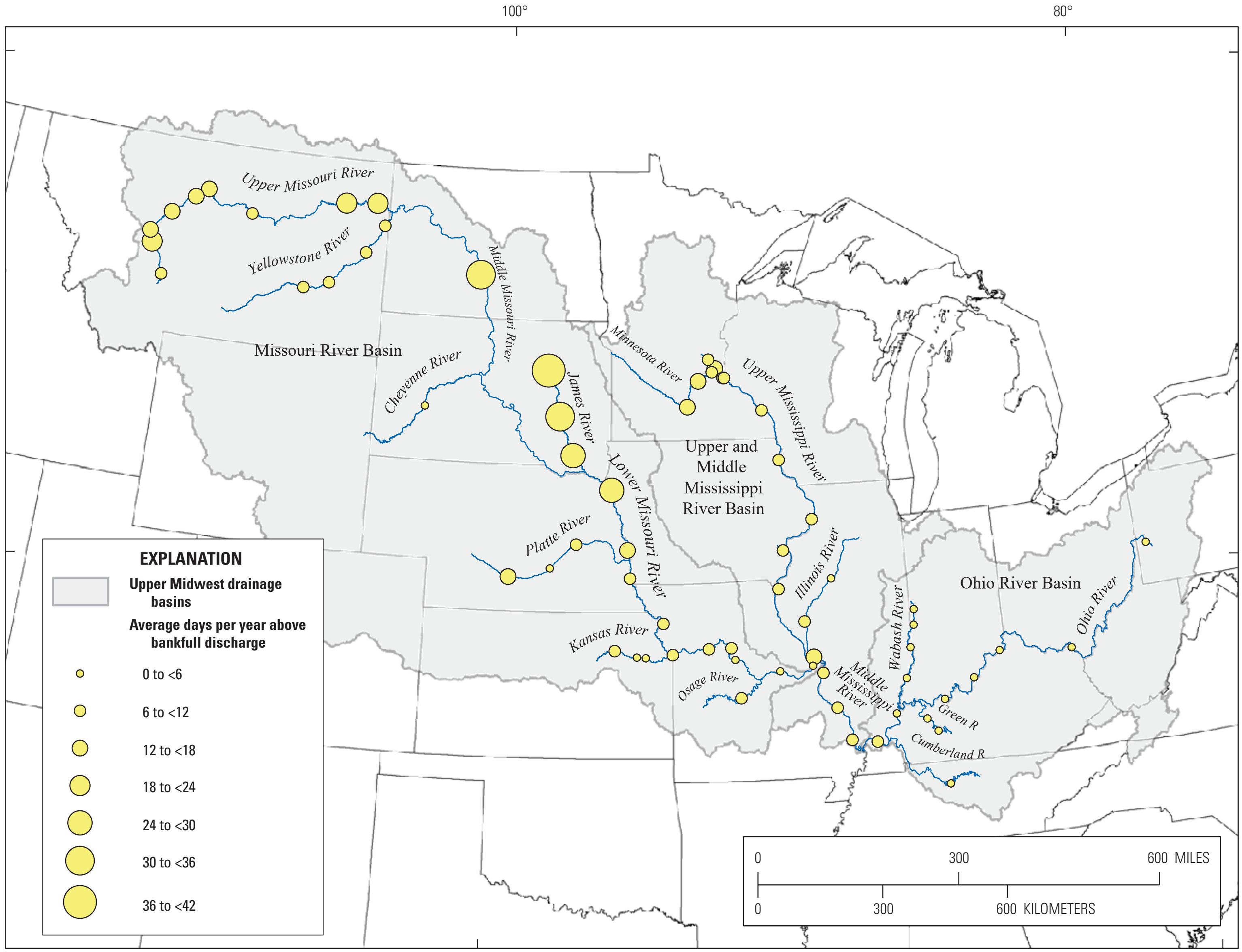
Figure 8. The distribution of bankfull discharge among large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).



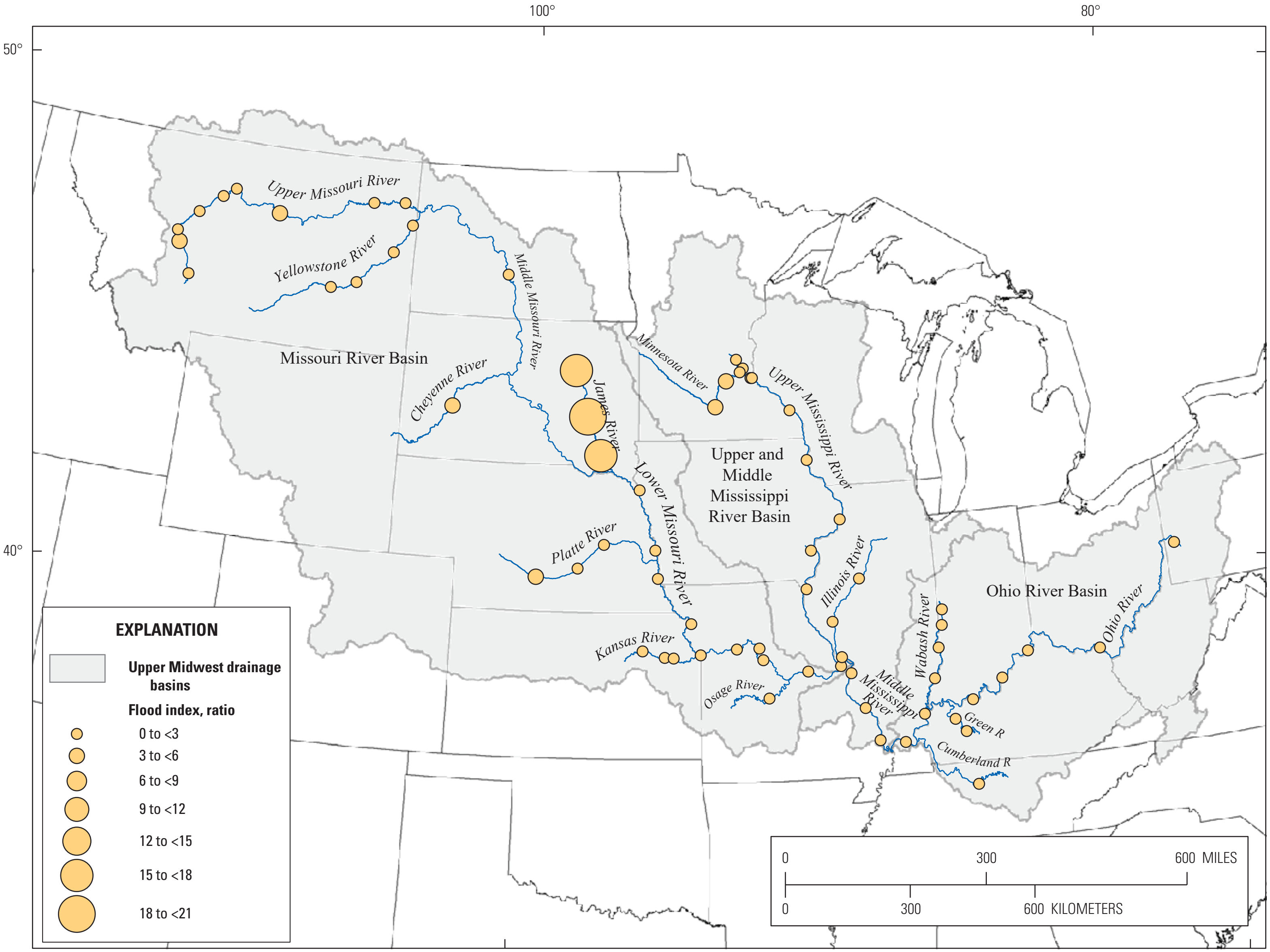
Base from U.S. Geological Survey digital data, 2012
Albers Equal-Area Conic projection

Figure 9. The distribution of bankfull discharge normalized by upstream drainage area for large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).



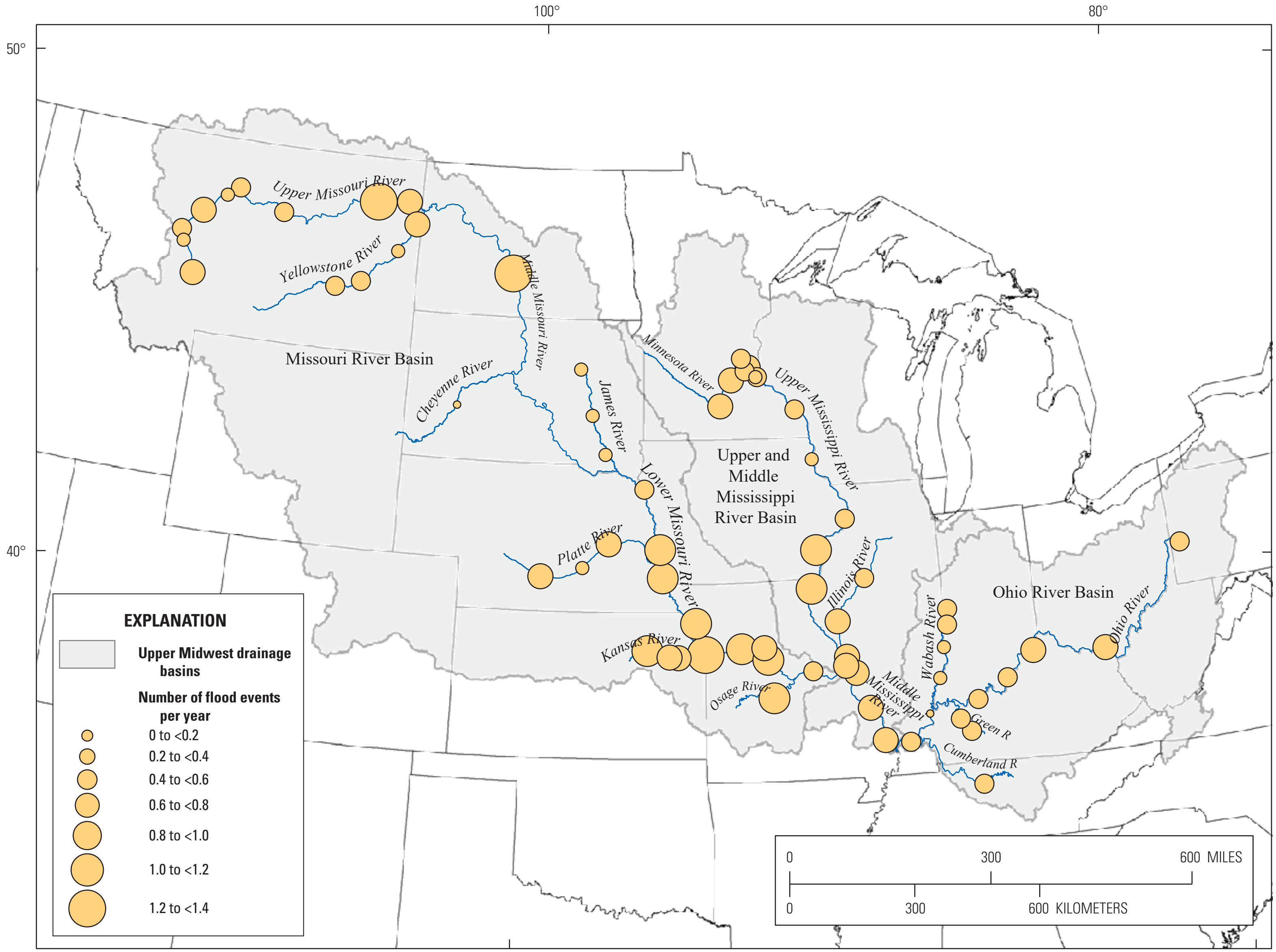
Base from U.S. Geological Survey digital data, 2012
Albers Equal-Area Conic projection

Figure 10. The distribution of average duration of floods greater than bankfull, large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).



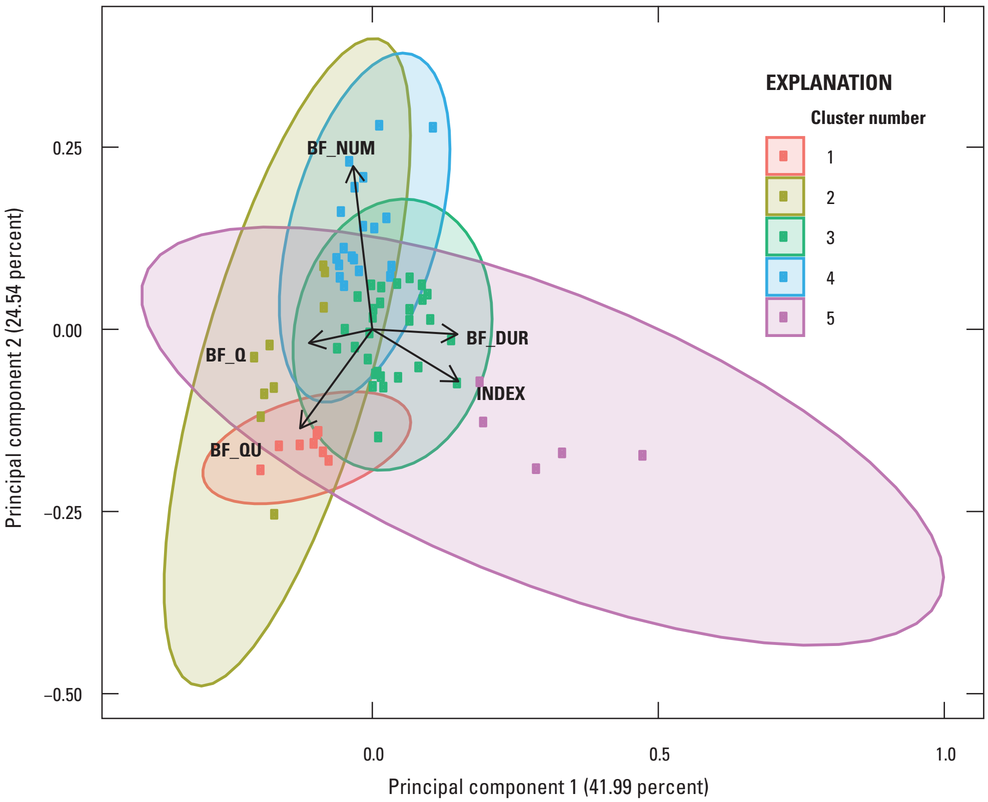
Base from U.S. Geological Survey digital data, 2012
Albers Equal-Area Conic projection

Figure 11. The distribution of the flood index calculated from the difference of the 1-percent annual exceedance probability flood and the 50-percent annual exceedance probability flood, divided by the 50-percent annual exceedance probability flood, to provide to provide a measure of temporal variability in connection events, large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).



Base from U.S. Geological Survey digital data, 2012
Albers Equal-Area Conic projection

Figure 12. The distribution of numbers of flood events greater than bankfull, a measure of frequency of connectivity, large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).



NOTE: BF_Q, bankfull flood magnitude; BF_QU, unit bankfull flood magnitude; INDEX, flood index; BF_NUM, number of events greater than or equal to bankfull per year; BF_DUR, average annual duration of bankfull floods. See text and table 3 for additional discussion of hydrologic metrics

Figure 13. The principal components analysis biplot of first two components for hydrologic metrics of connectivity. Data source: Jacobson and Rohweder (2019).

Sinuosity—calculated as the ratio of channel length to the shortest straight-line distance between the endpoints of each 10-km segment—is somewhat greater among smaller river segments because of the constant numerator and river scaling (fig. 20). Sinuosity is included as a connectivity metric because it is indicative of the potential for hydraulic interaction of a channel with its floodplain; in addition to increasing channel/floodplain interface with increasing sinuosity, a more sinuous channel provides more opportunities for water to be directed onto floodplains at bends. The James and Wabash Rivers are notable for their relatively large sinuosity. By contrast, the Platte River—with its highly braided channel through a sandy floodplain—is relatively straight at the 10-km segment scale.

The geomorphic data were analyzed using the same sequence of steps as the hydrologic analysis. NbClust returned two clusters as the optimum (with nine indices supporting). We considered two clusters to be uninformative for our classification purposes and therefore selected five clusters, which had the next most-supported number of indices with four.

The data were subsequently subjected to a k-means cluster for five clusters using the R k-means function. The separation of clusters in multivariate space is illustrated by bivariate plots of the first two components of a PCA (fig. 21); this was accomplished using the clusplot function in R. The cluster numbers were added back to the dataset and boxplots of the nonscaled values of each variable were developed to illustrate and interpret what each cluster represents (fig. 22). Cluster numbers were also added back as attributes to the reach shapefile to illustrate the geographic distribution of clusters (fig. 23).

Hydrogeomorphic Analysis of Lateral Connectivity

Similar to the preceding analyses of hydrologic and geomorphic variables, the hydrogeomorphic variables assigned to each 10-km reach were analyzed by determining the optimum number of clusters, k-means clustering, and PCA. NbClust returned eight clusters as the optimum, and the clusplot function was used to illustrate the clusters in multivariate space (fig. 24); this was accomplished using the clusplot function in R. The cluster numbers were added back to the dataset, and boxplots of the nonscaled values of each variable were developed to illustrate and interpret what each cluster represents (fig. 25). Cluster numbers were also added back as attributes to the reach shapefile to illustrate the geographic distribution of clusters (fig. 26).

Hydrogeomorphic Assessment of Connectivity of Large Rivers of the Upper Midwest

Categorical, hydrologic, geomorphic, and combined hydrogeomorphic classifications illustrate the breadth of variation across large rivers of the Upper Midwest. Recognition of that variation may be useful in organizing understanding of the rivers and for structuring sampling designs of large-river ecological characteristics.

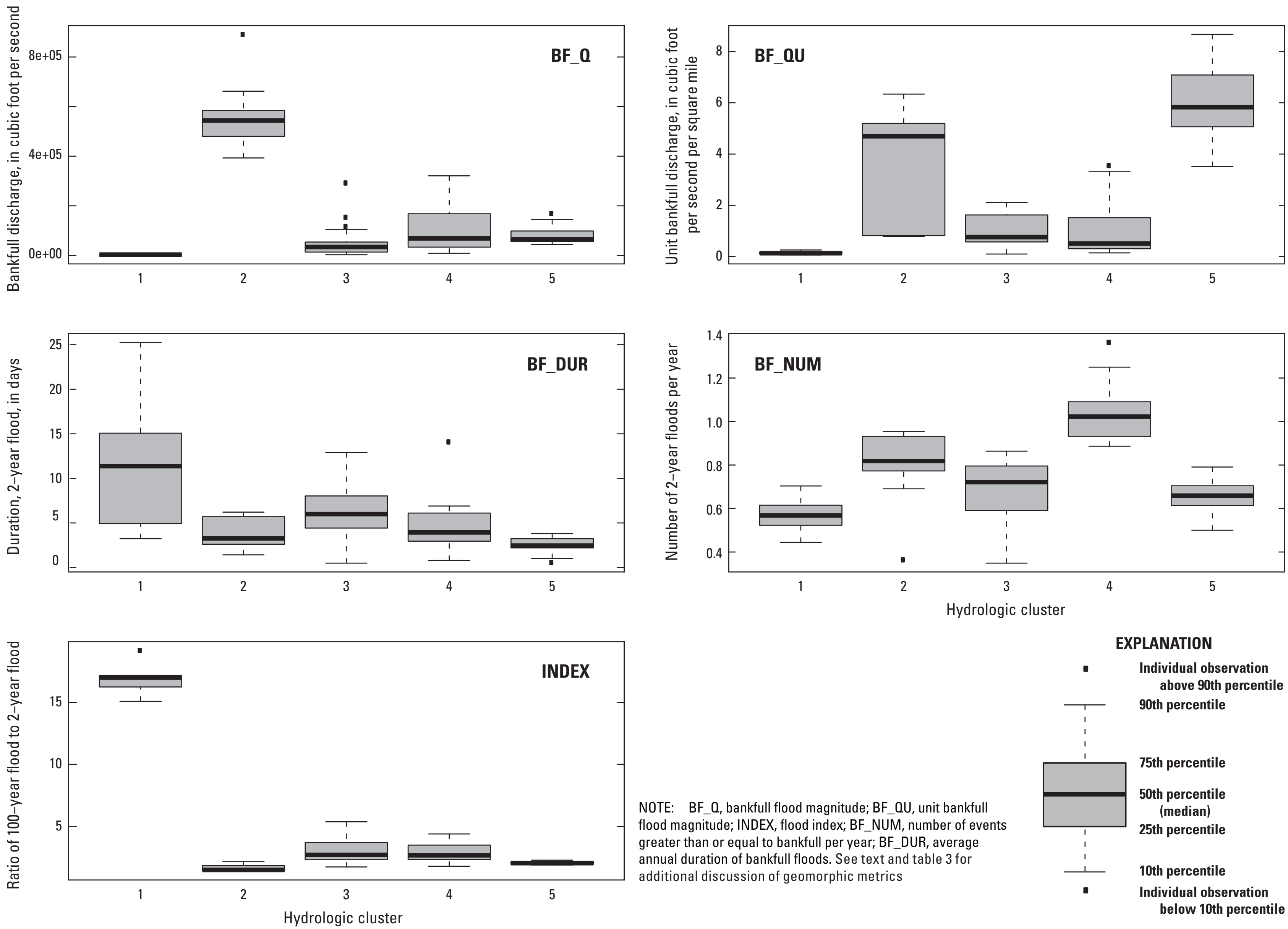
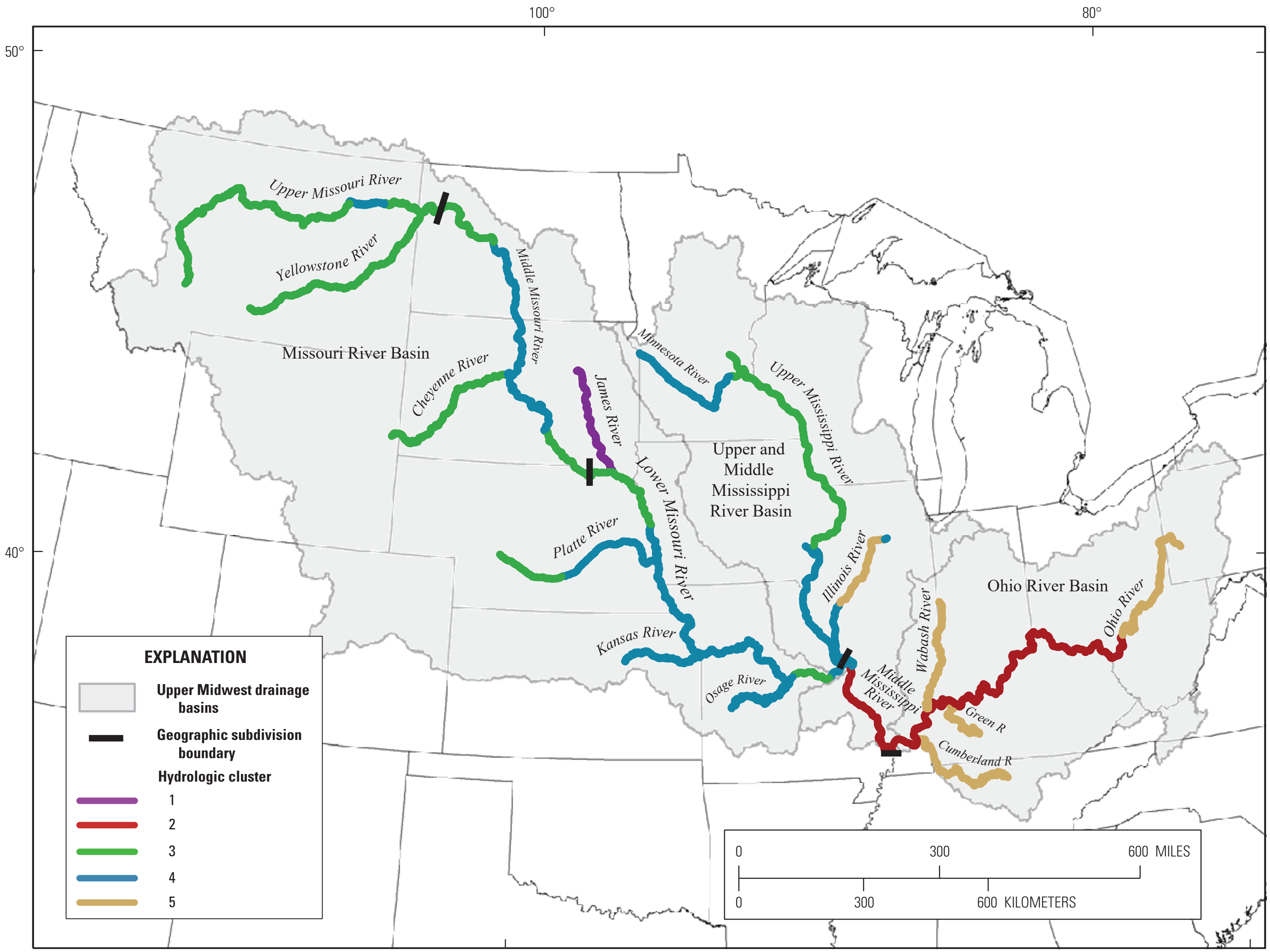
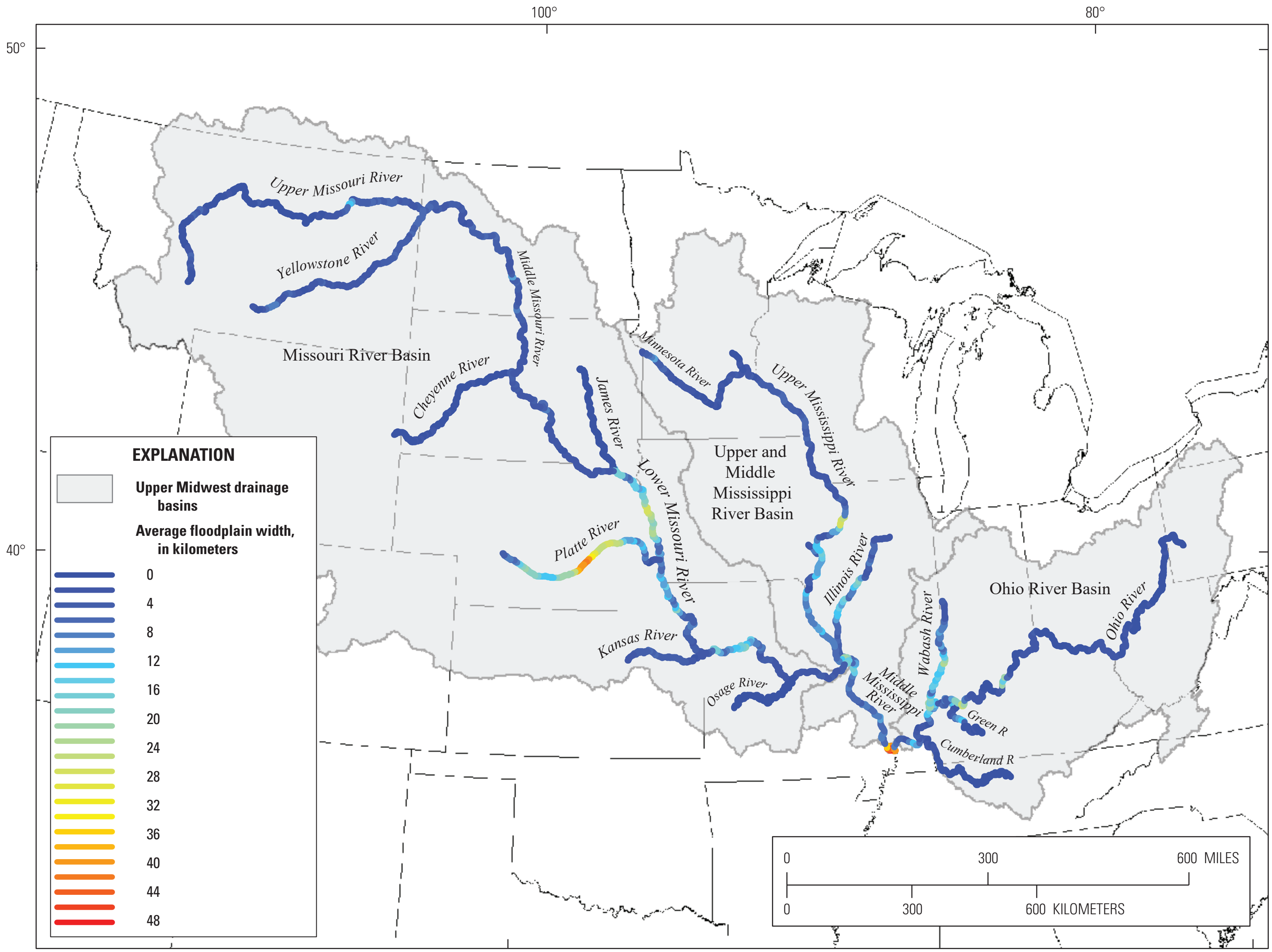


Figure 14. Distributions of hydrologic metrics by hydrologic cluster. Data source: Jacobson and Rohweder (2019).



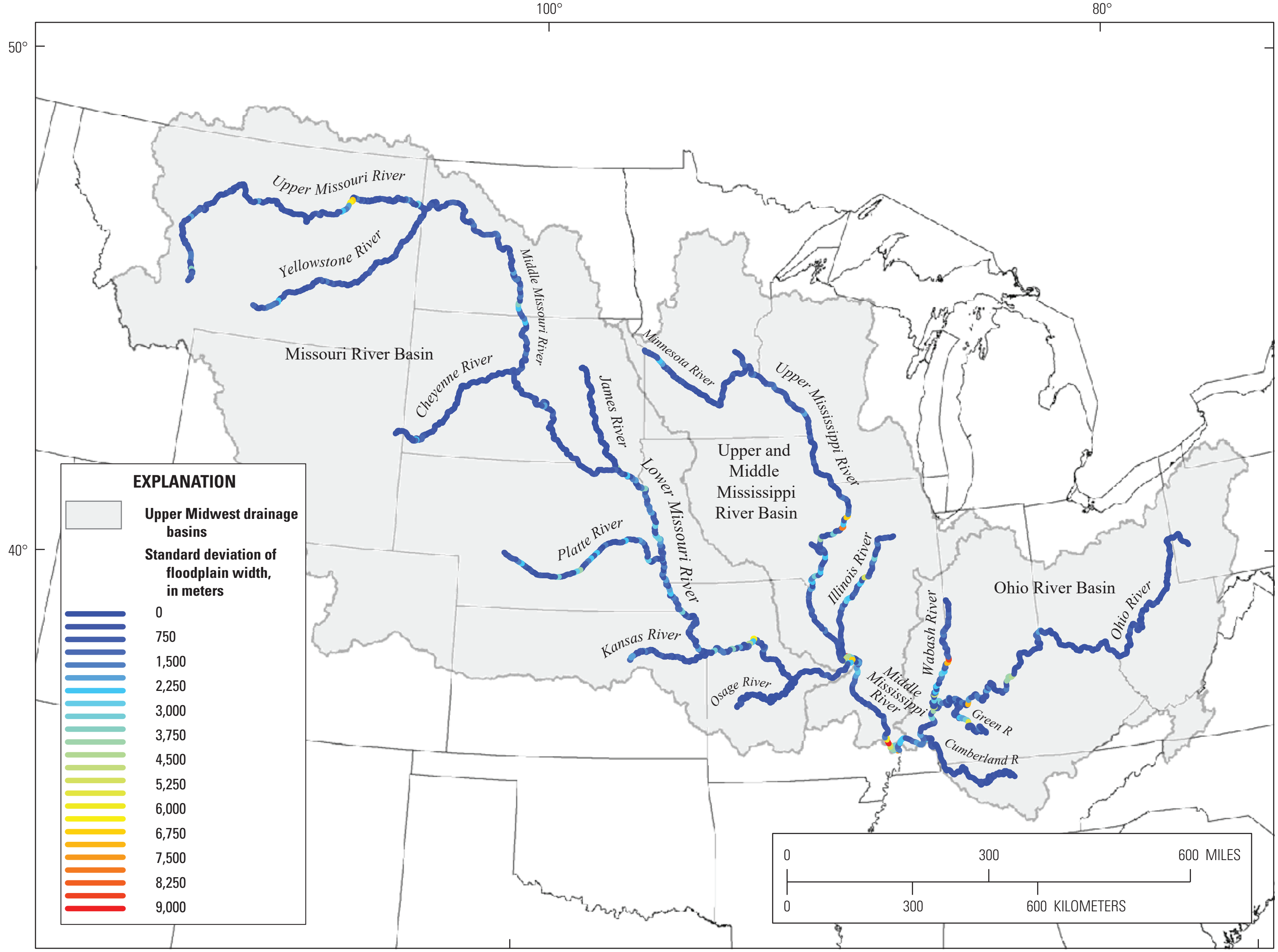
Base from U.S. Geological Survey digital data, 2012
Albers Equal-Area Conic projection

Figure 15. The distribution of hydrologic clusters, large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).



Base from U.S. Geological Survey digital data, 2012
Albers Equal-Area Conic projection

Figure 16. The average floodplain width within 10-kilometer segments, large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).



Base from U.S. Geological Survey digital data, 2012
Albers Equal-Area Conic projection

Figure 17. Standard deviations of floodplain width within 10-kilometer segments, large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).

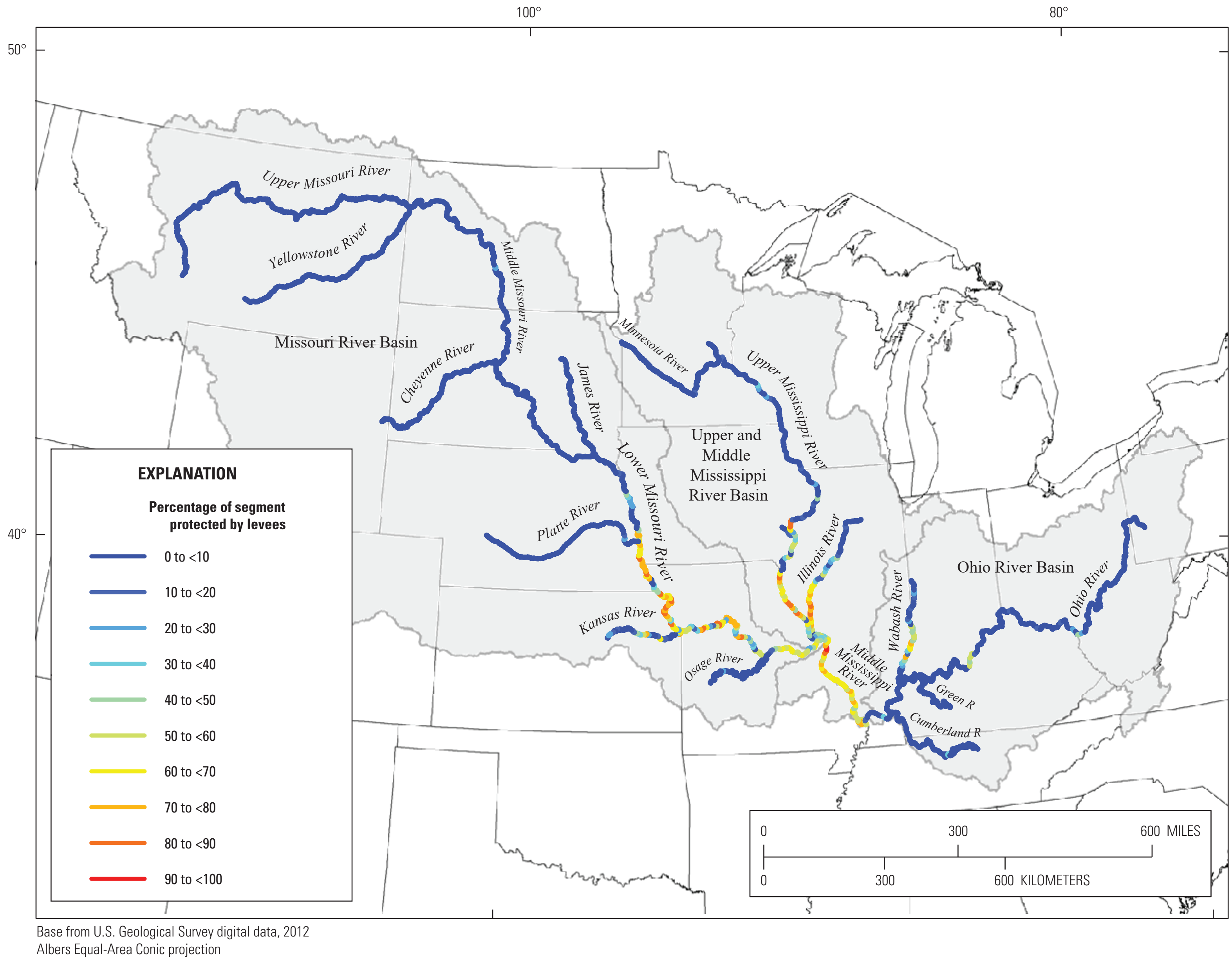
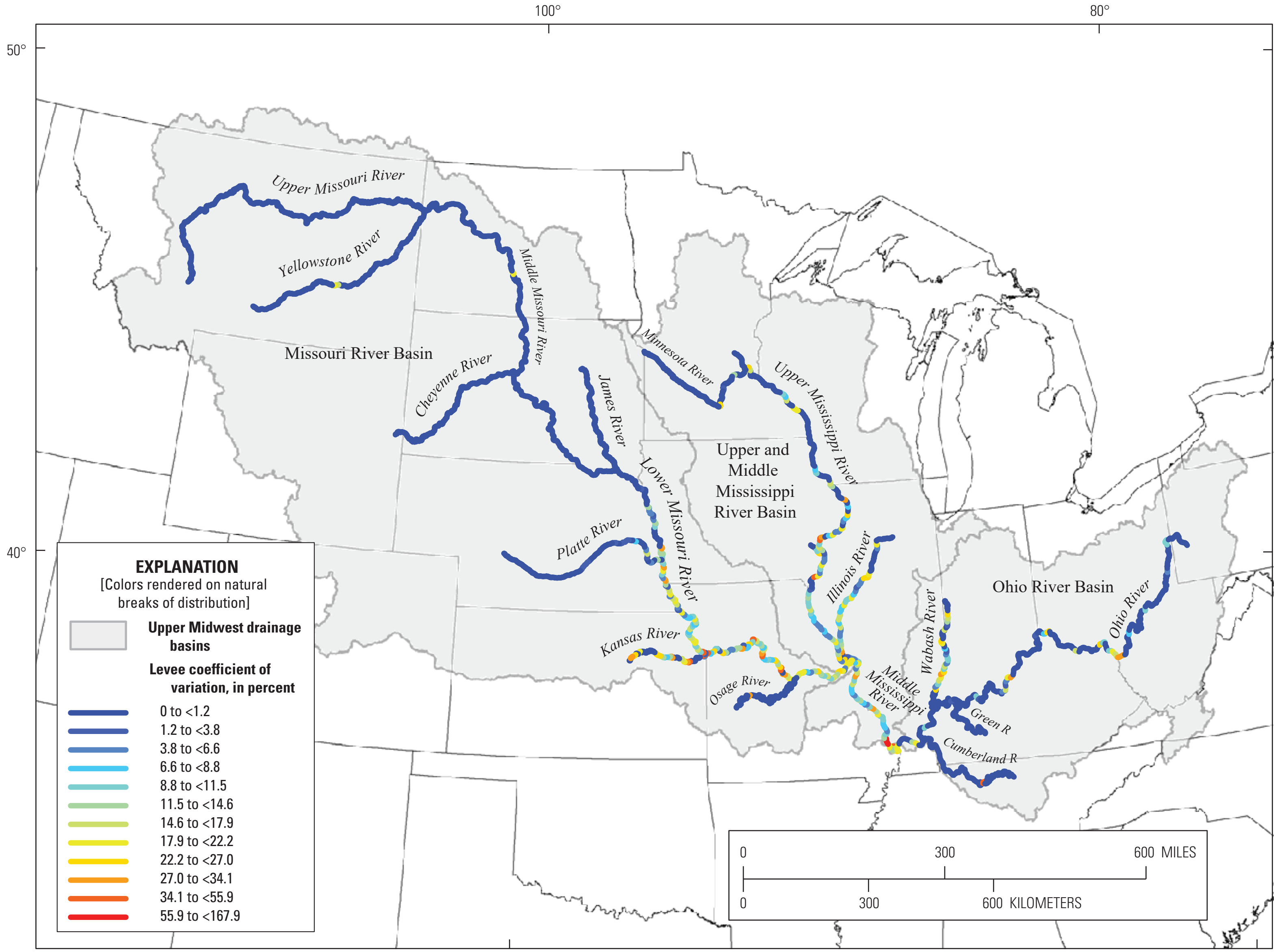
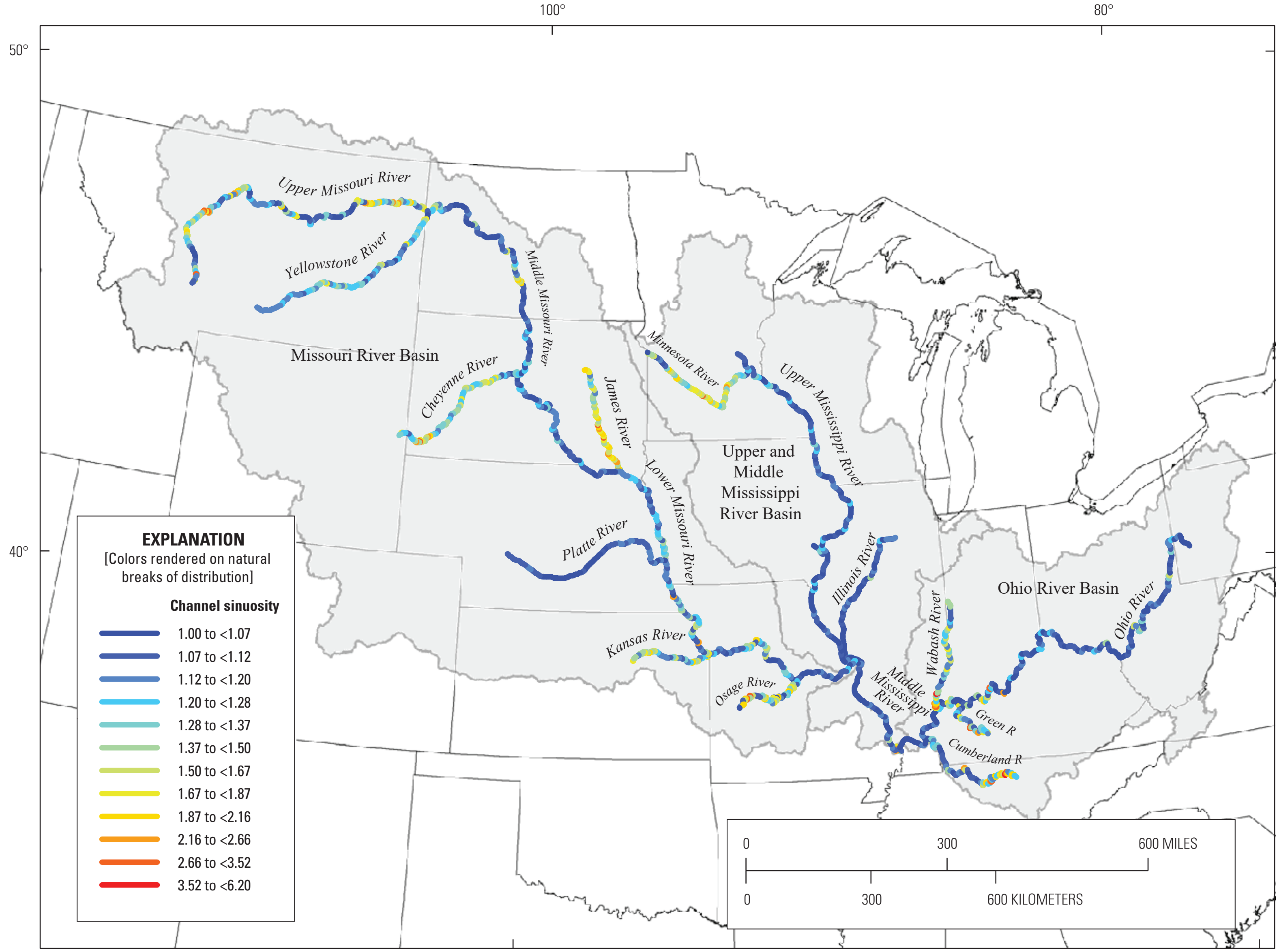


Figure 18. The percentage of river segments protected by levees, large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).



Base from U.S. Geological Survey digital data, 2012
Albers Equal-Area Conic projection

Figure 19. The levee coefficient of variation of protection by levees within a 10-kilometer river segment, large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).



Base from U.S. Geological Survey digital data, 2012
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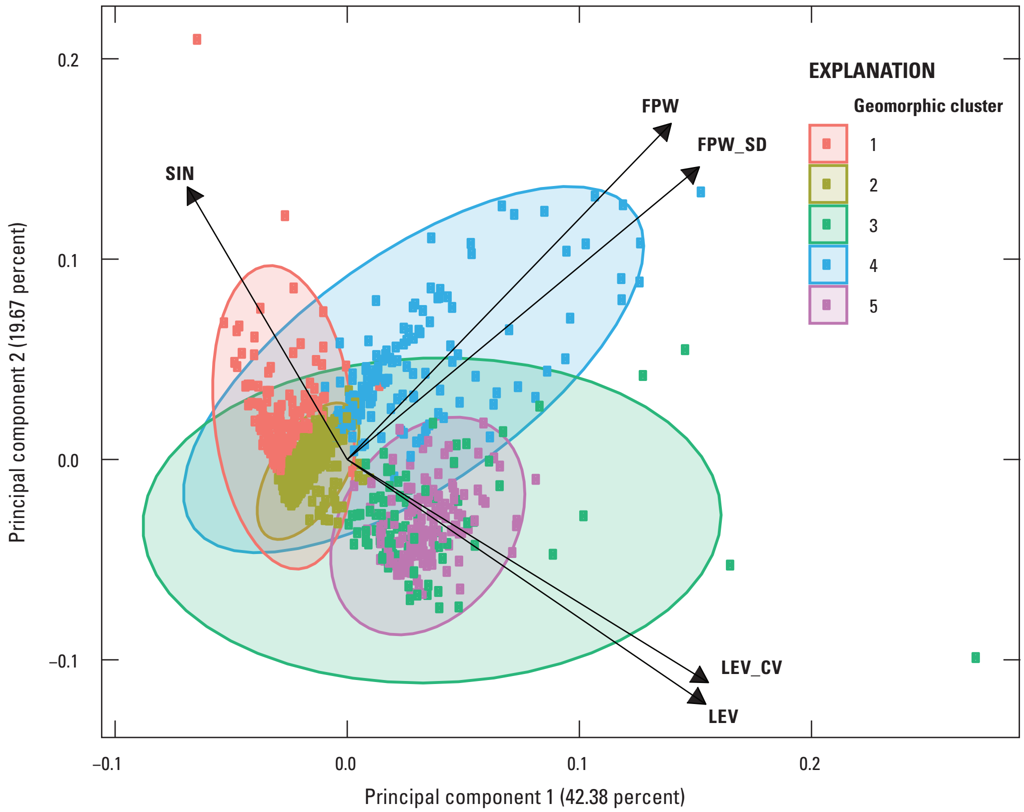
Figure 20. Channel sinuosity for each 10-kilometer segment, large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).



NOTE: SIN, sinuosity; FPW, average floodplain width; FPW_SD, standard deviation of floodplain width; LEV, average percent leveed; LEV_CV, coefficient of variation of percent leveed. See text and table 3 for additional discussion of geomorphic metrics

Figure 21. The principal components analysis biplot of the first two components for geomorphic metrics of connectivity. Data source: Jacobson and Rohweder (2019).

General Categorical Classification

We classified river segments into broad categories indicative of the degree of anthropogenic alteration: unimpounded, navigation pools, and storage reservoirs (fig. 4). This integrated classification simplifies some segments that grade from one type to another. For example, inter-dam reaches of the navigable Mississippi, Illinois, and Ohio Rivers are lumped as navigation pools, although in detail they are typically composed of a complex of alluvial reaches directly downstream from the navigation dams, grading downstream into variably connected backwaters, and then into impounded pools (Jacobson and others, 2010; Alexander and others, 2012; Skalak and others, 2013; Remo, 2016). Assignment to segment type is also affected by the 10-km resolution used in the classification because each 10-km segment is assigned to only one dominant type rather than being split into subsegments.

The general categories are useful for understanding the breadth of river segment types that exist in these rivers, but their application to lateral connectivity is somewhat ambiguous. Unimpounded segments are those without direct impoundment by storage reservoirs or navigation dams, although the hydrology may be controlled to a considerable extent by upstream reservoirs. Connectivity in unimpounded segments is controlled in part by the hydrology of the segment and may be increased or diminished by the degree of upstream flow regulation. Reservoir storage segments are no longer riverine, and in most cases large parts of the floodplains in these former riverine segments are completely inundated. In a sense, complete inundation has maximized connectivity but at the expense of some riverine functions, such as hydrologically driven flow pulses that episodically connect the floodplain (Junk and others, 1989). Navigation pool segments are similar to inter-reservoir segments (Skalak and others, 2013) in that they typically comprise an alluvial reach downstream from the upstream navigation dam, a reach of enhanced connectivity (the aquatic-terrestrial transition zone [ATTZ], Junk and others, 1989), and a downstream permanently inundated pool (fig. 27). The presence and extent of ATTZs in navigation pool segments contribute substantial lateral connectivity to this segment type. Not all navigation pools have the longitudinal variation that is apparent in the Mississippi River (fig. 27). For example, navigation pools in the Ohio River, and tributaries, tend to be narrower and lack the extensive ATTZs of the Mississippi River.

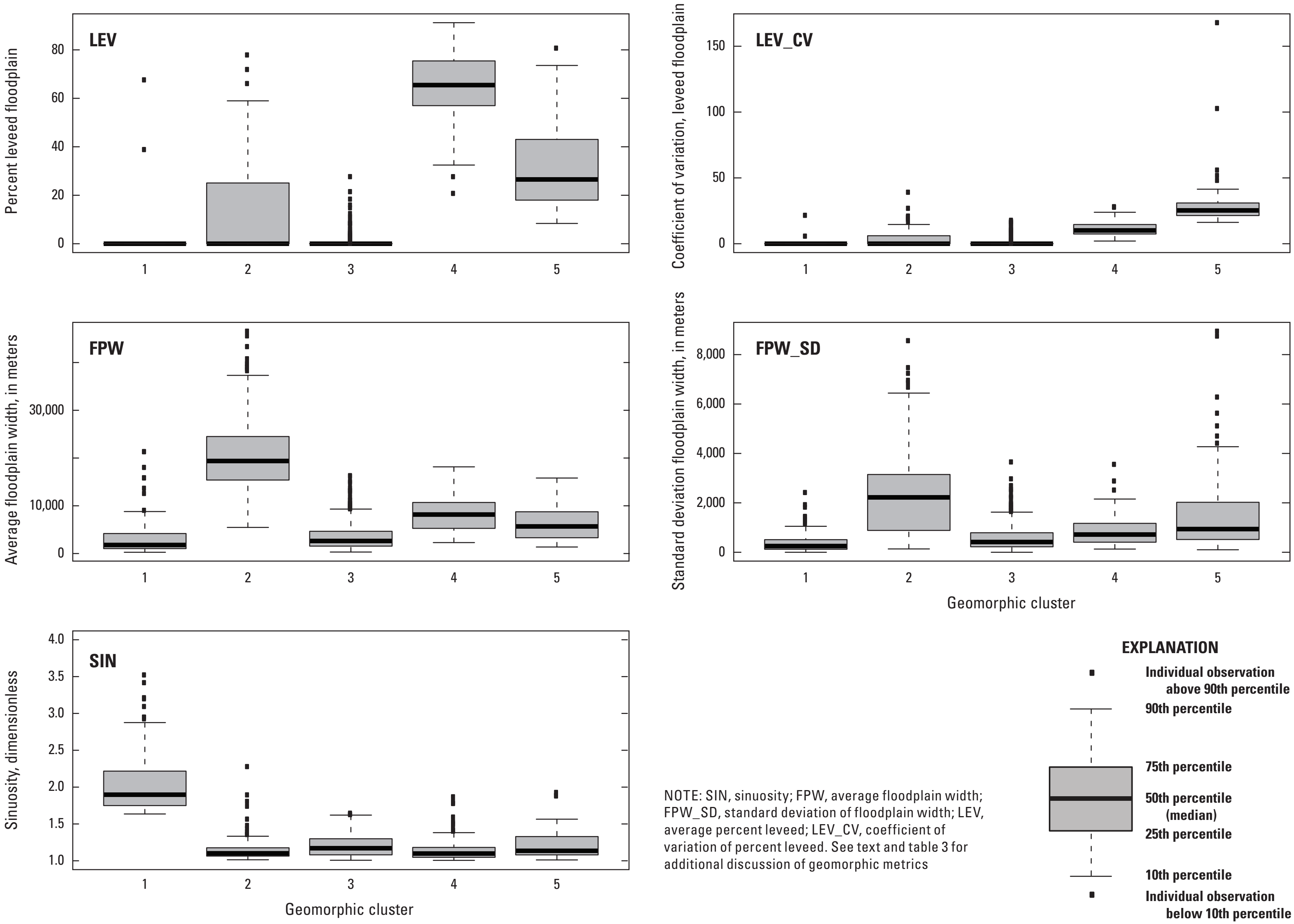
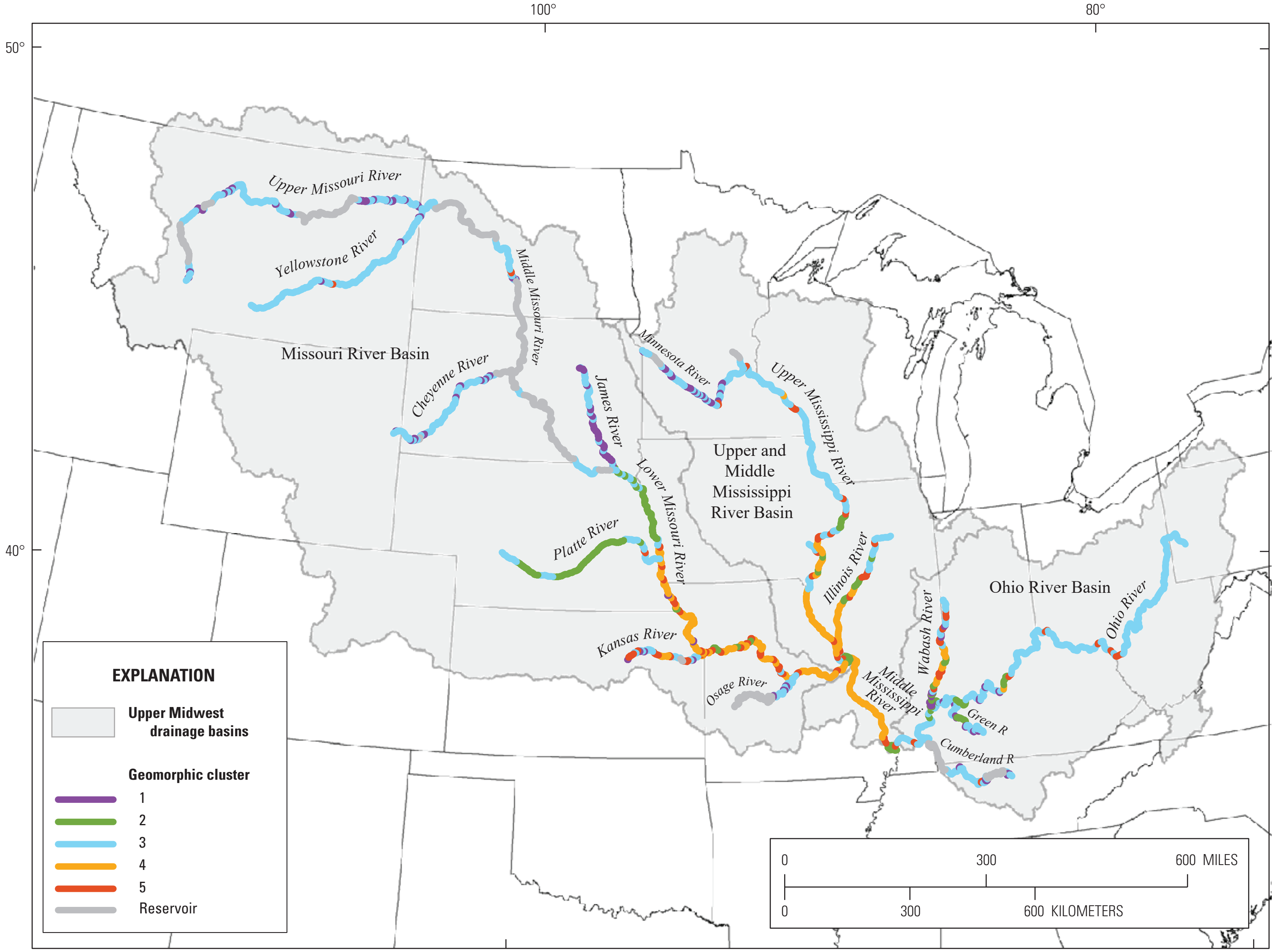


Figure 22. Distributions of geomorphic metrics by geomorphic cluster. Data source: Jacobson and Rohweder (2019).



Base from U.S. Geological Survey digital data, 2012
Albers Equal-Area Conic projection

Figure 23. The distribution of geomorphic clusters within 10-kilometer river segments, large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).

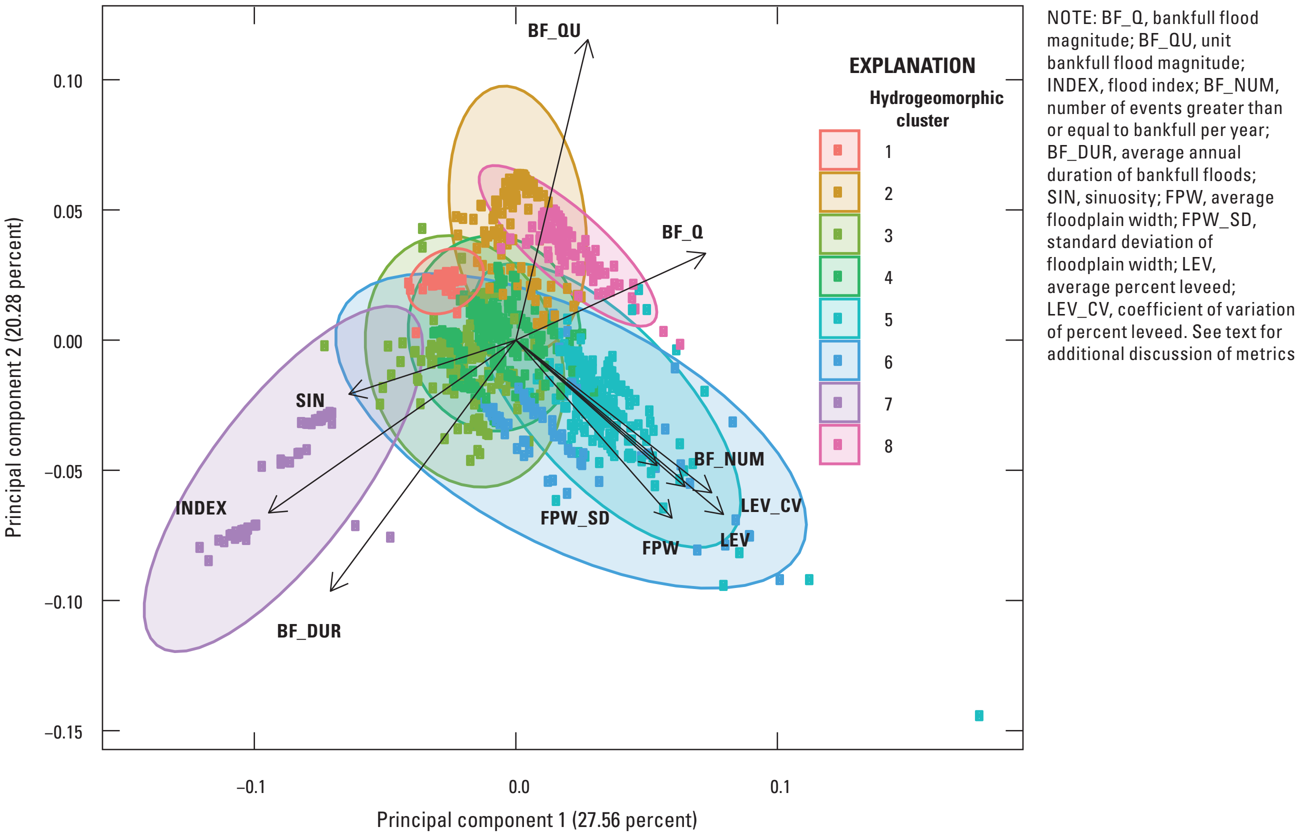


Figure 24. The principal components analysis biplot of the first two components for combined hydrogeomorphic metrics of connectivity. Data source: Jacobson and Rohweder (2019).

By type, most river length among these rivers is in unimpounded segments, followed by navigation pool, and storage reservoir segments (table 5). The Yellowstone, Wabash, Platte, James, Iowa, and most of the Kansas River main stems are categorized as unimpounded because they lack storage reservoir and navigation dams (although they may have other low-head diversions that are not included in the NID, like diversions on the Kansas River). In contrast, 34 percent of the length of the main-stem Missouri River exists under storage reservoirs operated by the U.S. Army Corps of Engineers and Bureau of Reclamation; the reservoir system stores more than 91 cubic kilometers (75 million acre-feet) of water. The Illinois, Ohio, and most of the Mississippi River upstream from the Ohio River confluence are in navigation pools.

Longitudinal Connectivity

Our simple analysis of channel network connectivity documents the range of variability and similarities among large rivers of the Upper Midwest. Considering all dams throughout each basin, the three main drainage basins have similar spatial densities of dams (table 6) although the dam heights in the Mississippi River basin are notably lower than the Missouri and Ohio (fig. 6). Among dams on the large-river segments only, those on the Missouri River are substantially higher than those of the Mississippi and Ohio, indicating the influence of large, main-stem storage reservoirs in diminishing connectivity (figs. 6, 7).

The effects of diminished connectivity are most apparent in changes to sediment fluxes associated with sedimentation in large reservoirs (Wohl and others, 2015). For example, the large, main-stem reservoirs on the Missouri River trap nearly 100 percent of the input sediment load, resulting in incision of channels directly downstream from the dams and simplification of habitats (Williams and Wolman, 1984; Schmidt and Wilcock, 2008; Jacobson and others, 2009; Skalak and others, 2013). Loss of connectivity of sediment fluxes from Upper Midwest river systems has been associated with sediment deficits and increased coastal flooding along the Gulf of Mexico (Kemp and others, 2016).

Diminished connectivity is not necessarily detrimental to all environmental concerns and can have beneficial effects. Deltaic sediment accumulations in the headwaters of reservoirs provide diverse habitats that may support novel plant communities (Dixon and others, 2015; Johnson and others, 2015; Volke and others, 2015) or that have numerous sandbars that support reproduction of threatened and endangered shorebirds (Catlin and others, 2015). On the other hand, deltaic sedimentation may also result in increased flood hazard to nearby communities (Skalak and others, 2013; George and others, 2017).

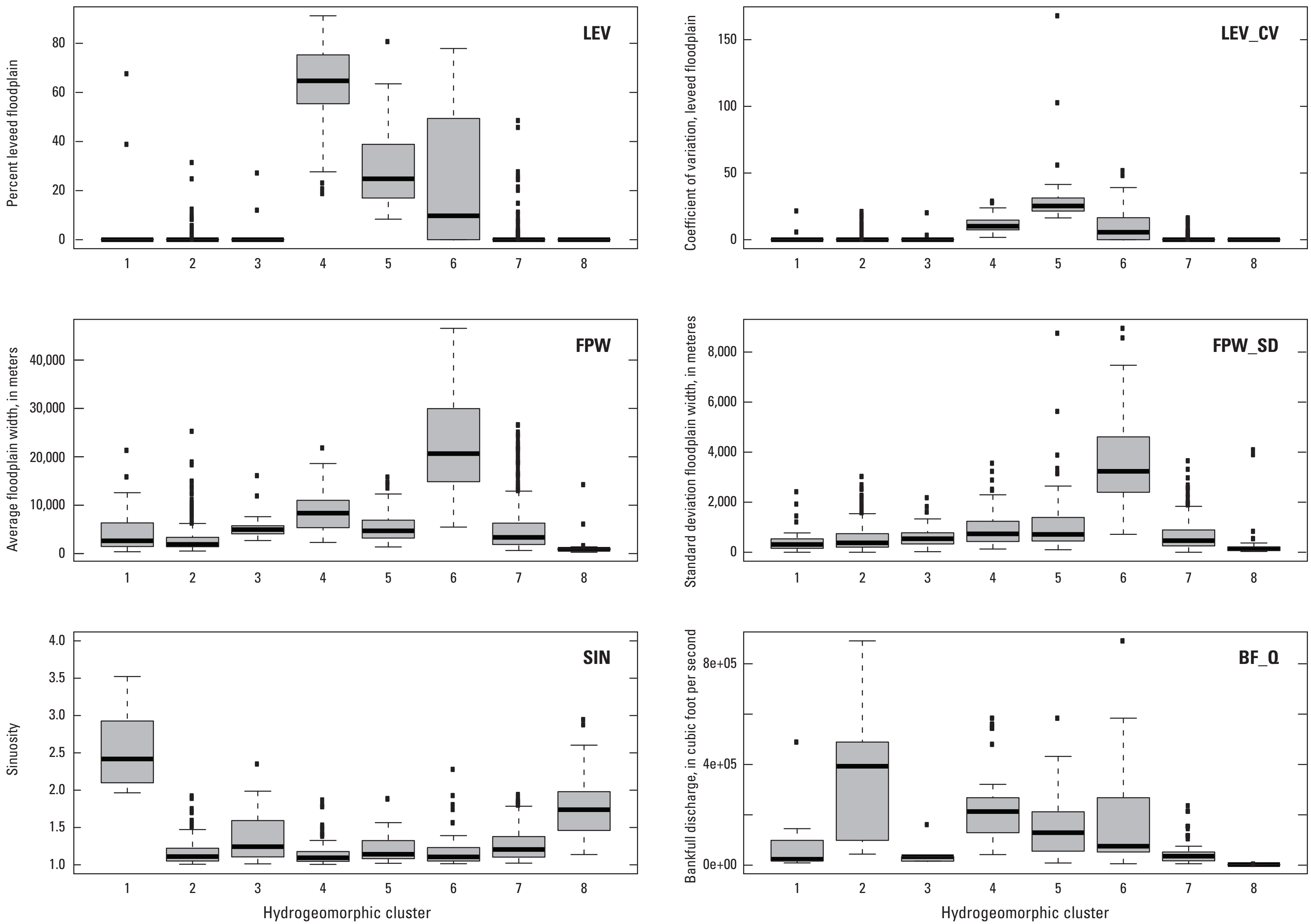
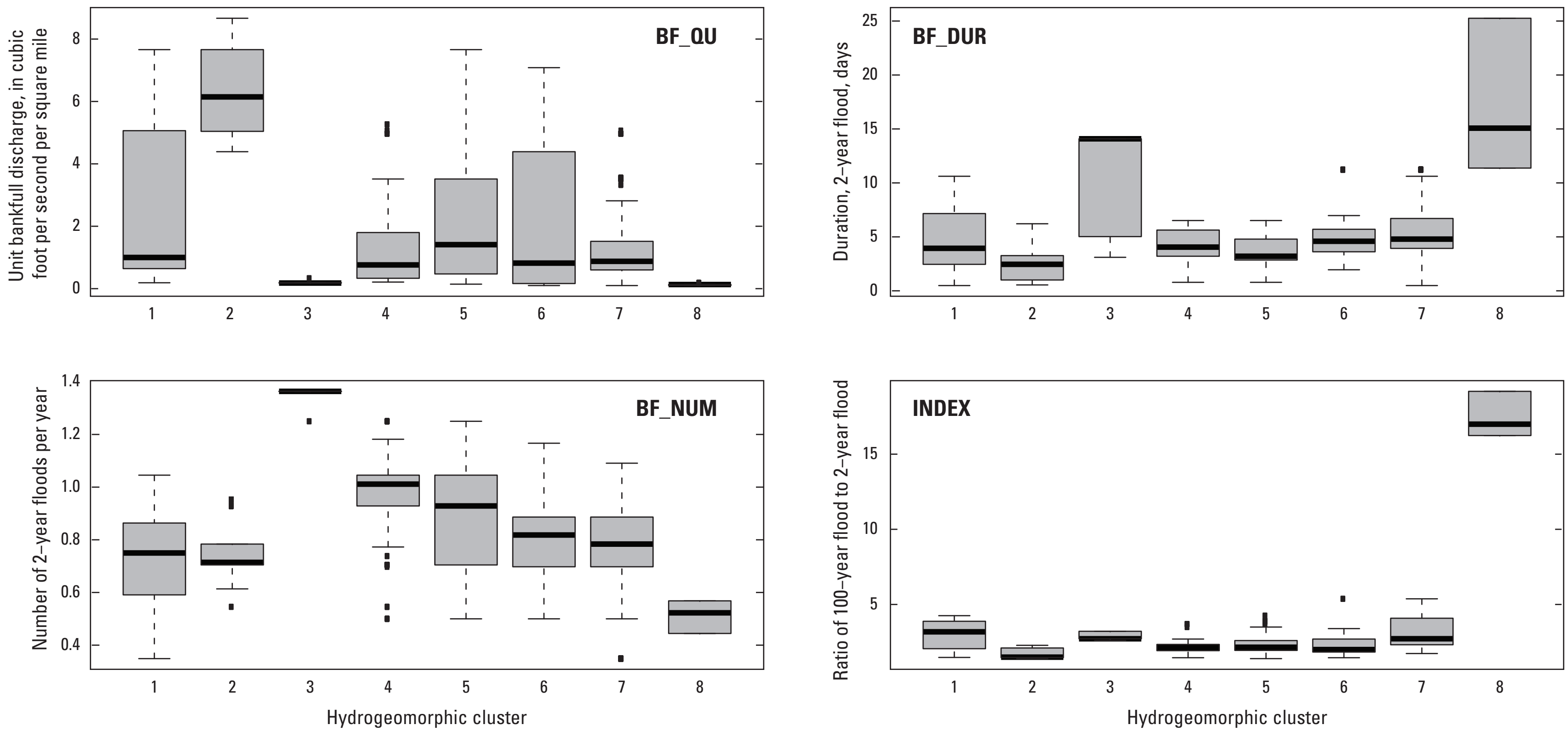
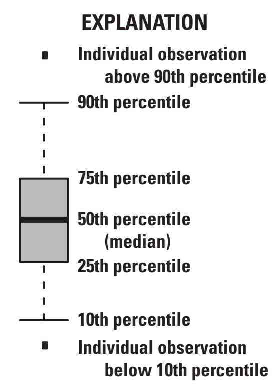


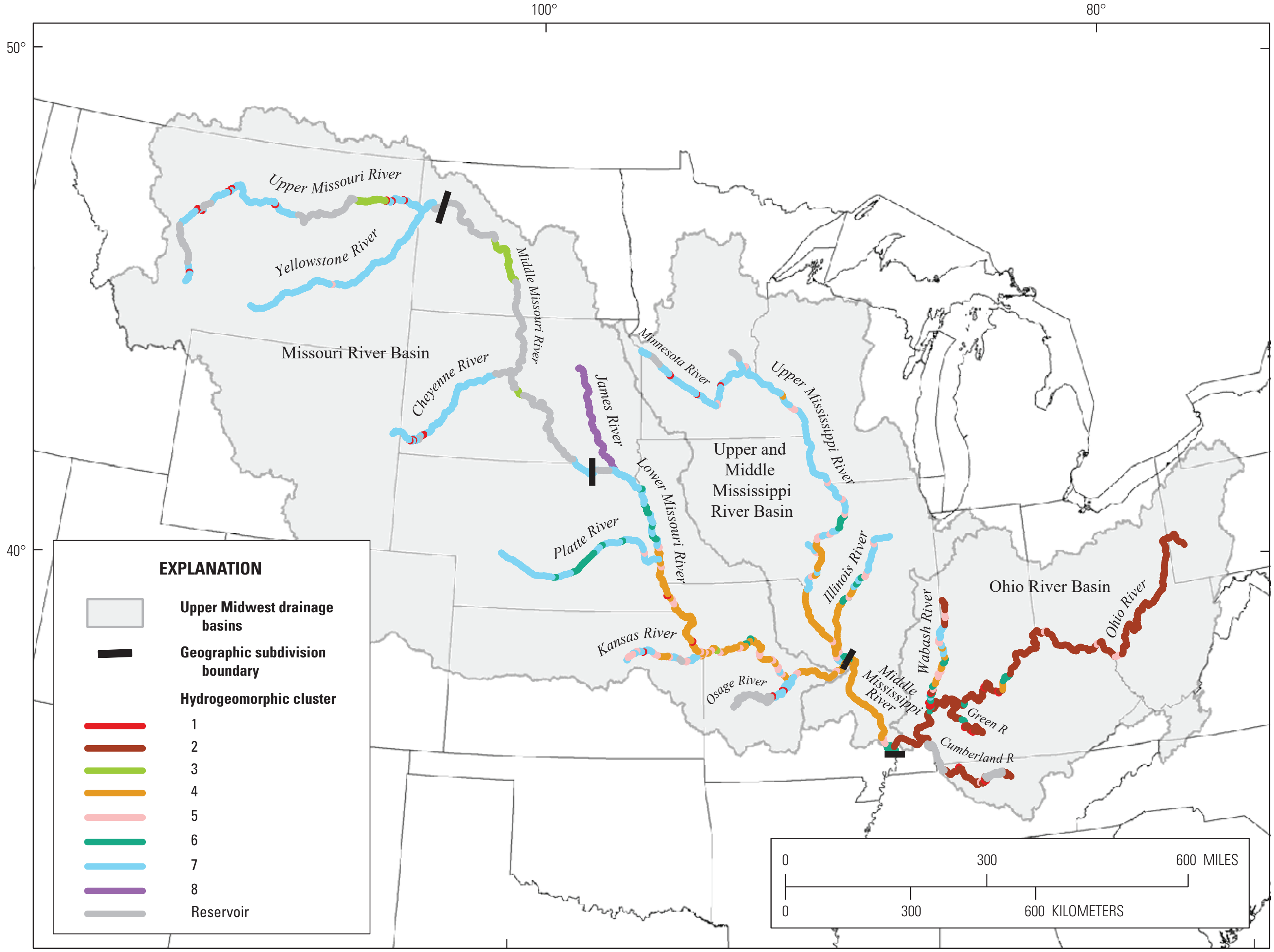
Figure 25. Distributions of hydrogeomorphic variables by hydrogeomorphic cluster. Data source: Jacobson and Rohweder (2019).





NOTE: BF_Q, bankfull flood magnitude; BF_QU, unit bankfull flood magnitude; INDEX, flood index; BF_NUM, number of events greater than or equal to bankfull per year; BF_DUR, average annual duration of bankfull floods; SIN, sinuosity; FPW, average floodplain width; FPW_SD, standard deviation of floodplain width; LEV, average percent leveed; LEV_CV, coefficient of variation of percent leveed. See text for additional discussion of metrics.

Figure 25. Distributions of hydrogeomorphic variables by hydrogeomorphic cluster. Data source: Jacobson and Rohweder (2019).—Continued



Base from U.S. Geological Survey digital data, 2012
Albers Equal-Area Conic projection

Figure 26. The distribution of hydrogeomorphic clusters within 10-kilometer river segments, large rivers of the Upper Midwest. Data source: Jacobson and Rohweder (2019).

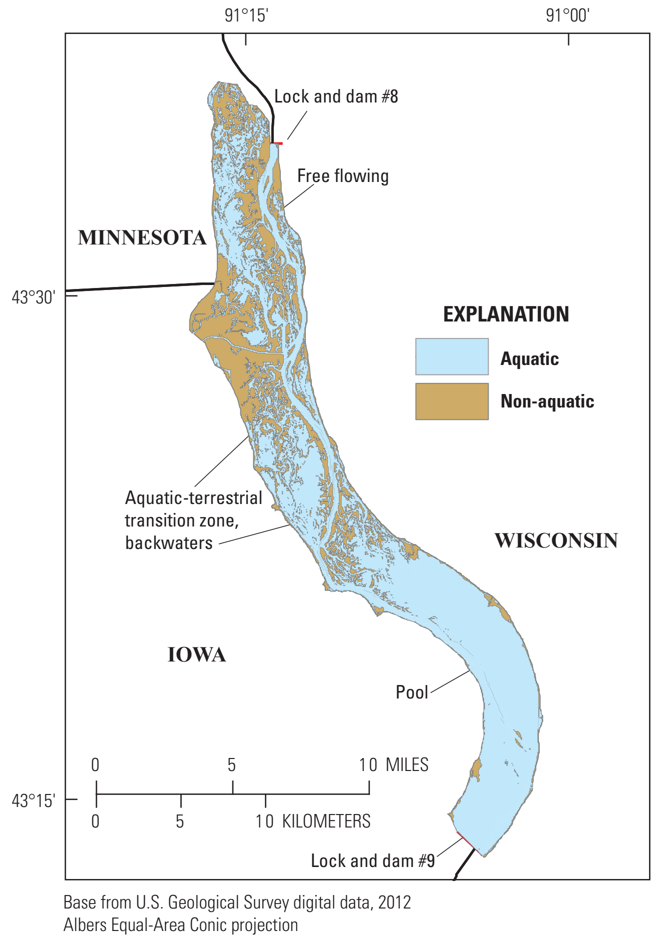


Figure 27. Pool 9 on the Upper Mississippi River showing typical reaches within a navigation-pool segment. Data source: Ruhser (2017).

Reservoirs slow the advection of water and transported constituents through river networks, allowing for some additional environmental benefits. Although sediment deficits downstream from reservoirs can be problematic, contaminants and carbon associated with sediments may be effectively sequestered in reservoir sediments. In addition, reservoirs can attenuate fluxes of nutrients like nitrogen and phosphorous. In the Missouri River drainage basin, the large main-stem reservoirs are successful in attenuating 76 percent of the total nitrogen (TN) and 88 percent of the total phosphorous supplied to them (Brown and others, 2011). The navigation dams and pools in the Upper Mississippi River are less efficient at removing TN, largely because the channels advect nitrogen (and phosphorous) through the pools, bypassing backwaters and floodplains, resulting in short residence times (Schramm and others, 2015; Loken and others, 2018). The entire Upper Mississippi River system of navigation pools has been estimated to remove only 9.5 percent (Schramm and others, 2015) and 12.5 percent (Loken and others, 2018) of the TN delivered to it. In this sense, the Upper Mississippi River is more longitudinally connected than the Upper Missouri River, but less laterally connected, and therefore less effective at sequestering or processing nutrient loads.

Longitudinal connectivity of river systems is of paramount concern for fish migrations. Some native species of these rivers, like the endangered pallid sturgeon (*Scaphirhynchus albus*), have evolved life cycles that include long upstream migrations (100s of kilometers) followed by commensurate distances of downstream dispersal of progeny (DeLonay and others, 2016). Dams present formidable, often impassable, obstacles to upstream migration of adult fish, and reservoirs present habitats thought to be lethal to very young fish (Guy and others, 2015; Jordan and others, 2016). Hence dams and reservoirs sever connectivity of migration patterns and may fragment rivers into segments that function poorly for some large-river fish species. River segments without storage reservoirs and navigation dams present the most opportunity for those native fishes whose reproductive ecology requires long-distance dispersal. The Lower Missouri River, plus segments of the James and Platte Rivers, combine with the Middle and Lower Mississippi Rivers to provide several thousand kilometers of connected, unimpounded channel.

Dams and reservoirs also serve as impediments to invasions of non-native flora and fauna, a situation where diminished connectivity produces ecological benefits. The high dams of the Missouri River main stem have (to date) prevented invasion of Asian carps upstream from Gavins Point Dam in South Dakota, whereas the low-head navigation dams of the Upper Mississippi, Illinois, and Ohio Rivers have only slowed the invasion (O’Connell and others, 2011; Nico and others, 2018a, b; fig. 7). It has also been argued that once an invading organism reaches a reservoir, the water-quality conditions may provide habitats that are supportive of the invaders, thereby providing a foothold for expansion in a drainage basin (Havel and others, 2005).

In contrast to the effects of dams and reservoirs in diminishing connectivity, channelization of rivers can concentrate velocities and fluxes, increasing longitudinal connectivity, but often at the expense of lateral connectivity. Channelization with river-training structures is ubiquitous throughout the Lower Missouri River (downstream from Sioux City, Iowa) and the Middle and Lower Mississippi Rivers. Channel training structures are designed to focus current velocities to maintain sediment transport and, therefore, navigable depths. At the same time, these structures speed downstream advection of water, nutrients, carbon, and sediment, essentially increasing connectivity of the river segments. In river segments where channelization is accompanied by levees, lateral connectivity is greatly diminished while downstream longitudinal connectivity is enhanced. Channelization can present further challenges to fishes that depend on upstream migrations for completion of their life cycles, and enhanced downstream transport of progeny may result in transport of larval fish into nonsupportive environments or beyond their native ranges (McElroy and others, 2012; Erwin and Jacobson, 2015).

Segment-Scale Classification of Lateral Connectivity

Our segment-scale classification combines statistical assessment of flow metrics, which were selected for their application to hydrologically driven lateral connectivity, with geomorphic metrics related to mediation of hydrologically driven connectivity. We then combined the two metrics into an integrated hydrogeomorphic classification at the segment scale.

Hydrologic Clusters

Hydrologic variation among the large-river streamgages shows expected longitudinal variation, with higher bankfull flows in the east compared to the west (fig. 8). The longitudinal variation is especially clear when bankfull flows are normalized by contributing drainage area (fig. 9); the Ohio River basin values are substantially higher than the Upper Mississippi River Basin values, which are, in turn, greater than the Missouri River Basin values.

Probably the most surprising hydrologic conditions among these large rivers are the anomalously high values of flood index for the James River in South Dakota (fig. 11). The flood index calculated for this report is the ratio of the magnitude of the 1-percent annual exceedance probability flood minus the magnitude of the 50-percent annual exceedance probability flood, compared to the 50-percent annual exceedance probability flood. It is meant as a simple measure of the variance of the flood-frequency distribution: how much larger in magnitude the rare floods are compared to the more frequent floods. The duration of bankfull floods on the James River is also substantially longer than many of the other large rivers (fig. 10). The explanation for the James River hydrologic anomaly is not entirely clear; it is possible that a combination of low gradient, high sinuosity, and the existence of years with deep snowpack accumulations contribute to large volumes of water that evacuate slowly from the basin (Benson, 1983).

The PCA by cluster (fig. 13) shows substantial overlap of the clusters but some useful relations. The number of bankfull events is positively loaded on component 2. The number of bankfull events per year is essentially a measure of flashiness because the expected value of bankfull events per year is 0.5 by definition. Values greater than 0.5 indicate connecting floods occur frequently during the year (and would not be measured as part of the annual peak series that was used to generate the flood frequency estimate). Some of the lowest values occur on the James River, and relatively high values occur throughout but with a tendency to increase toward the southern rivers (fig. 12). Number of bankfull events per year is expected to be less variable in rivers that experience one large annual snowmelt flood every year.

The PCA further indicates that flood index and duration of bankfull discharge are positively loaded on component 1, whereas bankfull discharge is negatively loaded on component 1. This is indicative of longer duration discharges and steep flood-frequency curves being associated with snowmelt (Upper Mississippi and Missouri basins) and larger flow magnitudes being associated with Lower Mississippi and Ohio Rivers (figs. 8, 11, 12).

Boxplots of distributions of the hydrologic variables by cluster number provide additional explanation for the geographic distribution of hydrologic classes (figs. 14, 15). Cluster 1 stands out because the three stations on the James River, S. Dak., have extremely low values of bankfull discharge, and unit bankfull discharge, but the highest values of the flood index and high values of duration. Cluster 2 stands out for having the highest bankfull discharge and lowest flood indexes; this cluster is associated with the Middle Mississippi River and the lower segments of the Ohio River main stem, rivers with high flows and relatively flat flood-frequency distributions. Cluster 3 is remarkable for having moderate values of all five variables, and cluster 3 segments are distributed among the Upper Mississippi, Upper and Lower Missouri, and Yellowstone Rivers. Cluster 4 is characterized by moderate values of all hydrologic variables except number of events greater than 50-percent annual exceedance probability flood per year, where the median is equal to about one event per year. This latter characteristic is associated with highly regulated parts of the Missouri River, where the high frequency of floodplain-connecting events may be associated with flow regulation, such as peak-following reservoir releases. Cluster 5 is remarkable for having the highest range of unit bankfull discharge, and is associated with tributaries to the Ohio River that drain humid parts of the eastern United States.

Geomorphic Clusters

Geomorphic characteristics of large rivers result from both natural processes and human alterations to connectivity. Floodplain width—the fundamental metric for potential for floodplain connectivity—generally increases with river size, but the downstream trends are interrupted by geologic influences related to factors such as bedrock erodibility, Pleistocene history, and channel confluences (fig. 16). Based on floodplain width (and the covarying standard deviation of floodplain width), the rivers with the greatest geomorphic connectivity potential are parts of the Lower Missouri, Platte, and Wabash Rivers, and confluence-affected segments of the Missouri, Mississippi, Illinois, and Ohio Rivers.

The intensity of levee development can be seen as a metric of diminished connectivity potential as well as an indicator where levee-setback decisions could increase actual connectivity (fig. 18). Most of these segments are on the Missouri, Mississippi, and Illinois Rivers, where wide, levee-protected floodplains have provided opportunities for agricultural development as well as for municipal developments around large cities (for example, Omaha, Nebraska; Kansas City, Mo.; St. Louis, Mo.; and Cincinnati, Ohio).

Sinuosity is greatest in upstream segments of the Missouri and in some of the moderate and smaller rivers—for example, the James, Cheyenne, Minnesota, Osage, and Cumberland Rivers (fig. 20). The high sinuosity of these rivers may have importance to connectivity because increased bend curvature is associated with increased steering of velocity vectors from the main channel to the floodplain during overbank (connecting) flows. Highly sinuous rivers are more likely to experience advection of transported constituents (water, organic carbon, sediment, nutrients) onto the floodplain compared to low-sinuosity rivers, which rely more on diffusive transport when velocity vectors remain parallel to the channel. High sinuosity may also drive lateral infiltration of water into banks and alluvial aquifers during less-than-bankfull floods (Gomez-Velez and others, 2017).

PCA of the geomorphic segments by cluster document the five overlapping clusters and their relations to the variables (fig. 21). Mean floodplain width and standard deviation of valley width are correlated, increasing with both component 1 and 2. Similarly, percent leveed and coefficient of variation of leveed are correlated and increase with component 1, decrease with component 2. Segment sinuosity is negatively loaded on component 1 and positively loaded on component 2. Boxplots (fig. 22) further define the relations:

- Cluster 1 is notable for having low values of every variable with the exception of sinuosity, for which it has the highest values.
- Cluster 2 is remarkable for having the widest floodplains and relatively high variation of floodplain width.
- Cluster 3 is remarkable for having low values for all five variables.
- Cluster 4 is notable for having the highest percentage of leveed area and relatively high variation of floodplain width.
- Cluster 5 is notable for having high percentages of leveed area and the highest values of leveed area variation.

In the mapped distribution of segments by cluster, leveed river segments stand out clearly as cluster 4 in the Missouri, Kansas, Mississippi, Illinois, and Wabash Rivers (fig. 23). Cluster 5 also has a high percentage of leveed area but differs from cluster 4 in also having very large variation of within-segment leveed area. Wide river segments (mostly associated with cluster 2) are associated with the unleveed part of the Lower Missouri River, the Platte River, and some isolated segments along the Mississippi and Illinois Rivers. Clusters 1 and 3 are juxtaposed in the Upper Missouri River, Yellowstone River, James River, Minnesota River, uppermost segments of the Mississippi River, and the Ohio River (and tributaries). These rivers are characterized by lack of levees and relatively narrow floodplains, with cluster 1 adding in higher values of sinuosity.

Hydrogeomorphic Clusters

Similar to the separate hydrologic and geomorphic clusters, the combined hydrogeomorphic clusters overlap considerably in PCA (fig. 24). Hydrologic variables load strongly on component 2, with unit bankfull discharge loading positively and flood index and average duration loading negatively on component 2 (and component 1). Sinuosity stands out as loading negatively on component 1. Notably, average floodplain width, standard deviation of floodplain width, percent leveed, coefficient of variation of leveed area, and average number of bankfull events per year load similarly on components 1 and 2.

Boxplots document the range of variability among the river segments and how they relate to the hydrogeomorphic variables selected to represent connectivity (fig. 25; and summarized in table 7, fig. 28). Connectivity potential of some river segments relates to the hydrologic drivers; for example, high unit discharges for Ohio River basin rivers (cluster 2) and long durations and high flood indices for the James River (cluster 8). Connectivity potential of other segments is more closely tied to river alterations. For example, cluster 4 is defined by river segments that are highly affected by levees, and cluster 6 contains parts of the wide floodplains of the Platte and Lower Missouri Rivers that have diminished connectivity because of water management.

Applications of the Large River Classification

The hydrogeomorphic classification documents large-river segments that are intrinsically different with respect to potential for lateral connectivity (fig. 28; table 7). As such, the classification can be used to help design water quality and ecological monitoring programs by providing a basis for stratifying sampling or to provide contrast among study sites. The classification also illustrates the joint importance of hydrologic drivers and geomorphology in determining connectivity classes. For example, the classes developed in this study could provide a framework for a stratified-random sampling design of large-river ecological characteristics; if strata are well defined, stratified-random designs can be more efficient and can provide more precise inferences compared to general random designs (Stevens and Olsen, 2004; Dobbie and others, 2008).

A particular value of spatial stratification is to ensure that rare classes are sampled. In the case of large rivers of the Upper Midwest, stratification based on the classifications presented here would ensure sampling of the James River (an unusual, rare river), whereas a sparse randomized sampling may undersample or completely fail to sample this rare case. A similar clustering approach was used to determine strata for a sampling design for environmental indicators in the Great Lakes (Danz and others, 2005).

The classification presented here may also be applied to design of restoration monitoring programs. For example, the cluster classes could be used to identify similar segments

Table 7. Dominant characteristics, geographic distribution, and notes on connectivity for the eight cluster classes for large rivers of the Upper Midwest.

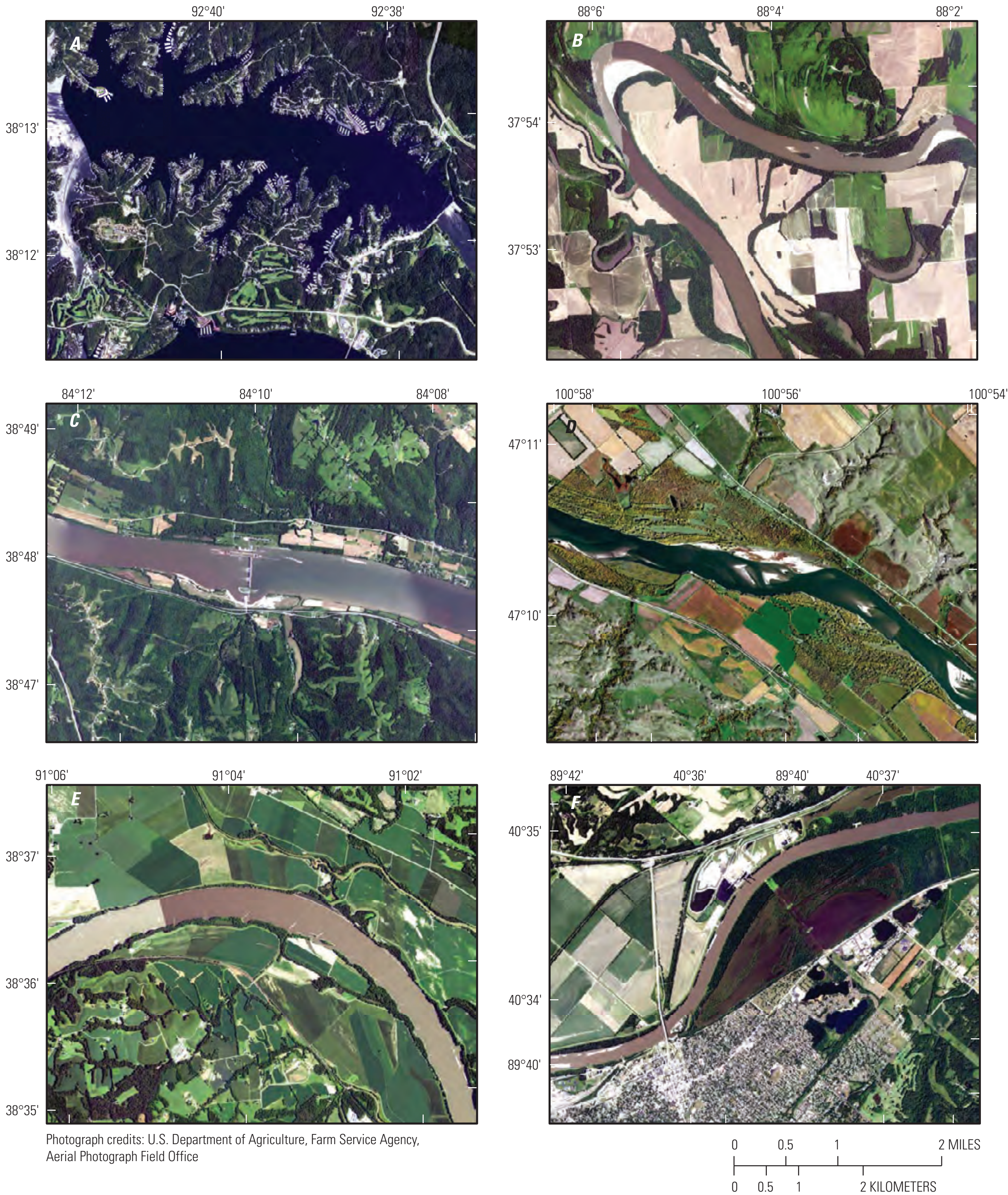
[km, kilometer]

Cluster number	Fig. 28	Dominant characteristics	Geographic distribution	Notes on connectivity	Length in class (km)	Percentage of total segment length
Reservoir	*A*	Storage reservoir segments excluded from cluster analysis	Mostly in the Missouri River system, but also in smaller segments throughout	Reservoir segments are permanently connected to their floodplains.	1,768	15.2
1	*B*	Second highest in percent leveed and highest in variation of percent leveed. Moderate average floodplain width and highest values of standard deviation of floodplain width. Relatively high sinuosity, bankfull discharge, and number of bankfull events per year	Isolated segments of the Missouri and Mississippi Rivers, approximately 340 km total length	These isolated segments occur in river confluences where the total floodplain width results from both rivers. These might be considered "hot spots" of connectivity because of the increased floodplain area. Moreover, hydraulic and hydrologic interactions between the rivers can provide greater frequency and duration of overbank events compared to nonconfluence areas.	340	2.9
2	*C*	Large bankfull discharge, unit bank-full discharge, and number of 2-year recurrence-interval floods. Low ratio of 100:2-year recurrence interval floods. Low areas in levees and low sinuosity (with high variabilityof sinuosity)	Ohio River main stem, Cumberland River, Green River	The rivers in the Ohio River drainage basin have abundant water but relatively narrow valleys, which limit flood-plain connectivity. Levees are limited but frequency and durations of floodplain connecting flows are low compared to other large rivers.	1,939	16.6
3	*D*	Uniformly low values of geomorphic variables. Highest value of number of 2-year recurrence-interval floods	Middle Missouri River inter-reservoir reaches, exclusively	The distinguishing characteristic of this cluster—increased frequency of connecting events—may be the result of peaking flows or other reservoir operations that increase the number of annual near-bankfull events. Because this cluster occurs in inter-reservoir reaches of the Upper Missouri River, the net effect of hydrologic and geomorphic characteristics on connectivity varies from downstream of the dam (where there is little potential for connectivity) to the headwaters of the downstream reservoir (where connectivity is enhanced; Skalak and others, 2013).	320	2.7
4	*E*	Highest percentage of floodplain leveed, moderate floodplain widths. Relatively low sinuosity. Moderate bankfull discharge, relatively high number of 2-year recurrence-interval floods	Lower Missouri River,southern segments of Upper Mississippi River, southern segments of Illinois River, Middle Mississippi River	Although characterized by moderately wide floodplains and moderately high frequency of connecting events, this cluster is characterized by abundant levees, thereby diminishing connectivity under current conditions. Connectivity could be enhanced in some areas by alternative levee configurations (Jacobson and others 2009; 2011).	1,540	13.2

Table 7. Dominant characteristics, geographic distribution, and notes on connectivity for the eight cluster classes for large rivers of the Upper Midwest.—Continued

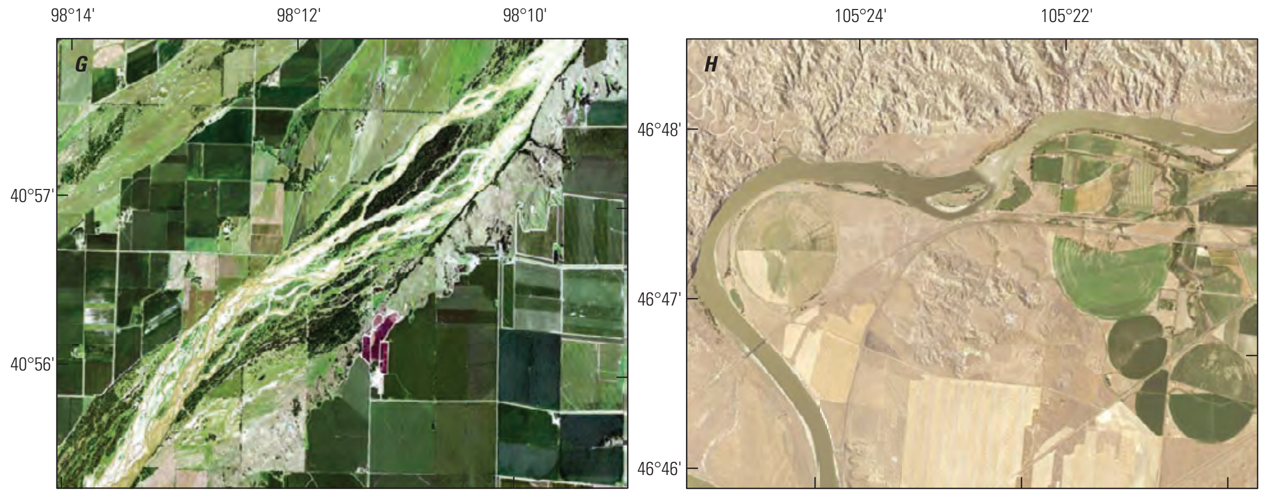
[km, kilometer]

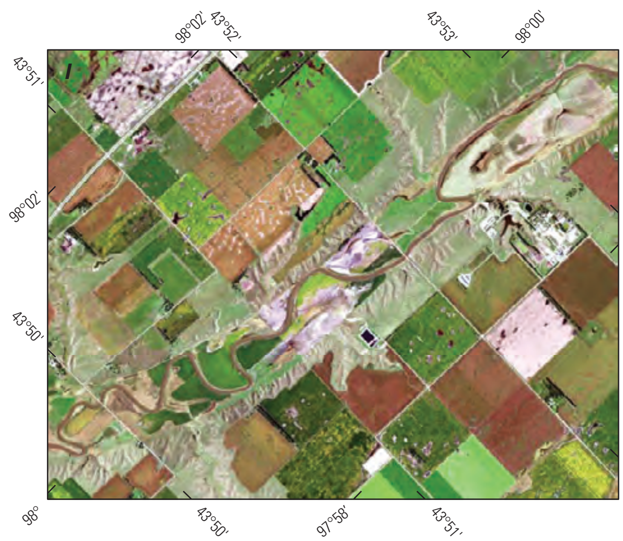
Cluster number	Fig. 28	Dominant characteristics	Geographic distribution	Notes on connectivity	Length in class (km)	Percentage of total segment length
5	*F*	Relatively narrow floodplains, moderate percent leveed, moderate and highly variable unit discharge	Isolated segments of the Yellowstone River, Platte River, Kansas River, Upper Mississippi River, Illinois River, and Wabash River	Connectivity is limited by relatively narrow floodplains, moderate levee development, and low contribution of hydrologic drivers of connectivity.	650	5.6
6	*G*	Highest floodplain widths, although variable. Variable leveed floodplain. Variable unit bankfull discharge. Moderate and low values of other variables	Parts of Platte, Lower Missouri, Upper Mississippi, Illinois, Wabash, and Ohio Rivers	Although characterized by wide floodplains, this cluster occurs mainly in segments of the Lower Missouri River that are highly affected by reservoir operations that have resulted in channel incision and diminished floodplain-connecting flows, and on the Platte River where low irrigation and power production withdrawals have diminished floodplain-connecting flows. Increased connectivity would require increasing water availability in an over-appropriated river system (Smith, 2011).	530	4.5
7	*H*	Relatively low values of all hydrologic and geomorphic variables	Upper Missouri River, Yellowstone River, Cheyenne River, Middle Missouri River, Platte River, northern segments of Upper Mississippi River, northern segments of Illinois River	By length, this is the cluster with the greatest representation among large rivers in the upper Midwest. This cluster has moderate values of hydrologic and geomorphic variables and is distinguished mostly by being rare in the Ohio River drainage basin. This cluster has few characteristics associated with connectivity but has the advantage of lacking levees.	4,092	35.1
8	*I*	High ratio of 100:2-year recurrence-interval floods, extremely long durations of 2-year recurrence-interval floods. Low bankfull discharge. Moderate-high range of sinuosity. Low leveed percent	James River, South Dakota (exclusive)	Long flood durations, the relatively enhanced contributions of rare magnitude events to connectivity, and high sinuosity determine high connectivity potential in the James River.	475	4.1



Photograph credits: U.S. Department of Agriculture, Farm Service Agency, Aerial Photograph Field Office

Figure 28. Aerial photographs showing examples of segments from the eight cluster classes of large rivers of the Upper Midwest. All photographs are presented at the same scale for comparability. *A*, Reservoir, Osage River, Misouri. *B*, Cluster 1, Wabash River, Indiana. *C*, Cluster 2, Ohio River, Ohio. *D*, Cluster 3, Middle Missouri River, North Dakota; *E*, Cluster 4, Lower Missouri River, Missouri. *F*, Cluster 5, Illinois River, Illinois. *G*, Cluster 6, Platte River, Nebraska. *H*, Cluster 7, Yellowstone River, Montana. *I*, Cluster 8, James River, South Dakota.





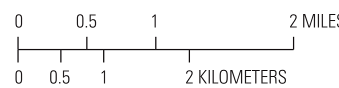


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Figure 28. Aerial photographs showing examples of segments from the eight cluster classes of large rivers of the Upper Midwest. All photographs are presented at the same scale for comparability. *A*, Reservoir, Osage River, Misouri. *B*, Cluster 1, Wabash River, Indiana. *C*, Cluster 2, Ohio River, Ohio. *D*, Cluster 3, Middle Missouri River, North Dakota; *E*, Cluster 4, Lower Missouri River, Missouri. *F*, Cluster 5, Illinois River, Illinois. *G*, Cluster 6, Platte River, Nebraska. *H*, Cluster 7, Yellowstone River, Montana. *I*, Cluster 8, James River, South Dakota.—Continued

within which controls and intervention reaches could be identified for a before-after-control-intervention experiment design. A similar, although more detailed, bend-scale geomorphic classification on the Lower Missouri River (Jacobson and others, 2017) has been used to select control and intervention bends for a channel reconfiguration experiment to improve understanding of rearing habitat for pallid sturgeon larvae (Fischenich and others, 2018).

Additional Dimensions of Connectivity

The classification presented here emphasized hydrologic and geomorphic variables that were readily calculated from existing data sources. Vertical dimensions were excluded from this analysis because the requisite data were not available for all the large rivers of the Midwest. Considering the vertical dimension of lateral connectivity may include surface water and groundwater; data on the latter are considerably more limiting than the former.

For small rivers and for some streamflow-gaging stations, the vertical dimension of surface-water hydrology can be explored explicitly and empirically through a streamgage-discharge rating curve. Such data can be used to determine the stage threshold when surface water goes over bank to connect to the floodplain and to calculate hydrologic metrics (exceedances, durations, seasonality, for example) for that threshold condition (Jacobson and Faust, 2014). Extrapolation of hydraulic conditions from streamflow-gaging sites to reaches or segments between gages can be tenuous, however, depending on the geomorphology of the gaged cross section compared to variability along the river. Most streamgages are selectively installed at stable, simple cross sections with easy access for making measurements (Rantz, 1982); thus, the geomorphology of gaged sites can be biased compared to intervening reaches of a river segment. The potential for bias is increased on large rivers where streamgages are preferentially located in narrow reaches and on bridges that are often associated with roadway constrictions and reduced floodplain conveyance. Reliable interpolation of water-surface elevations between streamgages requires either a large number of empirical water-surface-elevation surveys, a hydraulic model, or both.

Modeling of water-surface elevations using calibrated hydraulic models is increasingly feasible because elevation data and computational power have increased, although collection of robust bathymetric and calibration data remain a limitation (Nelson and others, 2016). Continental scale models of flood hazard and risk indicate future potential for quantifying floodplain connectivity over large areas (Wing and others, 2017, 2018), but such models do not presently incorporate ecological flow metrics.

Previous work has documented how the vertical dimension of connectivity has been quantified on 1,200 kilometers of the Lower Missouri River by integrating time series of hydrologic events, one-dimensional hydraulic models, and high-resolution floodplain elevation data (Jacobson and others, 2007, 2011; Chojnacki and others, 2012); an update of this approach used 82 years of unsteady daily water-surface elevations to evaluate connectivity on 500 kilometers of the river to allow for complex ecological queries about extent, duration, and timing of connectivity (Bulliner and others, 2017). The longitudinal distribution of area of the floodplain affected by inundation of varying frequency results from longitudinally varying hydrology (close to upstream dams compared to far downstream from the dams) and longitudinally varying incision and aggradation of the channel that modifies the threshold of floodplain connectivity (fig. 29). The unsteady flow analysis allows for ecologically relevant queries with high spatial resolution (fig. 30).

Another dimension of vertical connectivity that is not addressed in this report is connectivity through porous media in the bed, banks, and floodplain—processes that can be especially important in biogeochemical processes (Harvey and Gooseff, 2015). Documented sensitivity of floodplain aquifer potentiometric surfaces to main-channel stages indicates that such connections can be substantial in large rivers (Kelly, 2001, 2011). Exchange of surface water with the bed, banks, and floodplain depends on hydrologic drivers, geomorphic factors, and sediment characteristics that govern hydraulic conductivity. Although considering the interaction of these fine-scale factors is beyond the scope of this report, it is notable that hydrologic exchange with bank material is thought to increase with channel sinuosity, indicating the importance of flow vectors in the channel that are subparallel to the banks (Gomez-Velez and others, 2017). Simulations of hydrologic exchange flows in a river network indicated that exchange fluxes with bars and banks decrease with decreasing particle size and increasing stream order, whereas residence times of water increase in larger rivers; the authors concluded that exchanges with the bed, bars, and banks of large rivers can be important in geochemical processes at the basin scale, but that the longer total length of smaller rivers in the networks probably has a greater net effect (Gomez-Velez and others, 2017). Additional study of hyporheic and groundwater exchanges along large rivers is warranted, especially given the large variation in channel form and particle sizes among these rivers.

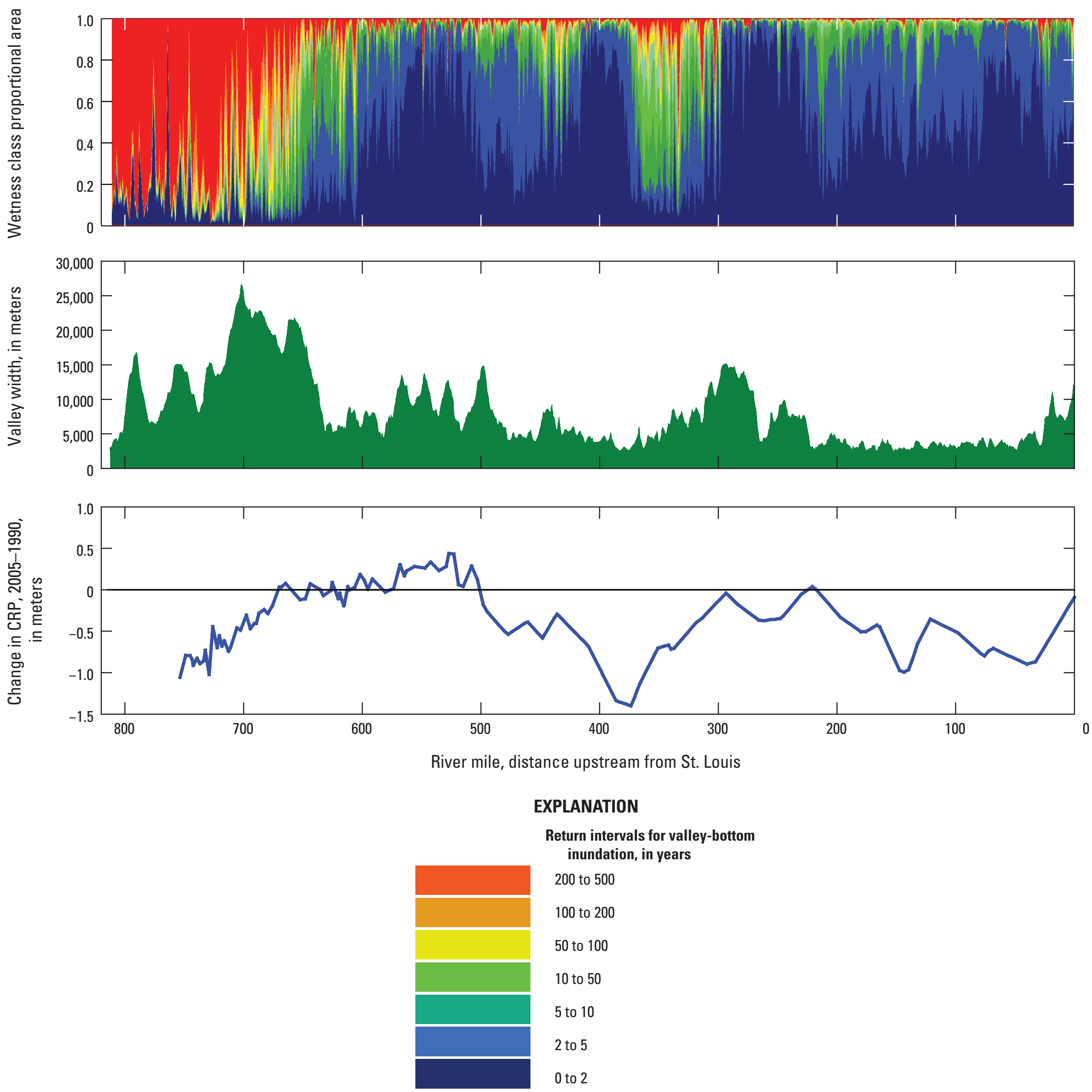

Figure 29. The longitudinal distribution of the percentage of the Lower Missouri River floodplain inundated at varying flow exceedances, valley width, and pattern of channel incision and aggradation. CRP is the Construction Reference Plan, a riverwise sloping datum defined at 75-percent flow exceedance. Data sources: Jacobson and others (2009, 2011) and Chojnacki and others (2012).

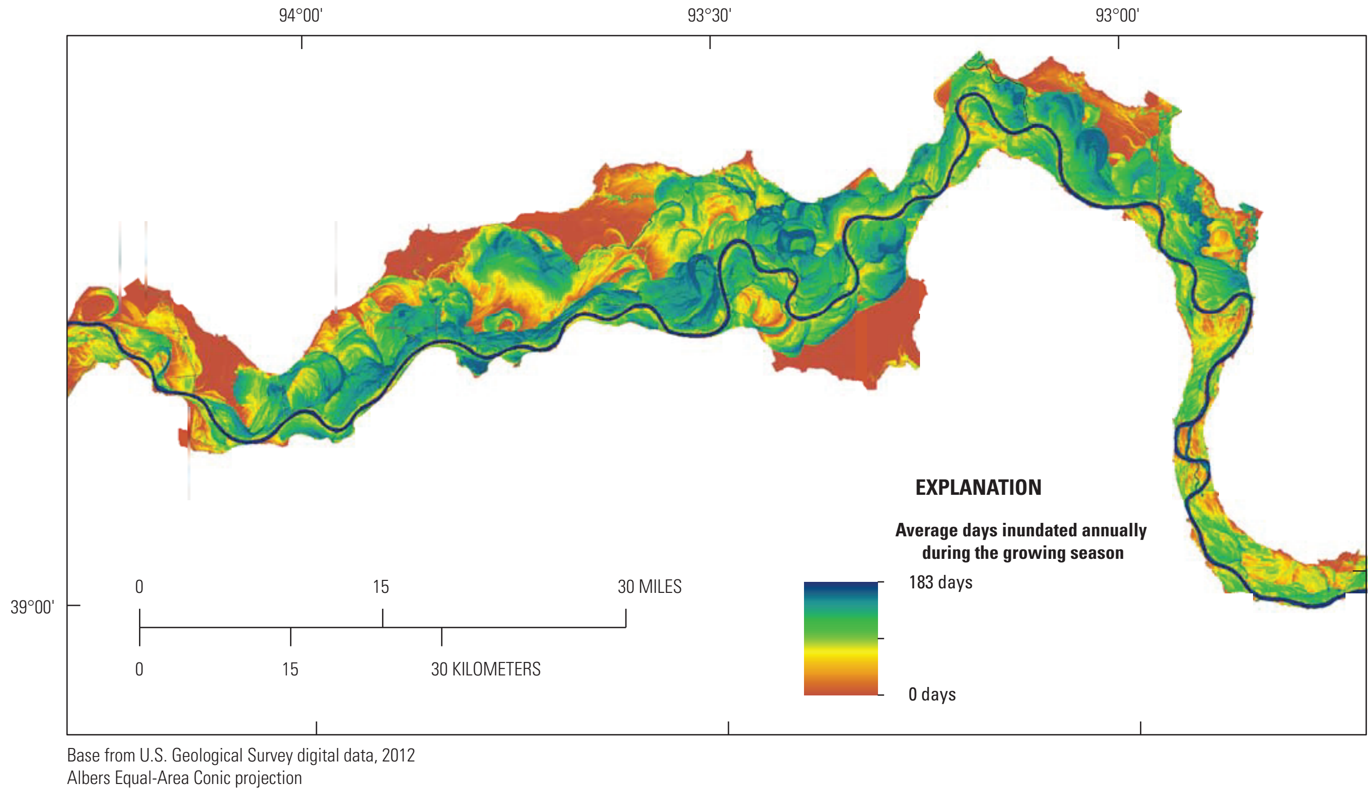

Figure 30. A section of the Lower Missouri River floodplain as an example of an ecological query about floodplain connectivity (in this case, average number of days of inundation during the growing season over 82 years of record). Data source: Bulliner and others (2017).

Summary and Conclusions

The concept of river connectivity—water-mediated exchange of matter, energy, and biota between different elements of the riverine landscape—integrates many perspectives about how flowing water influences ecological processes. Connectivity in large rivers is especially important because large rivers integrate fluxes of water, sediment, nutrients, contaminants, and other transported constituents over large drainage basins. Large rivers provide migration pathways for native flora and fauna that have evolved to use the channels, sandbars, and riparian areas to complete their reproductive cycles, and they provide invasion corridors for non-native species. Large rivers also are highly valued by society because they provide water for municipal and industrial uses, navigation, hydropower, recreation, and extensive floodplains for agriculture and development. Socioeconomic development of larger rivers and their floodplains has led to fragmentation and loss of connectivity.

Criteria for defining a large river are subjective because largeness may be based on many factors such as drainage area, length, discharge, sediment fluxes, or other factors such as socioeconomic value. Largeness also varies whether one considers rivers globally or locally. This report takes a limited geographic perspective to consider large rivers that are part of the Mississippi River drainage basin in the Upper Midwest. The geographic scope was set to provide an assessment of variability of large rivers within one integrating drainage basin (the Mississippi River) yet spanning a wide range of longitude (36 degrees), hydroclimatic conditions, land uses, and river alterations. The 15 rivers of the Upper Midwest in this report were selected based on being in the top 10 in categories of length, mean annual discharge, or drainage area (based on their downstream extent) in the Missouri, Middle and Upper Mississippi, and Ohio River drainage basins. Lengths of the rivers under consideration were then limited to Strahler stream orders of seven and above. Although quantitative, these criteria are still somewhat arbitrary and may result in biased selections because of factors like varying stream network density or river-naming conventions. Nevertheless, the selection of 1,172 segments of 15 rivers serves to sample and describe the geographic variation of large rivers of the Upper Midwest.

River classification systems vary considerably in their approach, scale, resolution, and objectives and the chief concern for developing a classification should be that it supports its objectives. Our objective was to develop a classification of large rivers of the Upper Midwest that would document and illustrate the existing range of river conditions that relate to riverine connectivity.

While there has been substantial emphasis over the past two decades on hydroecological assessments and classifications of discharge time series, the geomorphic context of hydroecological metrics typically has been given less attention. One of the benefits of the classification system documented in this report is that it combines hydroecological metrics and the geomorphic context that mediates hydrologic factors, especially in reference to connectivity. Including geomorphic context was one of the fundamental steps proposed in the Ecological Limits to Hydrologic Alteration framework.

The three types of classifications presented in this report provide a hierarchical view of these river systems. At the broadest level, segments in the 15 rivers were classified based on their degree of alteration: relatively unimpounded, engineered for navigation with locks and dams, and those that are completely inundated as storage reservoirs. A separate assessment of longitudinal connectivity considered density and height of dams as impediments to connectivity; this assessment documents the contrast between river segments with low-head navigation dams (Upper Mississippi, Illinois, Ohio, Green, and Cumberland Rivers) and those segments with high-head dams (mostly in the Upper Missouri River). In addition, this analysis documents that the longest unimpounded river pathways exist in the Lower Missouri River and connected tributaries. The nearly 1,300 kilometers of unimpounded Lower Missouri River—with the addition of nearly 1,800 kilometers of the unimpounded Middle and Lower Mississippi Rivers—provide migratory potential that may be critical for survival of species like the pallid sturgeon.

Our finest scale of resolution is a statistically based component classification at the 10-kilometer scale. Cluster analysis of hydrologic variables from 66 streamflow-gaging stations yielded 5 clusters calculated from 5 ecohydrological metrics related to connectivity. A separate cluster analysis of 5 geomorphologic variables associated with each of 1,172 river segments also yielded 5 clusters. When the hydrologic variables were associated with corresponding segments, the cluster analysis yielded eight clusters. Although the clusters overlap considerably in principal component space, the resulting hydrogeomorphic classification leads to a physically reasonable distribution of classes. The hierarchical classification should serve to increase geographic awareness of the range of large-river variation that occurs at multiple scales in the Upper Midwest, to increase understanding of the extent of river alteration, and to serve as a useful template for stratifying study designs of large rivers by indicating commonalities and dissimilarities among classes.

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References Cited

Acreman, M.C., Overton, I.C., King, J., Wood, P.J., Cowx, I.G., Dunbar, M.J., Kendy, E., and Young, W.J., 2014, The changing role of ecohydrological science in guiding environmental flows: Hydrological Sciences Journal, v. 59, nos. 3–4, p. 433–450. [Also available at https://doi.org/10.1080/02626667.2014.886019.]

Alexander, J.S., Wilson, R.C., and Green, W.R., 2012, A brief history and summary of the effects of river engineering and dams on the Mississippi River system and delta: U.S. Geological Survey Circular 1375, 43 p. [Also available at https://doi.org/10.3133/cir1375.]

Alexander, R.B., Smith, R.A., Schwarz, G.E., Boyer, E.W., Nolan, J.V., and Brakebill, J.W., 2008, Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin: Environmental Science & Technology, v. 42, no. 3, p. 822–830. [Also available at https://doi.org/10.1021/es0716103.]

Amoros, C., and Bornette, G., 2002, Connectivity and biocomplexity in waterbodies of riverine floodplains: Freshwater Biology, v. 47, no. 4, p. 761–776. [Also available at https://doi.org/10.1046/j.1365-2427.2002.00905.x.]

Angradi, T.R., 2006, The large and Great River "reference problem"—Surmounting the obstacles [Proceedings of the Great River Ecosystems Reference Condition Workshop, Cincinnati, Ohio, January 10–11, 2006]: U.S. Environmental Protection Agency, Workshop presentation. [Also available at https://archive.epa.gov/emap/archive-emap/web/html/refcond.html.]

Bayley, P.B., 1995, Understanding large river-floodplain ecosystems: Bioscience, v. 45, no. 3, p. 153–158. [Also available at https://doi.org/10.2307/1312554.]

Benson, R.D., 1983, A preliminary assessment of the hydrologic characteristics of the James River in South Dakota: U.S. Geological Survey Water-Resources Investigations Report 83–4077, 122 p. [Also available at https://doi.org/10.3133/wri834077.]

Bouska, K.L., Lindner, G.A., Paukert, C.P., and Jacobson, R.B., 2016, Stakeholder-led science—Engaging resource managers to identify science needs for long-term management of floodplain conservation lands: Ecology and Society, v. 21, no. 3, art. 12, 36 p. [Also available at https://doi.org/10.5751/ES-08620-210312.]

Brown, J.B., Sprague, L.A., and Dupree, J.A., 2011, Nutrient sources and transport in the Missouri River Basin, with emphasis on the effects of irrigation and reservoirs: Journal of the American Water Resources Association, v. 47, no. 5, p. 1034–1060. [Also available at https://doi.org/10.1111/j.1752-1688.2011.00584.x.]

Bulliner, E.A., Lindner, G., Bouska, K., Jacobson, R.B., and Paukert, C., 2017, Science to inform management of floodplain conservation lands under non-stationary conditions: U.S. Geological Survey data release, accessed September 2018 at https://doi.org/10.5066/F7HM56KG.

Carlisle, D.M., Wolock, D.M., and Meador, M.R., 2011, Alteration of streamflow magnitudes and potential ecological consequences—A multiregional assessment: Frontiers in Ecology and the Environment, v. 9, no. 5, p. 264–270. [Also available at https://doi.org/10.1890/100053.]

Catlin, D.H., Fraser, J.D., and Felio, J.H., 2015, Demographic responses of piping plovers to habitat creation on the Missouri river: Wildlife Monographs, v. 192, no. 1, p. 1–42. [Also available at https://doi.org/10.1002/wmon.1016.]

Charrad, M., Ghazzali, N., Boiteau, V., and Niknafs, A., 2014, Nbclust—An R package for determining the relevant number of clusters in a data set: Journal of Statistical Software, v. 61, no. 6, 36 p. [Also available at https://doi.org/10.18637/jss.v061.i06.]

Chojnacki, K.A., Struckhoff, M.A., and Jacobson, R.B., 2012, Land Capability Potential Index (LCPI) and geodatabase for the Lower Missouri River Valley: U.S. Geological Survey Data Series 736, 26 p. [Also available at https://doi.org/10.3133/ds736.]

Danz, N.P., Regal, R.R., Niemi, G.J., Brady, V.J., Hollenhorst, T., Johnson, L.B., Host, G.E., Hanowski, J.M., Johnston, C.A., Brown, T., Kingston, J., and Kelly, J.R., 2005, Environmentally stratified sampling design for the development of Great Lakes environmental indicators: Environmental Monitoring and Assessment, v. 102, nos. 1–3, p. 41–65. [Also available at https://doi.org/10.1007/s10661-005-1594-8.]

DeLonay, A.J., Chojnacki, K.A., Jacobson, R.B., Albers, J.L., Braaten, P.J., Bulliner, E.A., Elliott, C.M., Erwin, S.O., Fuller, D.B., Haas, J.D., Ladd, H.L.A., Mestl, G.E., Papoulias, D.M., and Wildhaber, M.L., 2016, Ecological requirements for pallid sturgeon reproduction and recruitment in the Missouri River—A synthesis of science, 2005–2012: U.S. Geological Survey Scientific Investigations Report 2015–5145, 224 p. [Also available at https://doi.org/10.3133/sir20155145.]

Dixon, M.D., Boever, C.J., Danzeisen, V.L., Merkord, C.L., Munes, E.C., Scott, M.L., Johnson, W.C., and Cowman, T.C., 2015, Effects of a ‘natural’ flood event on the riparian ecosystem of a regulated large-river system—The 2011 flood on the Missouri River, USA: Ecohydrology, v. 8, no. 5, p. 812–824. [Also available at https://doi.org/10.1002/eco.1613.]

Dobbie, M.J., Henderson, B.L., and Stevens, J.D.L., Jr., 2008, Sparse sampling—Spatial design for monitoring stream networks: Statistics Surveys, vol. 2, p. 113–153. [Also available at https://doi.org/10.1214/07-SS032.]

Domestic Names Committee, 2016, Principles, policies, and procedures—Domestic geographic names: U.S. Board on Geographic Names, 80 p.

Driscoll, R.S., Merkel, D.L., Radloff, D.L., Snyder, D.E., and Hagihara, J.S., 1984, An ecological land classification framework for the United States: U.S. Department of Agriculture, Forest Service, Miscellaneous Publication 1439, 56 p.

Dynesius, M., and Nilsson, C., 1994, Fragmentation and flow regulation of river systems in the northern third of the World: Science, v. 266, no. 5186, p. 753–762. [Also available at https://doi.org/10.1126/science.266.5186.753.]

Elliott, C.M., and Jacobson, R.B., 2006, Geomorphic classification and assessment of channel dynamics in the Missouri National Recreational River, South Dakota and Nebraska: U.S. Geological Survey Scientific Investigations Report 2006–5313, 66 p. [Also available at https://doi.org/10.3133/sir20065313.]

Eng, K., Grantham, T.E., Carlisle, D.M., and Wolock, D.M., 2017, Predictability and selection of hydrologic metrics in riverine ecohydrology: Freshwater Science, v. 36, no. 4, p. 915–926. [Also available at https://doi.org/10.1086/694912.]

Erwin, S.O., and Jacobson, R.B., 2015, Influence of channel morphology and flow regime on larval drift of pallid sturgeon on the Lower Missouri River: River Research and Applications, v. 31, no. 5, p. 538–551. [Also available at https://doi.org/10.1002/rra.2752.]

Ferreira, M., 2014, Perpendicular transects—A geographic information system toolbox: GIS 4 Geomorphology web page, accessed October 2014 at http://gis4geomorphology.com/stream-transects-partial/.

Ferrell, J., 1996, Soundings—100 years of the Missouri River navigation project: Omaha, Nebr., U.S. Army Corps of Engineers, 171 p.

Fischenich, J.C., Marmorek, D.R., Nelitz, M.A., Murray, C.L., Ma, B.O., Buenau, K.E., Long, G., Bonneau, J.L., Fleming, C.A., and Schwarz, C.J., 2018, Science and adaptive management plan: Missouri River Recovery Program, U.S. Army Corps of Engineers ERDC/EL TR–18–XX, 502 p.

Flotermersch, J.E., Stribling, J.B., and Paul, M.J., 2006, Concepts and approaches for the bioassessment of non-wadeable streams and rivers: Cincinnati, Ohio, U.S. Environmental Protection Agency, Office of Research and Development, EPA/600/R–06/127, 245 p.

Flynn, K.M., Kirby, W.H., and Hummel, P.R., 2006, User's manual for program PeakFQ annual flood-frequency analysis using bulletin 17B guidelines: U.S. Geological Survey Techniques and Methods, book 4, chap. B4, 42 p.

Frissell, C.A., Liss, W.J., Warren, C.E., and Hurley, M.D., 1986, A hierarchical framework for stream habitat classification—Viewing streams in a watershed context: Environmental Management, v. 10, no. 2, p. 199–214. [Also available at https://doi.org/10.1007/BF01867358.]

George, M.W., Hotchkiss, R.H., and Huffaker, R., 2017, Reservoir sustainability and sediment management: Journal of Water Resources Planning and Management, v. 143, no. 3, 8 p. [Also available at https://doi.org/10.1061/(ASCE)WR.1943-5452.0000720.]

Gomez-Velez, J.D., Wilson, J.L., Cardenas, M.B., and Harvey, J., 2017, Flow and residence times of dynamic river bank storage and sinuosity-driven hyporheic exchange: Water Resources Research, v. 53, no. 10, p. 8572–8595. [Also available at https://doi.org/10.1002/2017WR021362.]

Gu, R.R., Xianggui, Z., and Jha, M., 2010, Hydrologic impact of climate change on the Mississippi River, *in* Luo, Q., ed., Proceedings of the 2d Conference on Environmental Science and Information Application Technology, Wuhan, China, July 17–18, 2010: Institute of Electrical and Electronics Engineers, Inc., p. 36-39, [Also available at https://doi.org/10.1109/ESIAT.2010.5568480.]

Gupta, A., 2007, Introduction, *in* Gupta, A. ed., Large rivers—Geomorphology and management: Chichester, England, John Wiley and Sons, p. 1–5

Guy, C.S., Treanor, H.B., Kappenman, K.M., Scholl, E.A., Ilgen, J.E., and Webb, M.A.H., 2015, Broadening the regulated-river management paradigm—A case study of the forgotten dead zone hindering pallid sturgeon recovery: Fisheries, v. 40, no. 1, p. 6–14. [Also available at https://doi.org/10.1080/03632415.2014.987236.]

Harvey, J., and Gooseff, M., 2015, River corridor science—Hydrologic exchange and ecological consequences from bedforms to basins: Water Resources Research, v. 51, no. 9, p. 6893–6922. [Also available at https://doi.org/10.1002/2015WR017617.]

Havel, J.E., Lee, C.E., and Vander Zanden, J.M., 2005, Do reservoirs facilitate invasions into landscapes?: Bioscience, v. 55, no. 6, p. 518–525. [Also available at https://doi.org/10.1641/0006-3568(2005)055[0518:DRFIIL]2.0.CO;2.]

Henriksen, J.A., Heasley, J., Kennen, J.G., and Nieswand, S.P., 2006, Users' manual for the Hydroecological Integrity Assessment Process software (including the New Jersey Assessment Tools): U.S. Geological Survey Open-File Report 2006–1093, 72 p. [Also available at https://doi.org/10.3133/ofr20061093.]

Jacobson, R.B., Blevins, D.W., and Bitner, C.J., 2009, Sediment regime constraints on river restoration—An example from the Lower Missouri River: The Geological Society of America, GSA Special Papers, v. 451, 22 p. [Also available at https://doi.org/10.1130/2009.2451(01).]

Jacobson, R.B., Chojnacki, K.A., and Reuter, J.M., 2007, Land Capability Potential Index (LCPI) for the Lower Missouri River Valley: U.S. Geological Survey Scientific Investigations Report 2007–5256, 20 p. [Also available at https://doi.org/10.3133/sir20075256.]

Jacobson, R.B., Colvin, M.E., Bulliner, E.A., Pickard, D., and Elliott, C.M., 2018, Bend-scale geomorphic classification and assessment of the Lower Missouri River from Sioux City, Iowa, to the Mississippi River for application to pallid sturgeon management: U.S. Geological Survey Scientific Investigations Report 2018–5069, 46 p., [Also available at https://doi.org/10.3133/sir20185069.]

Jacobson, R.B., Colvin, M.E., Pickard, D., Bulliner, E.A., and Elliott, C.M., 2017, Bend-scale geomorphic classification and assessment of the Lower Missouri River from Sioux City, Iowa, to the Mississippi River for application to pallid sturgeon management: U.S. Geological Survey Scientific Investigations Report 2018–5069, 35 p. [Also available at https://doi.org/10.3133/sir20185069.]

Jacobson, R.B., Elliott, C.M., and Huhmann, B.L., 2010, Development of a channel classification to evaluate potential for cottonwood restoration, lower segments of the Middle Missouri River, South Dakota and Nebraska: U.S. Geological Survey Scientific Investigations Report 2010–5208, 38 p. [Also available at https://doi.org/10.3133/sir20105208.]

Jacobson, R.B., and Faust, T., 2014, Hydrologic connectivity of floodplains, northern Missouri - Implications for management and restoration of floodplain forest communities in disturbed landscapes: River Research and Applications, v. 30, no. 3, p. 269–286. [Also available at https://doi.org/10.1002/rra.2636.]

Jacobson, R.B., Janke, T.P., and Skold, J.J., 2011, Hydrologic and geomorphic considerations in restoration of river-floodplain connectivity in a highly altered river system, Lower Missouri River, U.S.A: Wetlands Ecology and Management, v. 19, no. 4, p. 295–316. [Also available at https://doi.org/10.1007/s11273-011-9217-3.]

Jacobson, R.B., and Rohweder, J.J., 2019, Segment-scale classification, large rivers of the Upper Midwest United States: U.S. Geological Survey data release, https://doi.org/10.5066/P9HFYOLO.

Johnson, W.C., Volke, M.A., Scott, M.L., and Dixon, M.D., 2015, The dammed Missouri—Prospects for recovering Lewis and Clark's River: Ecohydrology, v. 8, no. 5, p. 765–771. [Also available at https://doi.org/10.1002/eco.1534.]

Jordan, G.R., Heist, E.J., Braaten, P.J., DeLonay, A.J., Hartfield, P., Herzog, D.P., Kappenman, K.M., and Webb, M.A.H., 2016, Status of knowledge of the pallid sturgeon (*Scaphirhynchus albus* Forbes and Richardson, 1905): Journal of Applied Ichthyology, v. 32, suppl. S1, p. 191–207. [Also available at https://doi.org/10.1111/jai.13239.]

Junk, W.J., Bayley, P.B., and Sparks, R.E., 1989, The flood pulse concept in river-floodplain systems: Canadian Special Publication of Fisheries and Aquatic Sciences, v. 106, p. 110–127.

Kammerer, J.C., 1987, Largest rivers in the United States: U.S. Geological Survey Open-File Report 87–242, 2 p.

Kelly, B.P., 2001, Relations among river stage, rainfall, ground-water levels, and stage at two Missouri River floodplain wetlands: U.S. Geological Survey Water-Resources Investigations Report 2001–4123, 18 p.

Kelly, B.P., 2011, Contributing recharge areas, groundwater travel time, and groundwater water quality of the Missouri River alluvial aquifer near the City of Independence, Missouri, well field, 1997–2008: U.S. Geological Survey Scientific Investigations Report 2010–5232, 133 p. [Also available at https://doi.org/10.3133/sir20105232.]

Kemp, G.P., Day, J.W., Rogers, J.D., Giosan, L., and Peyronnin, N., 2016, Enhancing mud supply from the Lower Missouri River to the Mississippi River Delta USA—Dam bypassing and coastal restoration: Estuarine, Coastal and Shelf Science, v. 183, p. 304–313. [Also available at https://doi.org/10.1016/j.ecss.2016.07.008.]

Kennen, J.G., Henriksen, J.A., and Nieswand, S.P., 2007, Development of the hydroecological integrity assessment process for determining environmental flows for New Jersey streams: U.S. Geological Survey Scientific Investigations Report 2007–5206, 56 p. [Also available at https://doi.org/10.3133/sir20075206.]

Kondolf, G.M., Piégay, H., Schmitt, L., and Montgomery, D.R., 2016, Geomorphic classification of rivers and streams, chap. 7 *of* Kondolf, G., and Piégay, H., eds., Tools in fluvial geomorphology: Chichester, England, Wiley Blackwell, p. 133–158. [Also available at https://doi.org/10.1002/9781118648551.ch7.]

Leopold, L.B., 1994, A view of the river: Cambridge, Mass, Harvard University Press, 298 p.

Loken, L.C., Crawford, J.T., Dornblaser, M.M., Striegl, R.G., Houser, J.N., Turner, P.A., and Stanley, E.H., 2018, Limited nitrate retention capacity in the Upper Mississippi River: Environmental Research Letters, v. 13, no. 7, 13 p. [Also available at https://doi.org/10.1088/1748-9326/aacd51.]

McElroy, B., DeLonay, A.J., and Jacobson, R.B., 2012, Optimum swimming pathways of fish spawning migration in rivers: Ecology, v. 93, no. 1, p. 29–34. [Also available at https://doi.org/10.1890/11-1082.1.]

McKay, L., Bondelid, T., Dewald, T., Johnson, C., Moore, R., and Rea, A., 2014, NHDPlus version 2—User guide: U.S. Environmental Protection Agency and U.S. Geological Survey, 170 p.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., and Stouffer, R.J., 2008, Stationarity is dead—Whither water management?: Science, v. 319, no. 5863, p. 573–574. [Also available at https://doi.org/10.1126/science.1151915.]

Montgomery, D.R., 1999, Process domains and the river continuum: Journal of the American Water Resources Association, v. 35, no. 2, p. 397–410. [Also available at https://doi.org/10.1111/j.1752-1688.1999.tb03598.x.]

Montgomery, D.R., and Buffington, J.M., 1997, Channel-reach morphology in mountain drainage basins: Geological Society of America Bulletin, v. 109, no. 5, p. 596–611. [Also available at https://doi.org/10.1130/0016-7606(1997)109<0596:CRMIMD>2.3.CO;2.]

Nelson, J.M., McDonald, R.R., Shimizu, Y., Kimura, I., Nabi, M., and Asahi, K., 2016, Modeling flow, sediment transport and morphodynamics in rivers, chap. 18 *of* Kondolf, G.M., and Piégay, H., Tools in fluvial geomorphology: Chichester, England, Wiley Blackwell, p. 412–441. [Also available at https://doi.org/10.1002/9781118648551.ch18.]

Nico, L.G., Fuller, P., and Li, J., 2018a, *Hypophthalmichthys molitrix* (Valenciennes in Cuvier and Valenciennes, 1844): U.S. Geological Survey, Nonindigenous Aquatic Species Database, accessed December 2018 at https://nas.er.usgs.gov/queries/factsheet.aspx?speciesID=549.

Nico, L.G., Fuller, P., and Li, J., 2018b, *Hypophthalmichthys nobilis* (Richardson, 1845): U.S. Geological Survey, Nonindigenous Aquatic Species Database, accessed December 2018 at https://nas.er.usgs.gov/queries/FactSheet.aspx?speciesID=551.

O'Connell, M.T., O'Connel, A.U., and Barko, V.A., 2011, Occurrence and predicted dispersal of bighead carp in the Mississippi River System: Development of a heuristic tool, chap. *of* Chapman, D.C., and Hoff, M.H., eds., Invasive Asian carps in North America: Bethesda, Md., American Fisheries Society, p. 51–71

Olden, J.D., Kennard, M.J., and Pusey, B.J., 2012, A framework for hydrologic classification with a review of methodologies and applications in ecohydrology: Ecohydrology, v. 5, no. 4, p. 503–518. [Also available at https://doi.org/10.1002/eco.251.]

Olden, J.D., and Poff, N.L., 2003, Redundancy and the choice of hydrologic indices for characterizing streamflow regimes: River Research and Applications, v. 19, no. 2, p. 101–121. [Also available at https://doi.org/10.1002/rra.700.]

Pahl-Wostl, C., 2006, The importance of social learning in restoring multifunctionality of rivers and floodplains: Ecology and Society, v. 11, no. 1, art. 10, 14 p. [Also available at https://doi.org/10.5751/ES-01542-110110.]

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., and Stromberg, J.C., 1997, The natural flow regime: Bioscience, v. 47, no. 11, p. 769–784. [Also available at https://doi.org/10.2307/1313099.]

Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C., Henriksen, J., Jacobson, R.B., Kennen, J.G., Merritt, D.M., O'Keefe, J.H., Olden, J.D., Rogers, K., Tharme, R.E., and Warner, A., 2010, The ecological limits of hydrologic alteration (ELOHA)—A new framework for developing regional environmental flow standards: Freshwater Biology, v. 55, no. 1, p. 147–170. [Also available at https://doi.org/10.1111/j.1365-2427.2009.02204.x.]

Potter, P.E., 1978, Significance and origin of big rivers: The Journal of Geology, v. 86, no. 1, p. 13–33. [Also available at https://doi.org/10.1086/649653.]

Pringle, C.M., 2001, Hydrologic connectivity and the management of biological reserves—A global perspective: Ecological Applications, v. 11, no. 4, p. 981–998. [Also available at https://doi.org/10.1890/1051-0761(2001)011[0981:HCATMO]2.0.CO;2.]

R Development Core Team, 2013, R—A language and environment for statistical computing: Vienna, Austria, R Foundation for Statistical Computing website, accessed December 2018, at http://www.R-project.org/.

Rantz, S.E., 1982, Measurement and computation of streamflow—Volume 1, measurement of stage and discharge: U.S. Geological Survey Water Supply Paper 2175, 284 p. [Also available at https://doi.org/10.3133/wsp2175_vol1.]

Remo, J.W.F., 2016, Managing the Mississippi River in a nonstationary world—Past practices and future challenges, chap. *of* Chen, Y., Chapman, D., Jackson, J., Chen, D., Li, Z., Kilgore, J., Phelps, Q., and Eggleton, M., eds., Fishery resources, environment, and conservation in the Mississippi and Yangtze (Changjiang) River Basins: Bethesda, Md., American Fisheries Society, Symposium 84.

Richter, B.D., Baumgartner, J.V., Powell, J., and Braun, D.P., 1996, A method for assessing hydrological alteration within ecosystems: Conservation Biology, v. 10, no. 4, p. 1163–1174. [Also available at https://doi.org/10.1046/j.1523-1739.1996.10041163.x.]

Ries, K.G., III, Steeves, P.A., Coles, J.D., Rea, A.H., and Stewart, D.W., 2004, Streamstats—A U.S. Geological Survey web application for stream information: U.S. Geological Survey Fact Sheet 2004–3115, 4 p.

Rohweder, J.J., 2019, River valley boundaries and transects generated for select large rivers of the Upper Midwest, United States: U.S. Geological Survey data release, https://doi.org/10.5066/P9HFYOLO.

Rosgen, D.L., 1994, A classification of natural rivers: Catena, v. 22, no. 3, p. 169–199. [Also available at https://doi.org/10.1016/0341-8162(94)90001-9.]

Rowe, J.S., 1962, Soil, site and land classification: Forestry Chronicle, v. 38, no. 4, p. 420–432. [Also available at https://doi.org/10.5558/tfc38420-4.]

Ruhser, J., 2017, 2010/11 aquatic areas—Upper Mississippi river system—Pool 10: U.S. Geological Survey data release, U.S. Army Corps of Engineers' Upper Mississippi River Restoration (UMRR) Program Long Term Resource Monitoring (LTRM) element, accessed September 2018 at https://doi.org/10.5066/F7VD6WH8.

Schmidt, J.C., and Wilcock, P.R., 2008, Metrics for assessing the downstream effects of dams: Water Resources Research, v. 44, no. 4, p. 1–19. [Also available at https://doi.org/10.1029/2006WR005092.]

Schramm, H.L., Richardson, W.B., and Knights, B.C., 2015, Managing the Mississippi River floodplain—Achieving ecological benefits requires more than hydrological connection to the river, chap. *of* Hudson, P.F., and Middelkoop, H., eds., Geomorphic approaches to integrated floodplain management of lowland fluvial systems in North America and Europe: New York, N.Y., Springer-Verlag New York, p. 171–201.

Skalak, K.J., Benthem, A.J., Schenk, E.R., Hupp, C.R., Galloway, J.M., Nustad, R.A., and Wiche, G.J., 2013, Large dams and alluvial rivers in the Anthropocene—The impacts of the Garrison and Oahe Dams on the Upper Missouri River: Anthropocene, v. 2, p. 51–64. [Also available at https://doi.org/10.1016/j.ancene.2013.10.002.]

Smith, J.A., Cox, A.A., Baeck, M.L., Yang, L., and Bates, P., 2018, Strange floods—The upper tail of flood peaks in the United States: Water Resources Research, v. 54, no. 9, p. 6510–6542. [Also available at https://doi.org/10.1029/2018WR022539.]

Stevens, D.L., Jr., and Olsen, A.R., 2004, Spatially balanced sampling of natural resources: Journal of the American Statistical Association, v. 99, no. 465, p. 262–278. [Also available at https://doi.org/10.1198/016214504000000250.]

Strahler, A.N., 1957, Quantitative analysis of watershed geomorphology: Transactions—American Geophysical Union, v. 38, no. 6, p. 913–920. [Also available at https://doi.org/10.1029/TR038i006p00913.]

The Nature Conservancy, 2005, Indicators of Hydrologic Alteration version 7 user's manual: The Nature Conservancy, 42 p.

Thoms, M.C., and Parsons, M., 2002, Eco-geomorphology—An interdisciplinary approach to river science, chap. *of* The structure, function and management implications of fluvial sedimentary systems [Proceedings of an international symposium held at Alice Springs, Australia, September 2002]: International Association of Hydrological Sciences, publication no. 276, p. 113–119

Thorp, J.H., Flotemersch, J.E., Delong, M.D., Casper, A.F., Thoms, M.C., Ballantyne, F., Williams, B.S., O'Neill, B.J., and Haase, C.S., 2010, Linking ecosystem services, rehabilitation, and river hydrogeomorphology: Bioscience, v. 60, no. 1, p. 67–74. [Also available at https://doi.org/10.1525/bio.2010.60.1.11.]

Thorp, J.H., Thoms, M.C., and Delong, M.D., 2006, The riverine ecosystem synthesis—Biocomplexity in river networks across space and time: River Research and Applications, v. 22, no. 2, p. 123–147. [Also available at https://doi.org/10.1002/rra.901.]

Tockner, K., Malard, F., and Ward, J.V., 2000, An extension of the flood pulse concept: Hydrological Processes, v. 14, nos. 16–17, p. 2861–2883. [Also available at https://doi.org/10.1002/1099-1085(200011/12)14:16/17<2861::AID-HYP124>3.0.CO;2-F.]

Tockner, K., and Stanford, J.A., 2002, Riverine floodplains—Present state and future trends: Environmental Conservation, v. 29, no. 3, p. 308–330. [Also available at https://doi.org/10.1017/S037689290200022X.]

U.S. Army Corps of Engineers, 2013, National Inventory of Dams: U.S. Army Corps of Engineers database, accessed September 2018 at http://nid.usace.army.mil/.

U.S. Army Corps of Engineers, 2015 National Levee Database: U.S. Army Corps of Engineers database, accessed October 2015, at https://levees.sec.usace.army.mil/#/.]

U.S. Geological Survey, 2006, USGS small-scale dataset—Major dams of the United States 200603 shapefile: U.S. Geological Survey, digital data, accessed September 2016 at http://dds.cr.usgs.gov/pub/data/nationalatlas/dams00x020_nt00010.tar.gz.

Volke, M.A., Scott, M.L., Johnson, W.C., and Dixon, M.D., 2015, The ecological significance of emerging deltas in regulated rivers: Bioscience, v. 65, no. 6, p. 598–611. [Also available at https://doi.org/10.1093/biosci/biv040.]

Ward, J.V., 1998, Riverine landscapes—Biodiversity patterns, disturbance regimes, and aquatic conservation: Biological Conservation, v. 83, no. 3, p. 269–278. [Also available at https://doi.org/10.1016/S0006-3207(97)00083-9.]

Ward, J.V., and Stanford, J.A., 1995, The serial discontinuity concept—Extending the model to floodplain rivers: Regulated Rivers—Research and Management, v. 10, nos. 2–4, p. 159–168. [Also available at https://doi.org/10.1002/rrr.3450100211.]

Ward, J.V., Tockner, K., Arscott, D.B., and Claret, C., 2002, Riverine landscape diversity: Freshwater Biology, v. 47, no. 4, p. 517–539. [Also available at https://doi.org/10.1046/j.1365-2427.2002.00893.x.]

Waters, T.F., 1995, Sediment in streams—Sources, biological effects, and control: Bethesda, Md., American Fisheries Society, Monograph 7, 251 p.

Williams, G.P., and Wolman, M.G., 1984, Downstream effects of dams on alluvial rivers: U.S. Geological Survey Professional Paper 1286, 83 p. [Also available at https://doi.org/10.3133/pp1286.]

Wing, O.E.J., Bates, P.D., Sampson, C.C., Smith, A.M., Johnson, K.A., and Erickson, T.A., 2017, Validation of a 30 m resolution flood hazard model of the conterminous United States: Water Resources Research, v. 53, no. 9, p. 7968–7986. [Also available at https://doi.org/10.1002/2017WR020917.]

Wing, O.E.J., Bates, P.D., Smith, A.M., Sampson, C.C., Johnson, K.A., Fargione, J., and Morefield, P., 2018, Estimates of present and future flood risk in the conterminous United States: Environmental Research Letters, v. 13, no. 3, 7 p. [Also available at https://doi.org/10.1088/1748-9326/aaac65.]

Wohl, E., Bledsoe, B.P., Jacobson, R.B., Poff, N.L., Rathburn, S.L., Walters, D.M., and Wilcox, A.C., 2015, The natural sediment regime in rivers—Broadening the foundation for ecosystem management: Bioscience, v. 65, no. 4, p. 358–371. [Also available at https://doi.org/10.1093/biosci/biv002.]

Wolock, D.M., Winter, T.C., and McMahon, G., 2004, Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analyses: Environmental Management, v. 34, no. Supplement 1, p. S72–S87. [Also available at https://doi.org/10.1007/s00267-003-5077-9.]

Yadav, M., Wagener, T., and Gupta, H., 2007, Regionalization of constraints on expected watershed response behavior for improved predictions in ungauged basins: Advances in Water Resources, v. 30, no. 8, p. 1756–1774. [Also available at https://doi.org/10.1016/j.advwatres.2007.01.005.]

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