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UPPER MISSISSIPPI RIVER

River stage response to alteration of Upper Mississippi River channels, floodplains, and watersheds

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Abstract The Upper Mississippi River System (UMRS) is a large and diverse river system that changes character along its 1,200 mile network of rivers and canals and 2.6 million acres of floodplain. It supports more than 30 million people in its watershed, a significant commercial waterway, more than a million acres of "floodplain" agriculture and about one-half million acres of river-floodplain managed for fish, wildlife, and recreation. Large-scale geomorphology and climate patterns largely determine the hydrologic characteristics of a nested hierarchy of UMRS river reaches. The human impacts above are also important drivers determining hydrologic characteristics within the hierarchy. Understanding the relationship among physical and chemical processes and ecological responses is critical to implement an adaptive management framework for UMRS ecosystem sustainability. Historic or contemporary data from 42 locations were used to examine changes in UMRS hydrology and to demonstrate the utility of a multiple reference condition analysis for river restoration. A multivariate mathematical framework was used to show how river stage hydrology can be characterized by the variability, predictability, seasonality, and rate of change. Large-scale "geomorphic reaches" have distinct hydrologic characteristics and response to development throughout the UMRS region, but within navigation pool hydrology is similar among all impounded reaches regardless of geomorphic reach. Reaches with hydrologic characteristics similar to historic reference conditions should be examined to determine whether those characteristics support desired management objectives. Water levels can be managed, within limits to support navigation and agriculture, to more closely resemble natural hydrology for the benefit of a variety of species, habitats, and ecological processes.

Keywords Hydrologic indicators · Predictability · Multivariate analysis · Impact analysis · Floodplain river

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Introduction

Large rivers of the world support diverse, productive ecosystems that also provide important ecological and economic services (Welcomme, 1979; Sparks, 1995; Cowx et al., 2004; Nestler et al., 2007).

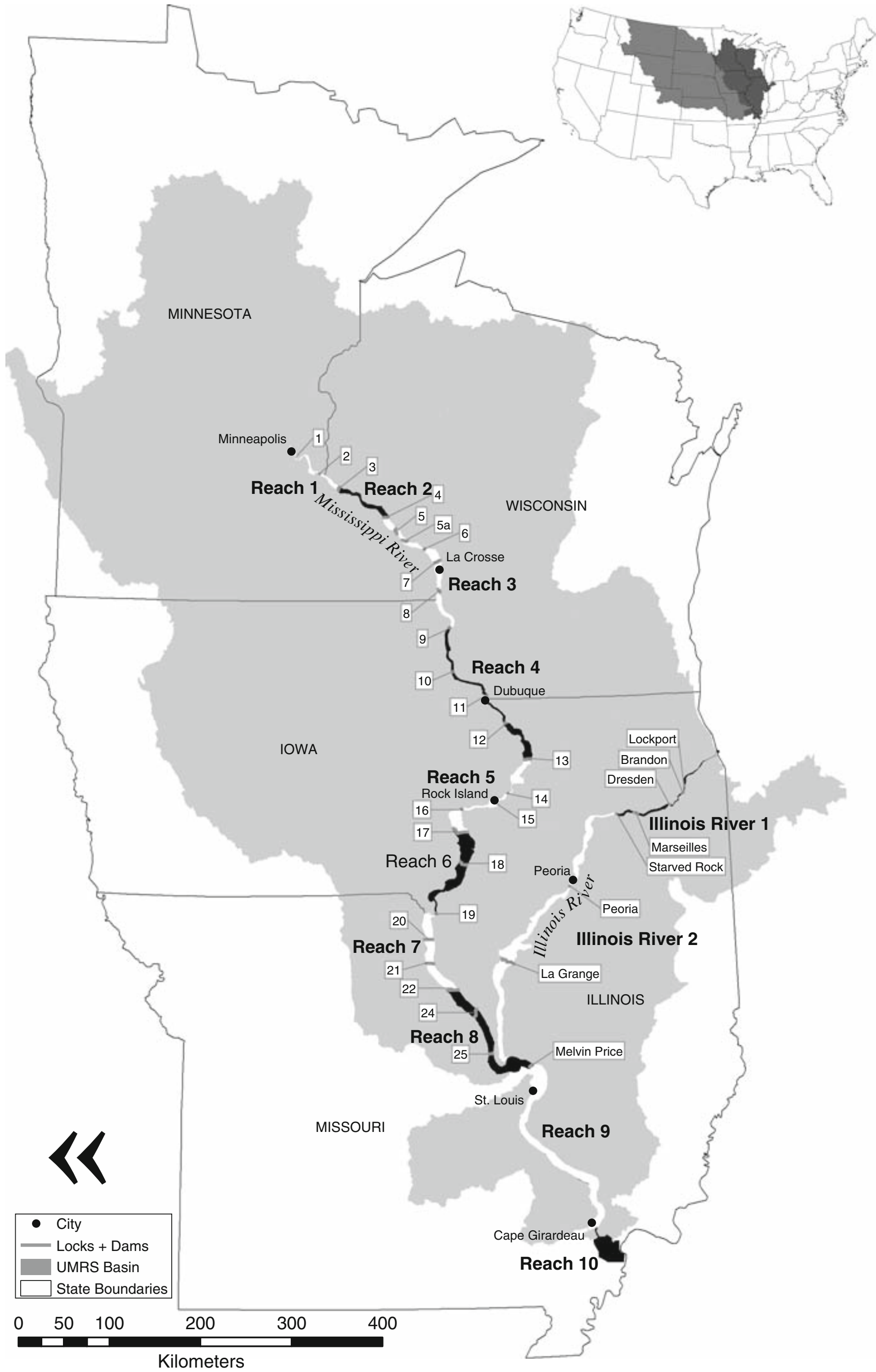


Fig. 1 The Upper Mississippi River System watershed, excluding the Missouri River basin (*inset*). The system has been classified into 12 distinct geomorphic reaches that share similar physical and ecological attributes. The navigation dams that comprise the navigation system are also illustrated

The Upper Mississippi River System (UMRS; Fig. 1) is an excellent example of such a multiple-use river. It supports large-scale commercial navigation (>120 million tons annually) with a 1,200 mile network of navigation channels, 37 lock and dams (Fig. 2), and thousands of local channel stabilization structures (USACE, 2004). There are 180 flood protection structures (i.e., levees and floodwalls) extending 2,200 miles to protect 1.1 million acres of agricultural and urban development which is about one-half of

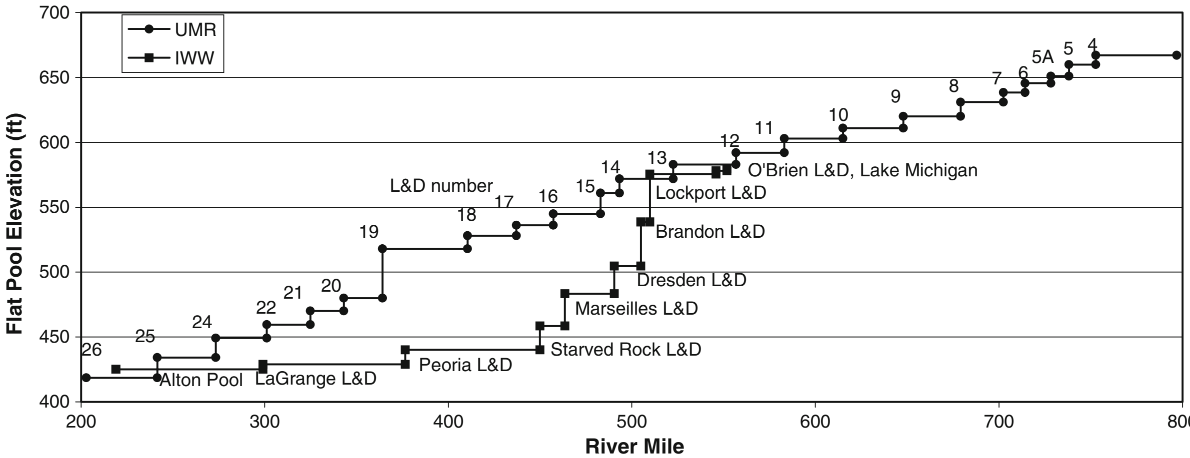


Fig. 2 Flat Pool Elevation for Upper Mississippi River System pools plotted against river mile

total floodplain area, and almost all located in the southern half of the system (Fig. 3; Thompson, 2002; USACE, 2006). Flood protection has prevented over $83 billion in economic damages over the last several decades (USACE, 2006), but catastrophic flooding sometimes occurs and causes large economic consequences (Belt, 1975; White & Meyers, 1993; Changnon, 1996; NOAA, 2008). A 1995 recreation economic analysis estimated annual spending of $1.2 billion in direct and secondary expenditures, and 11 million visitor-days of use by people who hunt, fish, boat, sightsee, and otherwise visit the river and the natural communities it supports (Carlson et al., 1995). The majority of the recreational spending and activity were located in the northern half of the basin where there is abundant public land (Fig. 3). A more recent estimate valued recreation at 12 million visitors spending $6.6 billion each year (Black et al., 1999). Urban areas once built on the industrial power and transportation advantages of the river now capitalize on the environmental benefits of the river by revitalizing unused industrial areas as green space and housing (City of Minneapolis, 2004).

The ecological production capacity of the Upper Mississippi and Illinois Rivers is immense, and the abundance of life in the UMRS was noted by early travelers and settlers (Carlander, 1954; Rahn, 1983). The high productivity of the system initially supported native human populations who developed the highly organized corn-based Late Woodland and Mississippian agrarian cultures between approximately 750 to 1300 AD with a peak near St. Louis between 900 and 1100 AD. Early European pioneers who "discovered" the region (Starrett, 1972) were followed by settlers practicing large-scale exploitation of natural resources including logging, mining, fur trapping, market hunting (Rahn, 1983), commercial fishing (Carlander, 1954; Fremling et al., 1989), and musseling industries at the turn of the twentieth century (Carlander, 1954; UMRCC, 2004). The abundance of life and quality of the Mississippi river ecosystem have changed with large-scale human encroachment and exploitation (Bellrose et al., 1983; Fremling & Claflin, 1984; Starrett, 1972; Sparks, 1984; Tucker et al., 1993; Havera, 1999; Chick & Pegg, 2001).

Recognition of the social value of the ecological functions of the UMRS prompted new legislative authority in 2007 that created substantial new opportunity for ecosystem restoration (>$1.2 billion US over 15 years in 2006 dollars) that focuses on natural processes to ensure ecosystem sustainability (WRDA, 2007). Understanding the relationship among physical and chemical processes and ecological responses is critical to implement the recommended adaptive management framework for UMRS ecosystem sustainability (Lubinski & Barko, 2003; Barko et al., 2006). This analysis explains the response of surface water elevations to dams, diversions, and levees on the Upper Mississippi River System. Understanding the type and amount of change can help set objectives for river management like alternative water level management to promote emergent plants (Kenow et al., 2007) or island construction to reduce lateral

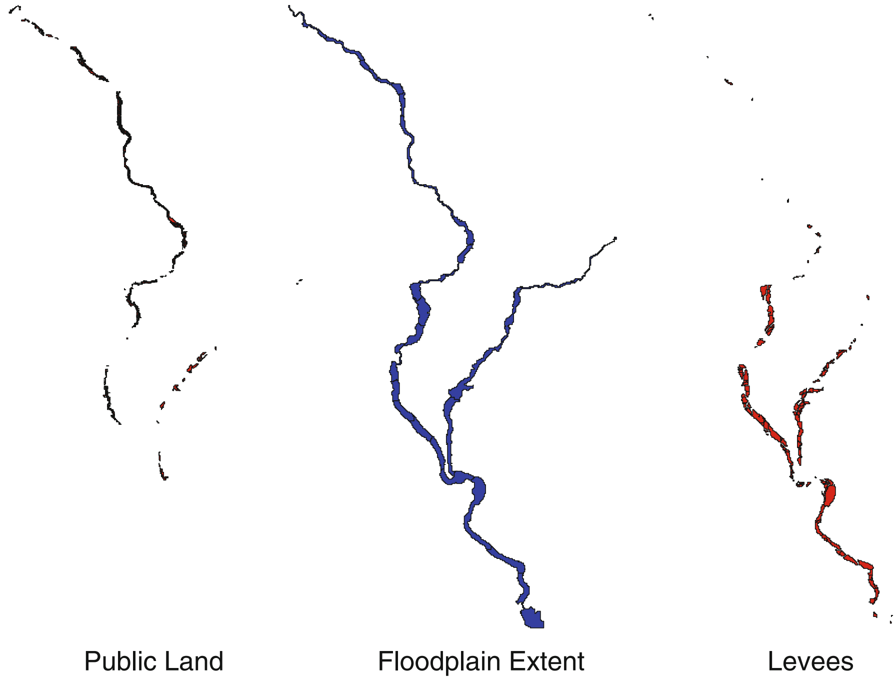


Fig. 3 Levees and public land are disproportionately distributed throughout the Upper Mississippi River System, with levees skewed toward the south and public land skewed to the north

connectivity in some lower pool areas (Langrehr et al., 2007).

Objectives of this synthesis

Our goals in this synthesis are to: (1) summarize and visualize large-scale impacts of UMRS development, primarily operation of the UMRS locks and dam system, (2) describe dam impacts at long-term gages in a single pool on the Illinois River and six navigation pools representing a geomorphically distinct reach on the Upper Mississippi River, (3) combine all data in a final analysis with model generated "without dam" conditions to demonstrate the utility of the multiple reference condition analysis to categorize and visualize different types of data over a large geographic area and multiple time periods, and (4) discuss ecological linkages and ecosystem management implications of alternative water management strategies.

Hydrologic drivers

Natural hydrologic processes and hydraulic patterns (H&H) fundamentally influence the high productivity characteristic of river floodplain ecosystems (Vannote et al., 1980; Ward & Stanford, 1983; Junk et al., 1989; Poff et al., 1997; Ward et al., 1999; Postel & Richter, 2003). Many large river species and communities are adapted to predictable seasonal hydrologic variation (Welcomme, 1979; Cross & Vohs, 1988; Junk et al., 1989; Bayley, 1995; Poff et al., 1997; Ward et al., 1999; Koel & Sparks, 2002). The hydro-geomorphic template of Upper Mississippi and Illinois River ecosystems, collectively referred to as the Upper Mississippi River System (UMRS), was largely established by the Wisconsin Glaciation hydrology over 11,000 years ago (Fremling et al., 1989; WEST Consultants, 2000), and alluvial filling since then (Nielsen et al., 1984; Bhowmik et al., 1986; Chen & Simmons, 1986; Bhowmik & DeMissie, 1989). At large scales within this template, plant community composition in the UMRS is structured by climatological gradients interacting with conditions across seven ecoregions (Omernik, 1987). At smaller scales, local channel floodplain morphology and hydrology determines the distribution of floodplain and riparian plants (Junk et al., 1989; Sparks, 1995; Nelson et al., 1996; Poff et al., 1997; Ward et al., 1999). Several climate shifts have occurred in the UMRS since glacial retreat (Knox, 1993; Bettis et al., 2008) and there are expectations for future shifts (U.S. Global Change Research Program, 2000; Gutowski et al., 2008). Discharge and large floods have generally increased basin-wide over the period of record (Changnon, 1983; Knox, 1993; Wlosinski, 1999; Zhang & Schilling, 2006).

The importance of natural hydrologic patterns for biodiversity conservation and sustainability suggests that naturalization of the hydrologic regime should be the first step in habitat restoration in large rivers (Poff et al., 1997; Richter et al., 1997; Sparks et al., 1998). It is critical to describe and understand how water resources development activities have affected the magnitude, timing, frequency, duration, and change rates of hydrologic events that characterize the natural hydro-geomorphic template of the UMRS (Poff et al., 1997; Richter et al., 1997, 1998; Postel & Richter, 2003). Within the UMRS region, conceptual models (Lubinski, 1993; Lubinski & Barko, 2003) and data summaries (USGS, 1999; Theiling et al., 2000; WEST Consultants, 2000) support the importance of hydrologic pattern and changes caused by multiple cumulative effects. More recently, a multiple reference condition framework for river restoration (Nestler et al., 2007) and a specific multivariate mathematical framework show how hydrology can be characterized to guide restoration planning using the reference condition concept (Nestler et al., 2010).

Richter et al. (1996) developed The Nature Conservancy's Indicators of Hydrologic Alteration (IHA) to calculate ecologically relevant statistics regarding: the timing, magnitude, frequency, duration, and rate of change of hydrologic parameters. The approach of the IHA analysis is to: (1) statistically characterize the temporal variability in hydrologic regimes using biologically relevant attributes of the annual hydrograph, (2) quantify hydrologic alterations associated with perturbations (such as channelization, dam operations, flow diversion, or watershed development), and (3) quantify the natural range of hydrologic variation to determine to what extent the perturbed range of hydrologic variation has exceeded natural bounds and whether these perturbations can be manipulated to more closely approximate the natural condition. The natural condition can serve as a beginning point for restoration "planning". As restoration progresses, natural resource managers who implement large restoration programs can learn and progressively refine their understanding of the relationship between biotic response and hydrologic pattern (Petts et al., 1995; Sparks, 1995; Barko et al., 2006).

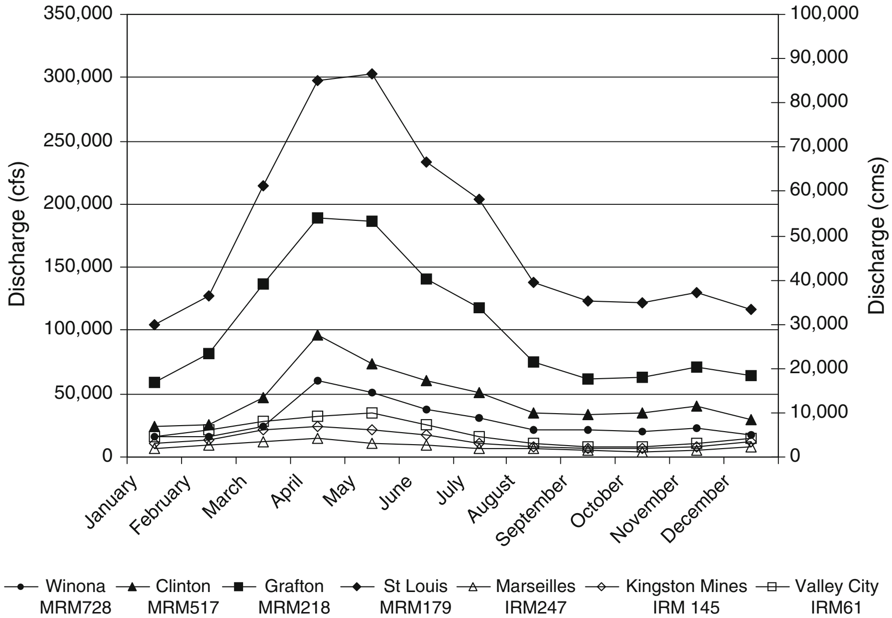
The Upper Mississippi River system

The Upper Mississippi River drains about 189,000 mi^2 (490,000 km^2; see Fig. 1). Upper Mississippi and Illinois River basins and tributaries have been logged, plowed, and channelized to support regional development and intensive corn and soybean row crop agriculture. More than 80% of the total basin area is developed, predominantly by agriculture (over 60%; Gowda, 1999; USEPA, 2008). As much as 26 million acres of wetlands have been drained in the Upper Mississippi and Missouri River Basins (Hey & Philippi, 1995). Illinois and Iowa have each lost 95% of their presettlement wetlands (Dahl, 1990). Land grading and clearing, tile drainage systems, ditches, and stream channelization all contribute to an increased rate of water delivery from the basin to the main stem rivers (Sparks, 1992; DeMissie & Khan, 1993; Sparks et al., 1998; USEPA, 2008).

At the river scale, bluffs and tributaries define 12 ecologically distinct river reaches (see Fig. 1; Theiling et al., 2000; WEST Consultants, 2000; Koel, 2001). In addition, four larger Floodplain Reaches are also commonly referred to (Lubinski, 1999) and they all nest together in a convenient hierarchy to help organize information at different scales (Theiling et al., 2000; Galat et al., 2007). Median long-term discharge in the main stem Mississippi River increases from 32,000 cubic feet per second (cfs) (905 cubic meters per second (cms)) at MRM 725, Winona, Minnesota (1,166 km) to almost 200,000 cfs (5,600 cms) south of the Missouri River confluence (Fig. 4). The Illinois River proper flows 273 mi (439 km) to the confluence with the Mississippi River, but the entire Illinois Waterway (including tributaries and canals linking it to Lake Michigan) is 327 mi (526 km) long (see Fig. 1). Median discharge in the Lower Illinois River is 28,500 cfs (803 cms) (Fig. 4). The Upper Mississippi River floodplain widens from 1 to 3 mi (2–5 km) wide north of Pool 14 to 5–7 mi (8–11 km) wide from Pool 15 to Pool 26, and 7–10 mi (11–16 km) wide in the Middle Mississippi Reach (see Fig. 1). The Lower Illinois River floodplain is 4–5 mi (6–8 km) wide (see Fig. 1) and the river has a low gradient (0.2 ft/mile; Starrett, 1972; Fremling & Claflin, 1984).

The lateral distribution of surface and ground water is related to river stage and responds directly to development like mainstem channelization (Chen & Simmons, 1986; Pinter et al., 2000; Franklin et al.,

Fig. 4 Long-term average discharge at Upper Mississippi River System gages distributed throughout the system. *MRM* Mississippi River Mile, *IRM* Illinois River Mile



2003; Brauer et al., 2005; Jemberie et al., 2008) and mainstem impoundments (Grubaugh & Anderson, 1988; Fremling et al., 1989; WEST Consultants, 2000; Franklin et al., 2003; Jemberie et al., 2008). Surface water flow is distributed across the river valley in main channels, side channels, bars, islands, backwaters, and floodplains to create diverse aquatic conditions that can be classified, measured, and compared as surface area, mean depth, mean current velocity, or susceptibility to wind-waves. The spatial distributions of aquatic area classes help to characterize river reaches and local habitat.

The Upper Mississippi River navigation system developed incrementally over 100 years and culminated in the construction of 29 locks and dams on the Mississippi River and 8 on the Illinois River during the 1930s (Table 1; WEST Consultants, 2000; Anfinson, 2003). Navigation dams are used to increase low and moderate discharge water surface elevations to a relatively constant level in the lower portions of each navigation pool (see Fig. 2). This, along with periodic maintenance dredging, are used to maintain the 9-ft (2.7 m) depth necessary for modern commercial towboats and barges. Navigation pools do not store flood water during high flows and consequently flood stages are not affected. Substantial differences in surface water response to impoundment occur among river reaches and within pools (Fig. 5; Table 2), but, dams effectively remove the low signals of the annual stage hydrograph (Figs. 6, 7; see below). Surface water distribution among aquatic areas (i.e., channels and backwaters; Fig. 5) is substantially altered by river regulation in northern river reaches and relatively little changed in southern reaches. River stage and discharge relationships are also affected to different extents depending on location in the system (Figs. 6, 7; WEST Consultants, 2000; Brauer et al., 2005). Groundwater levels, flooding, and soil permeability determine the distribution of isolated floodplain lakes and affect species composition of forests. Groundwater dynamics have been highly altered by low head navigation dams and extensive levee and drainage district systems to support floodplain agriculture in the southern reaches of the river (Thompson, 2002; USACE, 2006).

Steam mechanization in the late nineteenth century enabled large-scale floodplain wetland conversion to agriculture (Thompson, 2002). Local cooperatives and government support have evolved separately over time to provide various levels of flood protection on the UMRS as opposed to uniform Federal flood protection on the Mississippi River south of St. Louis, Missouri. The distribution of isolated floodplain area (see Fig. 3) relative to historically connected floodplain area among major river reaches is:

Table 1 Upper Mississippi River System Dam specifications (WEST Consultants, 2000)

Lock name or number	River Mile	Pool length (mi)	Drainage area (sq mi)	Average lift (ft)	Lock width (ft)	Lock length (ft)	Percent of time as open river[b]	Began operation
Lower St. Anthony Falls	854.1	0.6	19,680	25	56	400	N/A	1958
1	847.7	6.4	19,684	38	56	400	N/A	Rebuilt 1938
2	815.2	32.5	36,990	12	110	600	1	1931
3	796.9	18.3	45,170	8	110	600	14	1938
4	752.8	44.1	57,100	7	110	600	4	1935
5	738.1	14.7	58,845	9	110	600	1	1935
5A	728.3	9.8	59,105	5	110	600	13	1936
6	714.2	14.1	60,030	6	110	600	7	1936
7	702.5	11.7	62,340	8	110	600	5	1937
8	679.1	23.4	64,770	11	110	600	4	1937
9	647.9	31.2	66,610	9	110	600	15	1937
10	615.1	32.8	79,600	8	110	600	18	1937
11	583.0	32.1	82,100	11	110	600	3	1937
12	556.7	26.3	82,500	9	110	600	4	1938
13	522.5	34.2	85,600	11	110	600	4	1938
14	493.3	29.2	88,400	11	110	600	<1	1939
15	482.9	10.4	88,500	16	110	600	1	1934
16	457.2	25.7	99,500	9	110	600	12	1937
17	437.1	20.1	99,600	8	110	600	22	1939
18	410.5	26.6	113,600	10	110	600	7	1938
19	364.2	46.3	119,000	38	110	1,200	0	1913
20	343.2	21.0	134,300	11	110	600	21	1936
21	324.9	18.3	135,200	11	110	600	15	1938
22	301.2	23.7	137,500	11	110	600	12	1938
24	273.4	27.8	140,900	15	110	600	17	1936
25	241.4	32.0	142,000	15	110	600	20	1939
26/Melvin Price	202.9	38.5	171,500	24	110	600 1,200	19	1938 original 1997[a] replacement
27	185.1	N/A	N/A	21	110	1,200	N/A	1953
Lake Michigan*	333.0	–	–	–	–	–	–	–
O'Brien*	326.0	7.0	–	5	110	600	N/A	1968
Lockport*	291.0	35.0	740	40	110	600	N/A	1933
Brandon*	286.0	5.0	1,506	34	110	600	N/A	1933
Dresden*	271.5	14.5	7,278	20	110	600	N/A	1933
Marseilles*	244.6	26.9	8,259	24	110	600	N/A	1933
Starved Rock*	231.0	13.6	11,056	17	110	600	N/A	1933
Peoria	157.7	73.3	14,554	6	110	600	42	1939
La Grange	80.2	77.5	25,648	5	110	600	48	1939
Alton	–	80.2		–	–	–	–	–

*Upper Illinois River Locks and Dams do not go out of operation

[a] Lock and Dam No. 26 was replaced at a location approximately 2 miles downstream from the original Lock & Dam site and two locks (1,200 and 600 ft) were built to replace original 600 ft lock

[b] From USGS Open-File Report 95-708

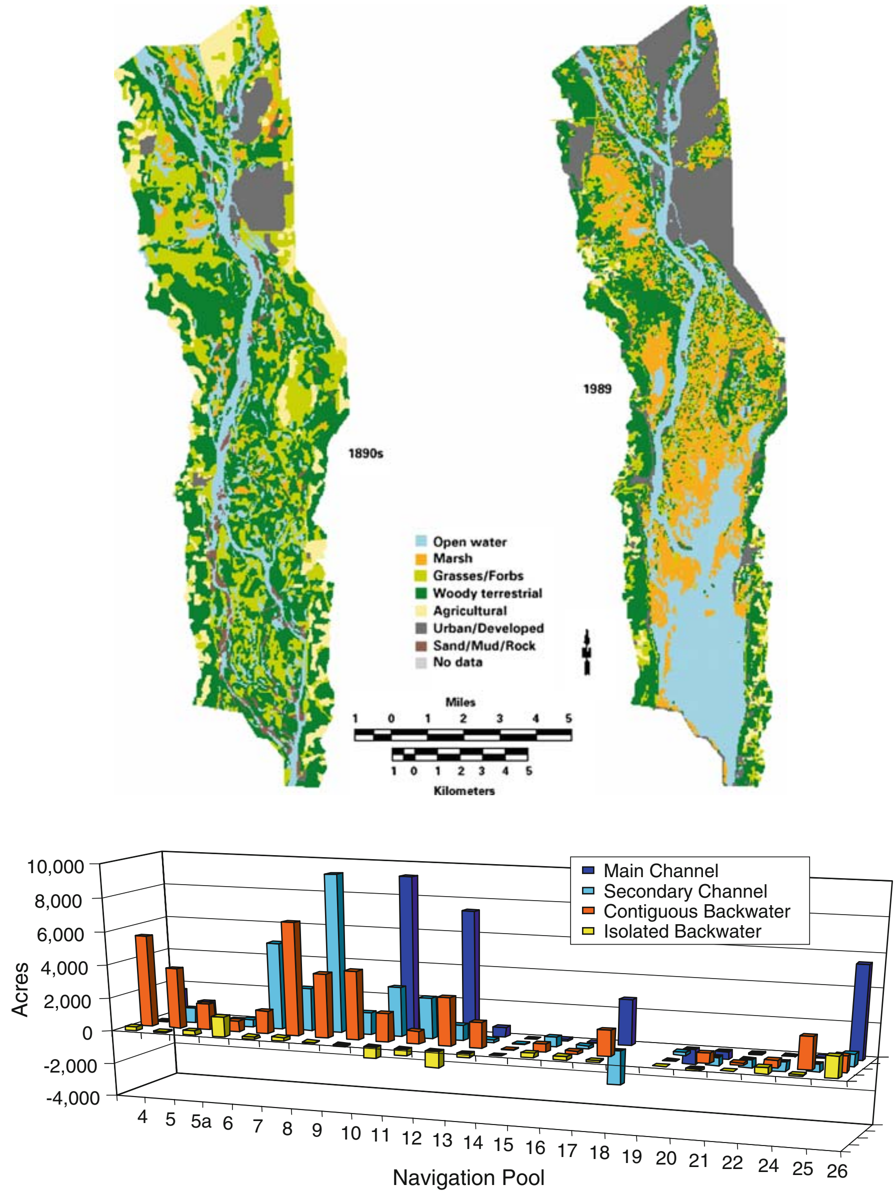


Fig. 5 The Upper Mississippi River System impounds water to maintain 9 ft (2.7 m) depths required for commercial navigation. This pre- and post-impoundment image of Pool 8 presents a clear example of the effect on surface water distribution. Water surface area is greatly expanded in the lower 1/2 to 2/3 of each navigation pool. The lower bar plot summarizes the increase in open water area for each of the classes listed, by pool

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

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

Table 2 Discharge and elevation Pearson correlation coefficients (*r*) in three Upper Mississippi River System navigation reaches

Pool	Pre-development	Upper pool	Middle pool	Lower pool
8	0.78	0.91	0.48	−0.11
26	0.98	0.92	0.63	−0.06
LaGrange	–	0.95	0.93	0.69

Correlations are calculated between the nearest discharge gauge and upper, middle, and lower pool elevation gauges in each navigation reach (Theiling, 2000)

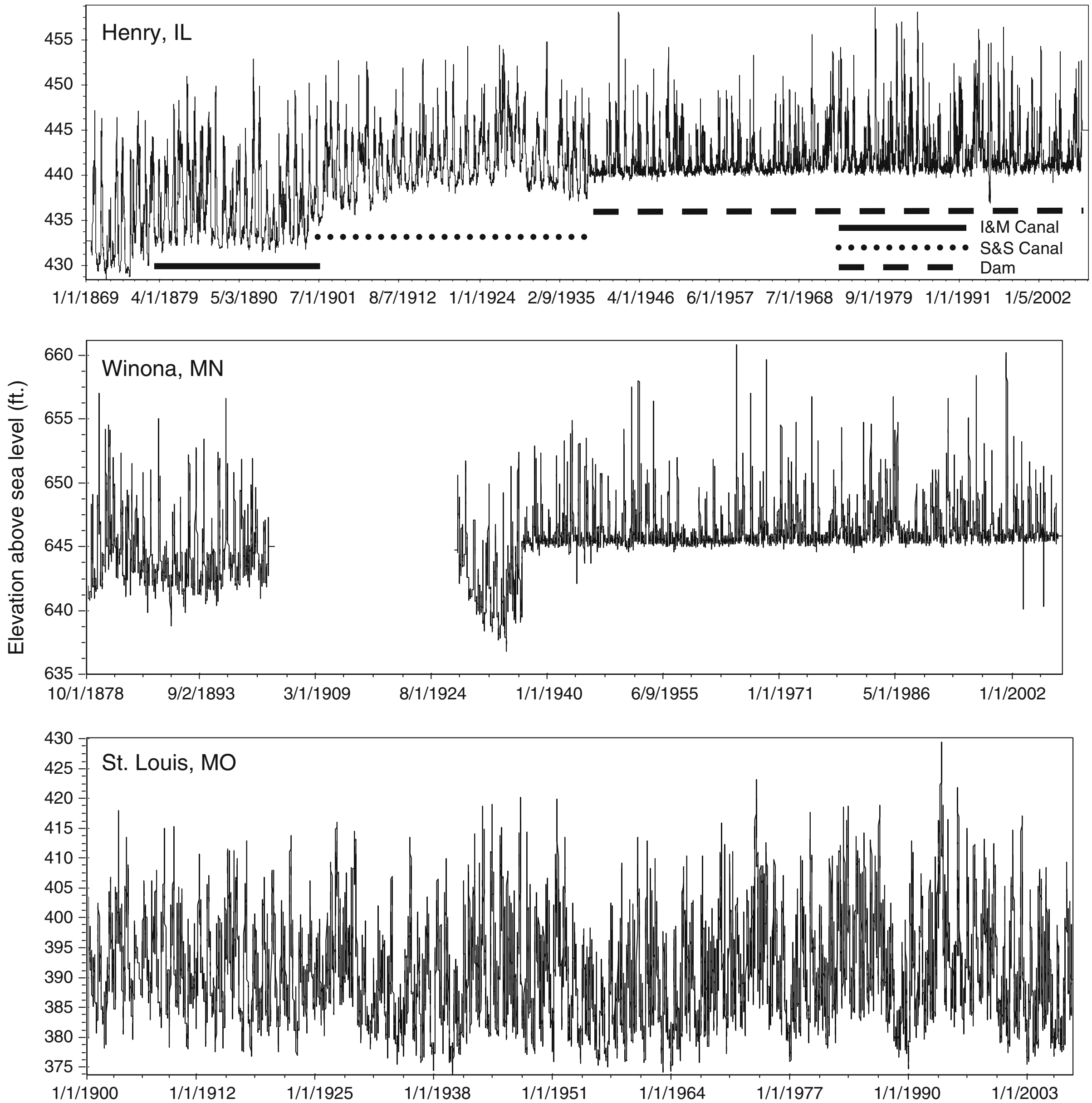


Fig. 6 Long-term daily river stage records from Henry, Illinois—Illinois River, Winona, Minnesota—Upper Mississippi River, and St. Louis, Missouri—Middle Mississippi River

flood zone (Belt, 1975; Chen & Simmons, 1986; Pinter et al., 2000; Remo & Pinter, 2007; Jemberie et al., 2008).

Methods

Climate and hydrologic data

River stage data to help describe pre-impact reference conditions are available at many sites throughout the UMRS. The general availability of hydrologic data sets for large areas and their documented importance as primary drivers of biotic response make them an important element in biodiversity assessment and conservation. For these reasons, data reduction and interpretation tools, like The Nature Conservancy's Indicators of Hydrologic Alteration (IHA; Richter et al., 1996), are important tools for relating hydrology to large river ecology. Our analysis includes river

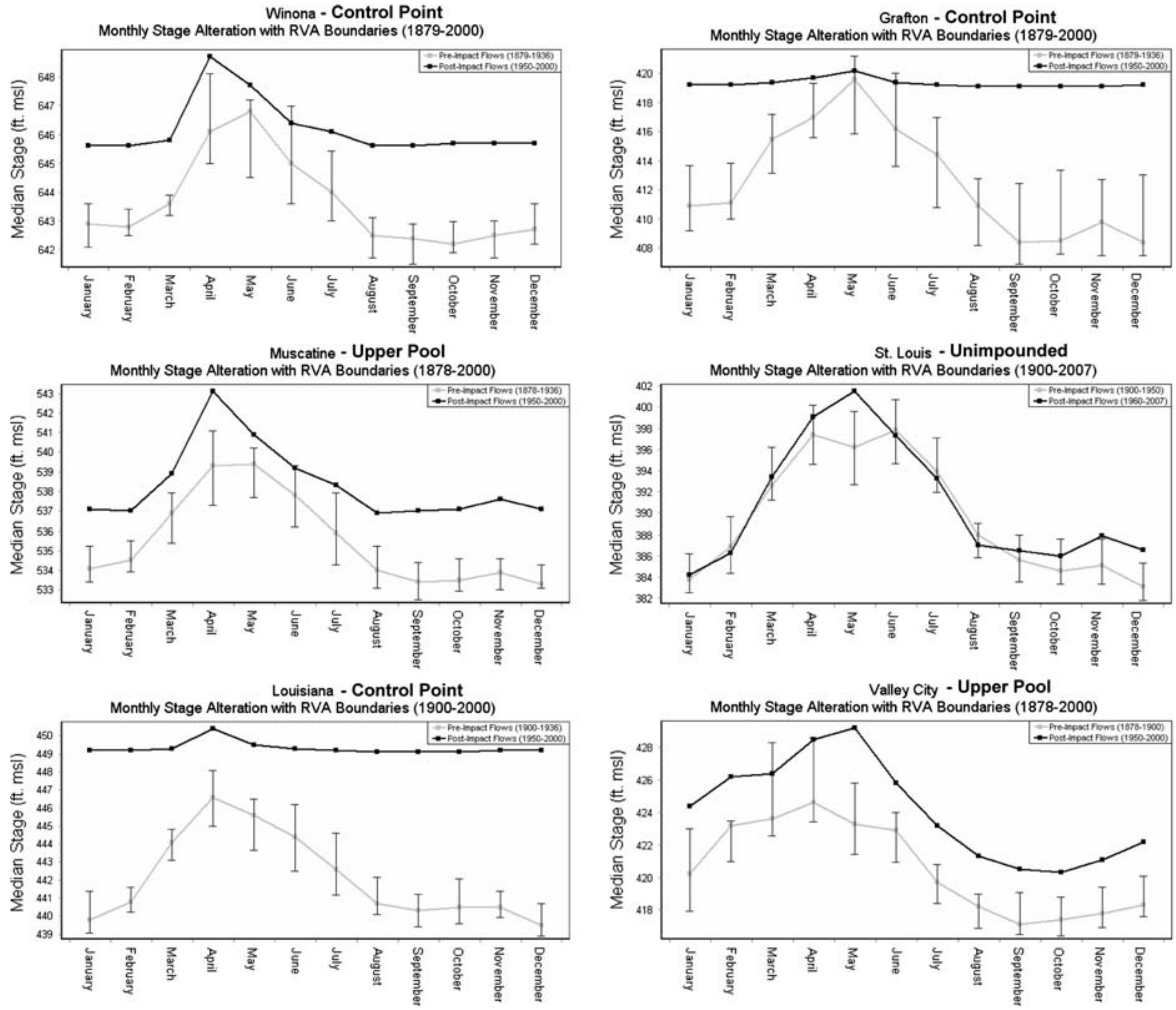


Fig. 7 Pre- and post-impact period median annual stage hydrographs from six long-term Upper Mississippi River System gages. Splines represent the range of variation (see text) around the pre-impact median. Analysis periods are included in each sub-plot legend

discharge and stage records spanning nearly 150 years at 42 locations in the following sets of gages: 7 discharge (Table 3), 7 long-term pre- and post-impact (Table 4), 7 Peoria Pool discharge and elevation (Table 5), 18 Geomorphic Reach (Table 6), and 3 "synthetic hydrograph" gages included in this analysis. Although, these data represent only a fraction of the contemporary data (<20%) and summary indices available for the UMRS (Rivergages.com), their analysis is a useful guide to understand the patterns of hydrologic alteration observed in the entire system.

Statistical analysis—Indicators of Hydrologic Alteration

Conventional applications of the IHA use river discharge data to address issues associated with flow quantity manipulation (Richter et al., 1996, 1997, 1998; Galat & Lipkin, 2000), and also to address other issues (http://www.nature.org/initiatives/freshwater/files/iha_apps.pdf). However, we applied the IHA to both discharge and stage data because, unlike many of the rivers for which the IHA was developed, the storage capacity of UMRS Locks and Dams is

Table 3 Upper Mississippi River System long-term discharge gauges

Discharge gauge	River Mile	Pool	Period of record	Watershed (sq. mi.)
Winona, MN	725.5	6	Jan 1929–Dec 2007	59,200
Clinton, IA	516.6	14	Jan 1874–Dec 2007	85,600
Grafton, IL	218.0	26	Jan 1934–Dec 2007	171,300
St. Louis, MO	179.6	MMR	Jan 1861–Dec 2007	697,000
Chester, IL	109.9	MMR	Jan 1943–Dec 2007	708,600
Thebes, IL	43.7	MMR	Jan 1934–Dec 2007	713,200
Marseilles	246.5	Marseilles	Jan 1920–Dec 2000	8,259

Discharge statistics were calculated between 1950 and 2000 for all gauges

sufficiently small so that impoundment affects river stage much more than river discharge (Chen & Simmons, 1986; Sparks, 1995; Koel & Sparks, 2002). Stage analysis can be used to understand the pattern of connection among the main channel, non-channel aquatic habitat, extensive fringing wetlands, and the entire floodplain. It can also be used to infer long-term dynamics in plant community patterns and other resource categories tied to soil moisture patterns and inundation duration. Discharge is included in this analysis as a baseline indicator to demonstrate the similarity of this driver throughout the UMRS and to quantify alterations to the stage–discharge relationship. We normalized stage data prior to analysis by subtracting the minimum value in the period of record at each gage minus one foot for each stage reading.

The IHA computes 33 ecologically relevant hydrologic parameters in five groups (The Nature Conservancy, 2007):

1. Magnitude of monthly water conditions,
2. Magnitude and duration of annual extreme water conditions,
3. Timing of annual extreme water conditions,
4. Frequency and duration of high and low pulses, and
5. Rate and frequency of water condition changes.

The IHA also calculates parameters for five different groups of Environmental Flow Components (EFCs): low flows, extreme low flows, high flow pulses, small floods, and large floods. We used the default option for non-parametric statistics because of non-random temporal variation in the UMRS hydrograph. Monthly medians were plotted to visualize change in the magnitude, timing, and duration of annual stage hydrograph imposed by hydrologic alterations. The flood peak is estimated as the annual variation between the highest and lowest monthly median water surface elevation rather than from daily values.

IHA Range of Variation Analysis (RVA) is used to compare hydrologic alterations in the monthly median river stage between pre- and post-project periods of record. In this analysis, the full range of pre-impact data for each parameter is divided into three different equal-sized categories based on percentile values: low—stages less than or equal to the 33rd percentile; middle—stages between the 34th to 67th percentiles; and high—stages greater than the 67th percentile. An overlay of pre- (whiskers present) and post-impact (no whiskers) hydrographs for several river reaches shows how development has altered the magnitude, timing, and duration of hydrologic cycles across large scales (see Fig. 7). The separation between the pre-impact RVA whiskers and the post-impact monthly median indicates the amount of hydrologic change.

The IHA parameters: Annual CV, Predictability, Constancy, Contingency (seasonality), Low Pulse Count, High Pulse Count, and Reversals were identified as parameters with ecological relevance in large floodplain rivers and were, therefore, considered for correspondence analyses (Table 7). Annual coefficient of variation is calculated as the standard deviation of daily flow values, divided by the mean annual flow. Predictability, constancy, and contingency (Colwell, 1974), as applied by Poff & Ward (1989) for hydrologic analysis, are parameters that describe general characteristics of periodic phenomena. Predictability is a measure of the regularity of the occurrence of an event. Predictability ranges in value from 0 to 1 and is composed of two additive

Table 4 Upper Mississippi River System water level (stage) gauge locations, watershed area, dam influence, period of record, analysis periods, vertical elevation datum, and value used to normalize stage data relative to the minimum value in each period of record

Gauge location	River Mile	Pool	Watershed (sq. mi.)	Dam influence	Period of record	Analysis period		Datum	Minimum value (ft. msl)	
						Pre-impact	Post-impact		Pre-impact	Post-impact
Winona, MN	725.5	6	59,200	Weak	Aug 1878–Dec 1902; Mar 1928–Dec 2007	Oct 1879–Dec 1902; Mar 1928–Dec 1936	Oct 1975–Sep 2000	1912	636.75	640.14
Muscatine, IA	453.0	17	99,450	Weak	Aug 1879–Dec 2007	Jan 1878–Dec 1936	Jan 1950–Dec 2000	1912	529.84	533.24
Louisiana, MO	282.9	24	149,700	Strong	Jan 1878–Dec 2007	Jan 1900–Dec 1936	Jan 1950–Dec 2000	1929	434.13	445.63
Grafton, IL	218.0	26	171,300	Strong	Aug 1878–Dec 1904; Jan 1929–Dec 2007	Oct 1879–Sep 1892; Apr 1894–Dec 1804; Jan 1929–Dec 1936	Oct 1950–Dec 2000	1929	402.99	416.39
St. Louis, MO	179.6	MMR	697,013	NA	Jan 1860–Dec 2007	Jan 1900–Dec 1950	Jan 1955–Dec 2000	1927	373.74	374.14
Henry, IL	196.0	Peoria (IR)	13,543	Moderate	Jun 1869–Dec 2007	Oct 1869–Sep 1899	Oct 1950–Dec 2000	1929	428.40	436.90
Valley City, IL	61.3	Alton (IR)	26,070	Moderate	Nov 1878–Dec 2007	Nov 1878–Dec 1899	Oct 1950–Dec 2000	1929	414.32	417.30

components: constancy (C) and contingency (M). Constancy is a measure of flow uniformity over time. For example, a groundwater fed stream from a small watershed area would exhibit high constancy. Contingency is a measure of the seasonality of an event, such as a spring flood pulse. Consequently, some systems may be predictable based on the regularity of cycles, others can be predictable based on flow uniformity over time. The IHA program reports predictability and the quotient of constancy/predictability.

Selection of specific hydrologic summary variables produced by the IHA software were based on the results of a correlation analysis (Table 8). Contingency and Constancy were perfectly negatively correlated ($r = -1.00$), so we deleted contingency from further consideration. High Pulse Count and Low Pulse were correlated at $r = 0.81$ ($P < 0.0001$). Both of these variables increase with dam operation for navigation, with levee construction that reduces channel conveyance of high flows, and with increased runoff rate from the watershed associated with land use change. We created a new variable, "flashiness", defined as the sum of the High Pulse Count and Low Pulse Count and dropped the two pulse count variables from further consideration because they were not needed. Flashiness was correlated at $r = 0.96$ and $r = 0.94$ to high and low pulse count, respectively. We also noted that "flow reversals" were highly correlated to low and high pulse count ($r = 0.86$ and $r = 0.68$, respectively) and that it was highly correlated to the new "flashiness" variable at $r = 0.82$). Therefore, we dropped flow reversal because its information content appeared to be similar to that of the Flashiness variable. Other high correlations were also observed, but inspection of the raw data showed that they were based on correlations of high values that were not paralleled across intermediate and low values. Although similar from a statistical standpoint, we kept the other variables because they had potential explanatory power for future ecological response variables. We made no further adjustments to the hydrologic variable list and used the following four variables in our analysis: annual coefficient of variation, predictability, constancy, and flashiness.

We then summarized these four variables output from the IHA software as a contingency table of hydrologic summary variables as columns and gauging stations as rows. The contingency table was used

Table 5 Peoria Pool, Illinois River, discharge (cfs), and elevation gauges

Gauge location	River Mile	Location in pool	Gauge type	Watershed (sq. mi.)
Starved Rock Dam	231.1	Upper	Dchg	11,056
Peoria Dam	157.9	Lower	Dchg	14,554
Starved Rock Tailwater	231.1	Upper	Elev	11,056
LaSalle	224.7	Middle	Elev	12,572
Henry	196.0	Middle	Elev	13,543
Peoria City	164.6	Lower	Elev	14,165
Peoria Dam	157.9	Lower	Elev	14,554

Discharge statistics are based on data collected between 1987 and 2007, elevation statistics are based on data collected between 1950 and 2000

Table 6 Upper Mississippi River System post-dam gauges in Geomorphic Reach 3

Gauge location within pools	River Mile
Upper pool 5	752.8
Mid pool 5	749.2
Lower pool 5	738.1
Upper pool 5a	738.1
Lower pool 5a	728.5
Upper pool 6	728.5
Mid pool 6	725.5
Lower pool 6	714.3
Upper pool 7	714.3
Mid pool 7	707.2
Lower pool 7	702.5
Upper pool 8	702.5
3/4 pool 8	696.9
1/4 pool 8	688.3
Lower pool 8	679.2
Upper pool 9	679.2
Mid pool 9	663.0
Lower pool 9	647.9

With one exception (Pool 5a), there is a gauge at each upper and lower dam and at least one in between

Table 7 Indicators of hydrologic alteration parameters included in correspondence analyses

	Gauge A	Gauge B	Etc.
Annual coefficient of variation			
Predictability			
Constancy			
Contingency			
High pulse count			
Low pulse count			
High pulse duration			
Low pulse duration			
Reversals			

as input for cluster analysis (SAS, 1988) and correspondence analysis (CA) (Greenacre, 1993). We use the cluster analysis to depict similarity among the gages with the idea that similar gages could be treated with similar management actions with similar outcome expectations. We use CA to visualize the pattern in two-dimensions and relate the pattern to underlying hydrologic variables (variable plots and joint plots). CA is a geometric technique for displaying rows and columns of a two-way contingency table as points in low-dimensional space to obtain a global view of pattern in data useful for interpretation. (see CA of rainfall data in Silveira, 1997 as an example hydrologic analysis). Correspondence analysis is based on chi-squared tests (χ^2) to measure discrepancy between observed frequencies in a contingency table and the expected frequencies calculated under the hypothesis of homogeneity of row or column profiles. Discrepancy is expressed in term of inertia (variation) and can be interpreted as the weighted average of squared χ^2 distances (as opposed to Euclidian distance) between the row profiles and their average profile or equivalently between the column profiles and their average. Results are displayed in 2-dimensional scaled maps because most of the variability is captured by the first two axes of the CA output. CA provides projections based on simplifications that depict pattern in the data for easy visualization, but the projection changes as variables or sites are added or removed so that

Table 8 Pearson correlation coefficients (*top entry*) and probabilities (*second entry*) for IHA hydrologic variables listed in Table 4

	Annual coefficient of variation	Predictability	Constancy	Contingency	Low pulse count	High pulse count	Reversals	Flashiness	Flashiness + high & low pulse count
Annual coefficient of variation	1.00	−0.44	−0.74	0.74	−0.40	−0.40	−0.41	−0.42	−0.43
		0.0512	0.0002	0.0002	0.0768	0.0834	0.0747	0.0643	0.0554
Predictability		1.00	0.43	−0.43	0.06	−0.037	0.12	0.014	0.06
			0.0567	0.0563	0.8112	0.8774	0.6058	0.9519	0.8167
Constancy			1.00	−1.00	0.68	0.66	0.67	0.70	0.7235
				<.0001	0.0009	0.0017	0.0012	0.0005	0.0003
Contingency				1.00	−0.68	−0.65	−0.67	−0.70	−0.7235
					0.0009	0.0017	0.0012	0.0005	0.0003
Low pulse count					1.00	*0.81*	*0.86*	*0.96*	*0.96*
						<.0001	*<.0001*	*<.0001*	*<.0001*
High pulse count						1.00	0.68	*0.94*	*0.8881*
							0.0009	*<.0001*	*<.0001*
Reversals							1.00	*0.82*	*0.92086*
								<.0001	*<.0001*
Flashiness								1.00	*0.98*
									<.0001

Note: Italics indicate parameters dropped from analysis or combined because they were highly correlated (see text)

associations among gages are best represented by the cluster analysis.

Results

Univariate synthesis assessing impacts of river regulation

System-wide long-term change

Examples of hydrologic alteration of the UMRS are presented for three long-term daily stage gages (Fig. 6) at upstream and downstream locations in the river system. The gage at Henry, Illinois, below the "Great Bend" (Starrett, 1972) in the Lower Geomorphic Reach (Theiling et al., 2000; WEST Consultants, 2000), illustrates effects of a sequence of disturbances impacting Illinois River hydrology (Fig. 6). The Illinois River was impacted first in 1878 by the Illinois & Michigan (I&M) diversion canal designed to transport commodities to and from the growing population in Chicago, Illinois. The I&M Diversion Canal raised average water levels a couple of feet (2/3 m), but did not change stage variation. The Chicago Sanitary and Ship (S&S) Canal was a larger 1,500–7,500 cfs diversion (42.3–212 cms) completed in 1903 to provide greater sewage flushing capacity away from Chicago's Lake Michigan water supply and also to accommodate increased commercial shipping needs (Starrett, 1972; Theiling, 1999). The S&S Canal increased water levels by 3–6 ft (1–2 m) depending on location in the river but stages maintained a range of variation similar to pre-dam conditions so that the net effect of the canal was to increase base flow of the Illinois River. An early lock and dam system operated by the State of Illinois was modernized by the U.S. Army Corps of Engineers in 1939 to maintain river stage during low flow periods. The dams did not increase water levels appreciably during moderate to high discharges, but did effectively remove low stages of the hydrograph so that commercial navigation could operate during low discharge periods. The dams currently operate when depth is insufficient for navigation (about 50% of the time).

The stage gage at Winona, Minnesota represents dam impacts exhibited throughout the impounded reaches of the Upper Mississippi River (Fig. 6B).

This gage also illustrates problems with data gaps at some sites because it does not capture an extreme drought that occurred during the 1920s. Dam impacts on river stage beginning abruptly in 1938 are pronounced at this location, as they are in other impounded reaches. The general pattern of impacts is consistent throughout the system with an increase in low flow river stage at the dam headwaters of 5–15 ft (2–5 m) at most locations and in excess of 25 ft (8 m) at a few sites (see Table 1, WEST Consultants, 2000). Hydrologic alteration varies consistently within each pool reach depending on proximity of the immediate downstream dam, with the greatest stage variation in the upper pool to highly regulated (maintained at a near constant stage for non-flood flows) near the dam. Within this general pattern, tributaries, local riverbed slope, floodplain geomorphology, and specific dam operations further effect stage–discharge relationships and surface water distribution.

The St. Louis, Missouri gage represents river stage in the unimpounded reach below the confluence with the Missouri River (Fig. 6C). The total discharge of the Illinois, Mississippi, and Missouri Rivers combined with extensive channel training structures and maintenance dredging is sufficient to maintain navigable river depths without the need for impoundment. The St. Louis gage does not clearly illustrate significant hydrologic impacts like the upper impounded reaches. However, downcutting of the channel has been reported (Chen & Simmons, 1986; Wlosinski, 1999; Pinter & Heine, 2005; Remo & Pinter, 2007) as has increased flood stages due to constriction of the river conveyance area by levees (Belt, 1975; Wlosinski, 1999; Pinter & Heine, 2005; Remo & Pinter, 2007).

Regional effects from impoundment

Longitudinal gradients in flow and geomorphology are reflected in elements of dam design and operation as well as in hydrologic response in the river. The Winona gage is the Pool 6 Control Point, which is a location in the pool where dam operation maintains relatively stable river stages (Fig. 7). The post-dam median flood pulse is about 3 ft (1 m) in contrast to the median pre-dam spring flood at the Winona gage which exhibited a 5 ft (1.6 m) pulse starting in March and extending to August. The pre-dam seasonal range of variation (RVA) was 3 ft (1 m) or more for flood season and 1–2 ft (0.3–0.6 m) during low flow periods. Post-dam river stage falls outside of the range of variation in all months except June where the high end of the range of variation crossed the post-dam median. Base elevation increased 3 ft (1 m) between August and February, but the spring flood season is more similar between periods. Monthly medians mask a small fall flood apparent in many years. Caution must be applied in evaluating summary data because some impacts and extreme events may not be apparent. For example, the pre-dam range between minimum and maximum values versus the post-dam range was 20 ft (6 m) and 15.8 ft (5 m), respectively, because of the increased base elevation (Table 9). Precise estimates of river stage and inundation area relationships are not readily available for most of the river, but stage differences in the range of a few feet, or one meter, may result in thousands of acres of inundation in a 30–40 mile river reach depending on location in the river system and river stage. Floodplain inundation frequency is a subject of great interest for ecosystem restoration and flood protection purposes. The amount of open water created by the dams (see Fig. 5) was much greater in the Upper Impounded Reach (Lubinski, 1999) upstream of Pool 14 than in the Lower Impounded Reach which extends from Pool 14 downstream to Pool 26.

The upper regions of each pool are least altered by the UMRS navigation dams (see below). The Muscatine gage is located in the hydrologically responsive upper pool region of Pool 17 where the range of stage variation and seasonal pattern are very similar between pre-dam and post-dam periods (Fig. 7). The median pre-dam spring flood at the Muscatine gage

Table 9 Raw data minimum and maximum values for pre- and post-impact periods

Elevation gauge	Pre-dam			Post-dam		
	Min	Max	Diff	Min	Max	Diff
Winona	636.8	657.0	20.2	645.0	660.8	15.8
Muscatine	529.8	549.8	20.0	536.0	556.3	20.3
Louisiana	434.1	458.2	24.1	449.0	465.6	16.6
Grafton	403.0	439.7	36.7	418.0	441.8	23.8
St. Louis	374.4	417.9	43.5	374.1	429.4	55.3
Valley City	414.3	44.00	25.7	420.0	444.7	24.7

Post-dam minimum is the regulated stage to maintain navigation exhibited a 5 ft (1.5 m) pulse starting in February, peaking in April, then receding through August. The pre-dam seasonal range of variation was 4 ft (1.2 m) for flood season and 2 ft (0.6 m) during low flow periods. Post-dam river stage falls outside of the range of variation in all months except June where the high end of the range of variation reaches the post-dam median. Base elevation is increased 4 ft (1.2 m) between September and January, but the spring flood season is more similar among periods. A small fall flood that occurs in many years is apparent in the medians. The range between minimum and maximum stages was 20 ft (6 m) for both the pre-dam and post-dam periods of record, but the baseline stage is shifted up 6 ft (1.8 m) in the post-dam period (Table 9). Despite the increased base elevation, the area of surface water seemed relatively unchanged in the post-dam period (see Fig. 5, WEST Consultants, 2000). Steeper-sloped channels in the Lower Impounded Reach restrict the regulated river stage within channels. Groundwater influenced low flood-plain areas were isolated from the channel by levees and then drained for agriculture.

The ranges of variation, seasonal signals, and dam impacts at the Louisiana and Grafton gages are similar (Fig. 7) because both are in the same Geomorphic Reach and both are strong control points in their respective pools. River stages at the control points in Pools 24, 25, and 26 are maintained by large drawdowns at the dam (3–6 ft; 1–2 m). These draw-downs are implemented to reduce local flooding from backwater effects of the dams during times when navigable channel depths are achievable by discharge alone (i.e., without stage control). The median pre-dam spring flood was 7 ft (2.1 m) and 10 ft (3 m) at Louisiana and Grafton, respectively, and both show the same seasonal pattern as the Winona and Musca-tine gages further upstream. The median range of variation was 4 ft (1.2 m) for the flood season and 2 ft (0.6 m) during low flow periods at Louisiana, like upstream, but between 5 and 6 ft (1.5–1.8 m) year round at Grafton below the Illinois River. A small fall pulse is detectable at both locations. Post-dam changes are dramatic. Post-dam river stages fall outside the range of variation in all months at Louisiana. The Grafton pre-dam spring flood RVA boundary crosses the median post-dam spring flood during May and June, but base elevation is increased about 10 ft (3 m) between September and January, which is a great difference between pre- and post-dam periods. At both locations, the post-dam median spring flood is barely discernible because of mid-pool control point dam operation. At Louisiana, the pre-dam and post-dam ranges between minimum and maximum stages were 24 and 16.6 ft (7 and 3 m), respectively, and post-dam stages are shifted up by 5–8 ft (1.2–2.4 m, Table 9). Similarly, at Grafton, the pre-dam versus post-dam ranges between minimum and maximum stages were 36.7 and 23.8 ft (11 and 7.3 m), respectively, and post-dam minimum stages are shifted up by 15 ft (4.6 m, Table 9). The greatly increased base elevation in Pool 26, doubled the open water surface area of the post-dam period, with post-dam increases in total open water of 8,000 acres apparent mostly in the Main Channel class as opposed to backwaters created upstream (see Fig. 5; WEST Consultants, 2000).

Hydrology at the St. Louis gage is very different than at the upstream gages because of the combined discharge from the Mississippi, Illinois, and Missouri River which all join within 40 miles (~60 km) upstream of this gage and also because there are no downstream dams. The differences between the pre- and post-impact periods are primarily determined by the extensive government sponsored channelization since 1824, operation of large storage reservoirs on the Missouri River since 1955, and a uniform level of flood protection provided by extensive mainline levees that isolate 83% of the historic floodplain area. More detailed assessments have been completed to separate out channelization and levee impacts (Wlosinski, 1999; Pinter & Heine, 2005; Remo & Pinter, 2007). The pre-impact spring flood at St. Louis was bi-modal with first rain then Rocky Mountain snowmelt driven peaks before a long decline in stage through fall and winter (Hesse et al., 1989; Fig. 7). In contrast, a uni-modal spring flood is present post-impact. Water levels are higher in the fall because of scheduled reservoir releases on the Missouri River to maintain higher river stage to support navigation on the Mississippi River. An increase in maximum flood stage of almost 12 ft (3.7 m) was observed during the 1993 flood of record (Table 9) but no change in the low stage has been observed since 1955. We did not specifically test for changes in the stage–discharge relationship, but other authors have noted that low flow stages are lower from downcutting of the channel and high stages are higher because of levees constricting the floodway (Wlosinski, 1999; Pinter et al., 2000;

Jemberie et al., 2008). Examining the longer period of record graphically, however (see Fig. 6), there appears to be a decrease in low stage of several feet because of downcutting of the river bed in response to extensive channelization activities prior to the Missouri River dams (Chen & Simmons, 1986; Pinter & Heine, 2005; Remo & Pinter, 2007).

Hydrologic alterations at the Valley City gage on the Illinois River reflect mostly the 1903 diversion of flow from Lake Michigan because the gauge is located 80 miles (130 km) upstream from the nearest impounding dam, Melvin Price Dam at Alton, Illinois on the Mississippi River. The diversion increased river stage up to several feet (1–2 m) depending on the location in the system, but the range and pattern of river stage variability remained similar despite the higher base level (see Fig. 6) until 1940 when low head navigation dams were completed. Dams stabilized the low river stage to support navigable channel depths during low discharge periods. When discharge exceeds a moderate threshold, the gate design is such that they can be lowered to the bottom of the river and barge traffic passes over the dam without having to use the locks (USACE, 2004). The entire stage hydrograph increased 3–6 ft (1–2 m) at Valley City, with the greatest change being a higher spring flood that extends later into May (Fig. 7). The magnitude of the median spring flood level is about 8 ft during both pre- and post-dam periods (Fig. 7). The range of hydrologic variation is similar in both periods, but the minimum and maximum river stages were increased by about 5 ft each (1.5 m; Table 9). Hydrologic changes on the Illinois River did not create the large lower pool impounded areas as shown in Fig. 5, rather, the increase in base stage created large floodplain lakes with variable levels of connectivity to the main channel along most of the floodplain where there are no levees. Leveed areas mostly downstream from Peoria (see Fig. 3) incur great expense to drain isolated floodplain areas through extensive ditching, tiling, and pumping. Aquatic areas riverward of levees are exposed to altered hydrology and increased sedimentation (Bellrose et al., 1983; Bhowmik & DeMissie, 1989; Sparks, 1992).

Within-pool hydrology

Peoria Pool on the Illinois River and Geomorphic Reach 3 (Pools 5 to 9) on the Mississippi River were selected to illustrate within-pool hydrologic gradients caused by the dams. Peoria Pool is 73 miles (117 km) long, like La Grange and Alton Pools, exhibits impacts associated with very low gradient rivers. In contrast, Pools 5 to 9 reflect a broader range of characteristics found on the Upper Mississippi River. The Peoria Pool reach was historically characterized by large seasonal wetlands and backwater lakes formed by tributary deltas. Many of these features were permanently flooded by the dams which created large, shallow lakes throughout the reach. The long-term stage at Henry, Illinois near the middle of the pool has a pre-diversion (1869–1900) median spring flood of about 10 ft (3 m; Fig. 8). The post-dam median spring flood is 6 ft (1.8 m) at the upstream end of the pool (i.e., Starved Rock), and only 2 ft (0.6 m) at the lower dam (i.e., Peoria Pool). Flood height decreases from the upper to lower end of the pool where dams have the most influence on river stage.

Mean monthly stage pattern is generally similar in all six pools of Geomorphic Reach 3 (Fig. 9). The upper pool spring pulse increases from about 4 ft (1.2 m) in upper Pool 5 to 6 ft (1.8 m) in upper Pool 9. Mid pool hydrographs differ by location in the pool. Pool 8 (with 4 gages) best illustrates the spring pulse gradient with flood magnitude decreasing from the upper pool to the lower pool. Stage patterns among individual pools are determined by an operating curve for each pool that specifies target elevations at the control point and at the dam relative to discharge. At lower discharges, flow through the dam is reduced to impound water upstream to maintain navigation depth. At higher discharges, the gates are progressively opened to maintain target elevations at the mid pool control point. At high flows, the gates are pulled out of the water completely (open river conditions) and stages throughout the pool increase with increasing flows. The effect of midpoint control is most pronounced in pools 5 and 6 where the median stage at the dam decreases during the spring (less than 1.0 ft) while stage in other parts of the pool increases during the spring pulse. Median stages in Pools 5a and 9, however, exhibit small increases in stage near the dam during the spring pulse period. The differences between these two sets of pools primarily reflect the different periods of time that they are in open river conditions (see Table 1).

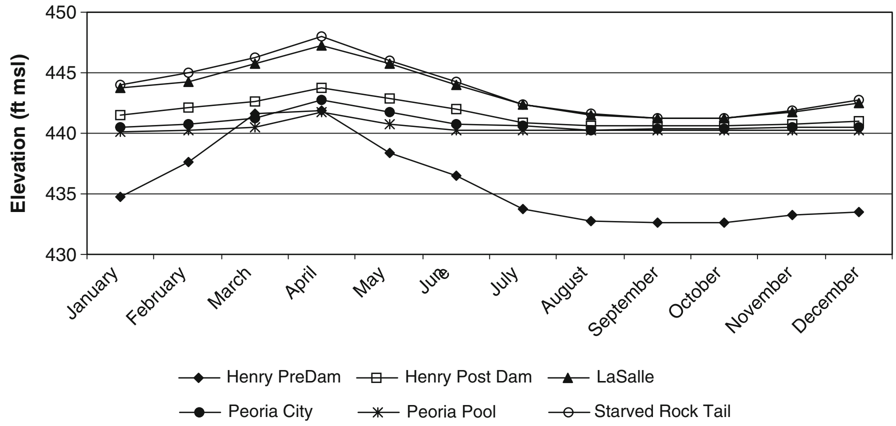


Fig. 8 Post-impact stage hydrographs for Peoria Pool, Illinois River. Post-dam hydrographs plot in downstream order from the upper dam to the lower dam and the Henry pre-dam hydrograph plots below them all for reference to the natural range of variation

Multivariate synthesis assessing impacts of river regulation

Cluster analysis

Simple, univariate descriptions of stage, discharge, and variation under pre-impoundment versus post-impoundment, described above, lead to a broader, multi-variate interpretation of hydrologic pattern over time and space. Cluster analysis was used in an exploratory examination of coefficient of variation, predictability, constancy, and flashiness characteristics to determine how they can be used to describe and understand natural patterns and changes in UMRS hydrology. Clustering yielded a split to two groupings at 13 Euclidean units (Fig. 10). Group 1 separated all of the lower pool and most mid pool gages (post-dam). The Marseilles discharge and Upper Pool 5a gage were also included, but the group represented the sites most hydrologically stabilized because of their proximity to the dams. The other group included everything else and was further subdivided. Control point (e.g., Group 2) and discharge gages (e.g., Group 3A) center the entire dendrogram. St. Louis discharge, St. Louis pre-dam, Louisiana Pre-dam, and both time period Muscatine gages cluster together in Group 3B indicating similar stage–discharge relationships in the unregulated and upper pool locations, respectively. The St. Louis and Muscatine clustering results confirm the similarity detected in the hydrographs (see Fig. 7). Both Valley City time periods cluster together with other pre-dam and modeled data in Group 3C. The nearness of the gages supports the similarity of hydrologic pattern seen at Valley City (see Fig. 7). All of the upper pool gages cluster with Mid-Pool 5, St. Louis Post-Dam, and Kingston Mines discharge gages in the last cluster. These gages cluster most distant from the stabilized lower pool region and are moderately separated from the discharge and pre-dam gages. The results support a well-known hydrologic gradient of stabilized hydrology at one end and more variable hydrology at the other along the length of the pool. The placement of discharge and pre-dam data on the cluster analysis dendrogram imply that mid-pool gages respond closest to discharge, which is how they are managed, but that upper pool stages are more similar to pre-dam river stages. The groupings in this cluster analysis indicate the utility of the multivariate approach and its potential application to other ecological drivers.

Correspondence analysis

Correspondence analysis was used next in our exploratory analysis to identify variables separating the clusters. Correspondence analyses (CA) were conducted using the same variables used in cluster analysis: coefficient of variation, predictability, constancy, and flashiness. Discharge data were inspected first to examine its relationship to stage. If there were associations and patterns found among discharge gages, those associations should be expected in stage data also where dam effects are negligible. Conversely, dam impacts would be exhibited by differences in stage:discharge relationships at single gauges or in reaches. There were few pre-impoundment discharge records, so a common post-impoundment

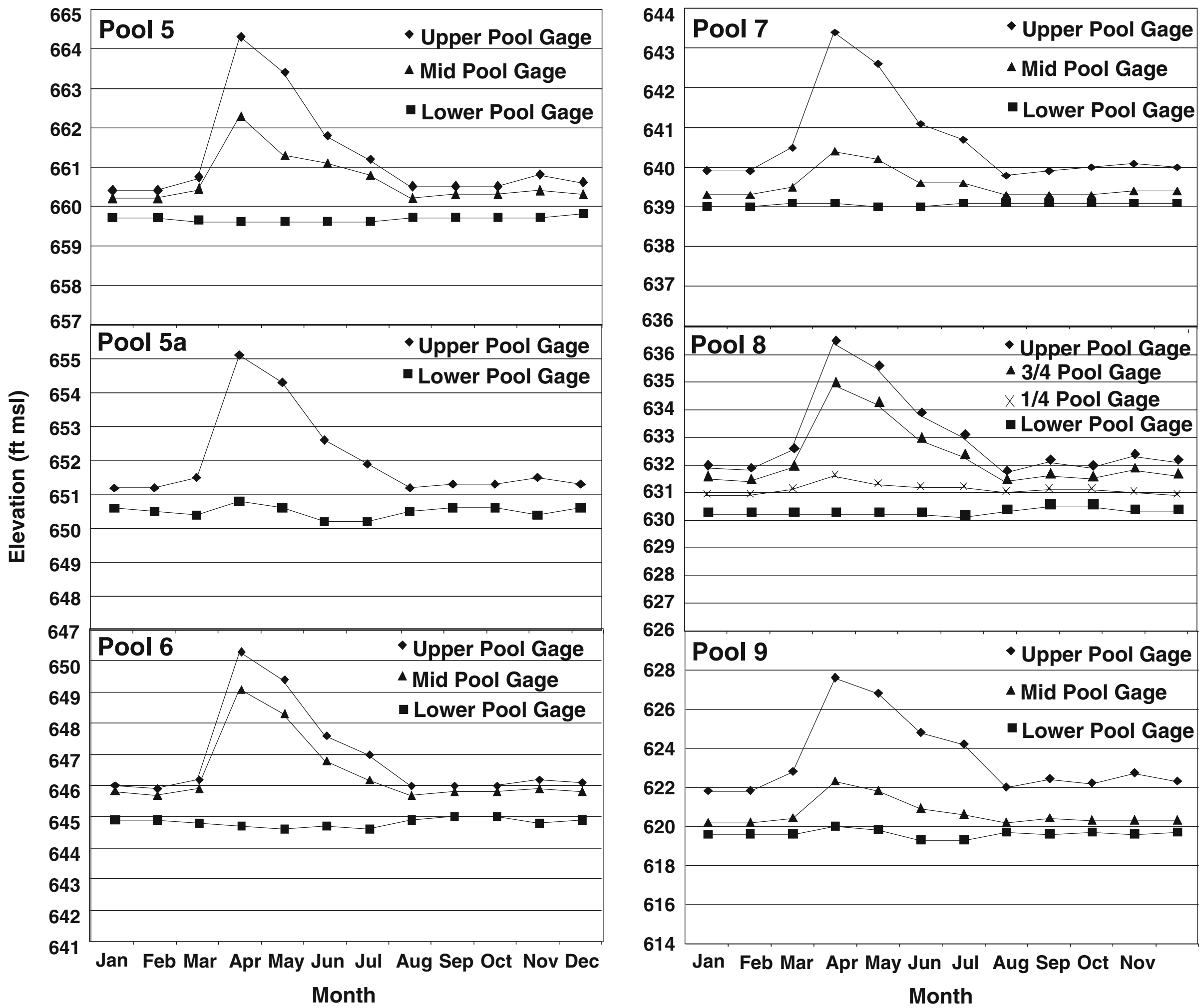


Fig. 9 Post-impact stage hydrographs for Mississippi River Geomorphic Reach 3 (Pools 5–9). Hydrographs plot in downstream order in each pool, from the upper dam to the lower dam

period was used to examine associations among gages. Coefficient of variation, predictability, and constancy plot together tightly in the discharge CA, showing little separation along either axis (Fig. 11). CA analysis shows gage locations are distributed with no apparent groupings or trends except that Illinois River sites are distributed down axis one and up axis two in the downstream direction. Predictability, constancy, and especially, flashiness all decrease downstream on the Illinois River (Table 10). Illinois River discharge characteristics indicate a predictable baseflow river stage with short duration floods changing downstream into a less predictable, more seasonally influenced river with much lower flashiness. All parameters are similar in magnitude with no apparent trend at the Mississippi River gages. The clumped CA variables indicate similarity among discharge gages.

Pre- and post-impact period river stage data separate most clearly along axis 1 with the control point or mid-pool gages separating on their high constancy values (Fig. 12, Table 11). St. Louis, pre- and post-dam characteristics remained most similar among time periods (Table 11). The pre-dam and post-dam upper pool gages are less predictable because of greater seasonal effects exhibited by lower constancy values. These gages also separate along a variability gradient along axis 2. Predictability is lower at all the pre-impact sites except St. Louis. Post-dam predictability increased from 0.55–0.70 to 0.73–0.84 with control point gages being most

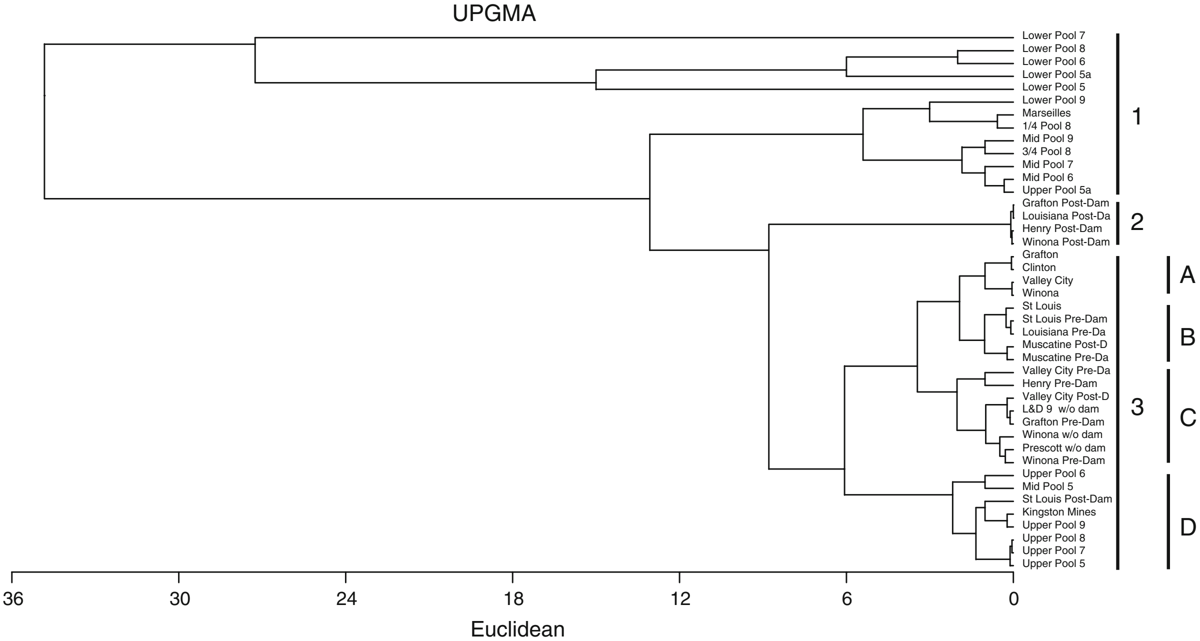


Fig. 10 Cluster analysis using coefficient of variation, predictability, constancy, and flashiness parameters (see text) to classify Upper Mississippi River System hydrologic records and several types of gages

predictable (Table 11). Pre-impact periods and upper pool gages demonstrated a stronger seasonal signal (i.e., low constancy; Table 11) compared to control point gages. Hydrologic variation was consistently higher for pre-impact periods, and upper pool gages were more variable than control points. Flashiness was lowest on the Illinois River, it increased downstream on the Mississippi River (excluding Grafton which is the mouth of the Illinois). Flashiness was most similar at Muscatine (upper pool) and increased at Valley City (upper pool) and St. Louis (unregulated) between pre- and post-dam periods. Flashiness was reduced at control point gages by operation of the dams.

The within-pool analysis of Peoria Pool showed that discharge has low predictability and similar seasonal hydrology (i.e., lower constancy) at gages into and out of the pool. Discharge is also variable and flashy as represented by these two gages (Starved Rock Dam and Peoria Dam, respectively; Fig. 13, Table 12). The Starved Rock tailwater stage showed similar low predictability and seasonality, but the coefficient of variation and flashiness were lower than they were for discharge (Table 12). An increase in predictability as near as the La Salle gage, only 6.4 miles downstream from the Starved Rock dam, demonstrates the influence of the dam 66 miles (106 km) downstream on the low gradient river. River stage coefficient of variation is much lower at the four gages in Peoria Pool compared to discharge gauges and the tailwater stage gage which illustrated the dampening effect from impoundment. The Henry gage at mid-pool is the most stable. The seasonal flood pulse decreases downstream from the tailwater.

The six pools in Geomorphic Reach 3 show similar within-pool hydrologic patterns, or gradients, with a separation of pool location along axis 1 (Fig. 14). Upper pool gages generally exhibit higher coefficients of variation (i.e., wider range of stage), less constancy which indicates more seasonality, and lower flashiness (Table 13) which indicates a smoother flood-pulse hydrograph. Upper pool predictability is mixed, with the short pools being more predictable than longer pools (see Table 1 and Fig. 2). Mid pool gages have mixed variability, but higher predictability due to constancy, and moderate flashiness compared to other regions of the pools (Table 13). Lower pool gages are most constant because of their narrow range of variation, but they are very flashy because of fine dam gate adjustments detected by the IHA default calculations. It is

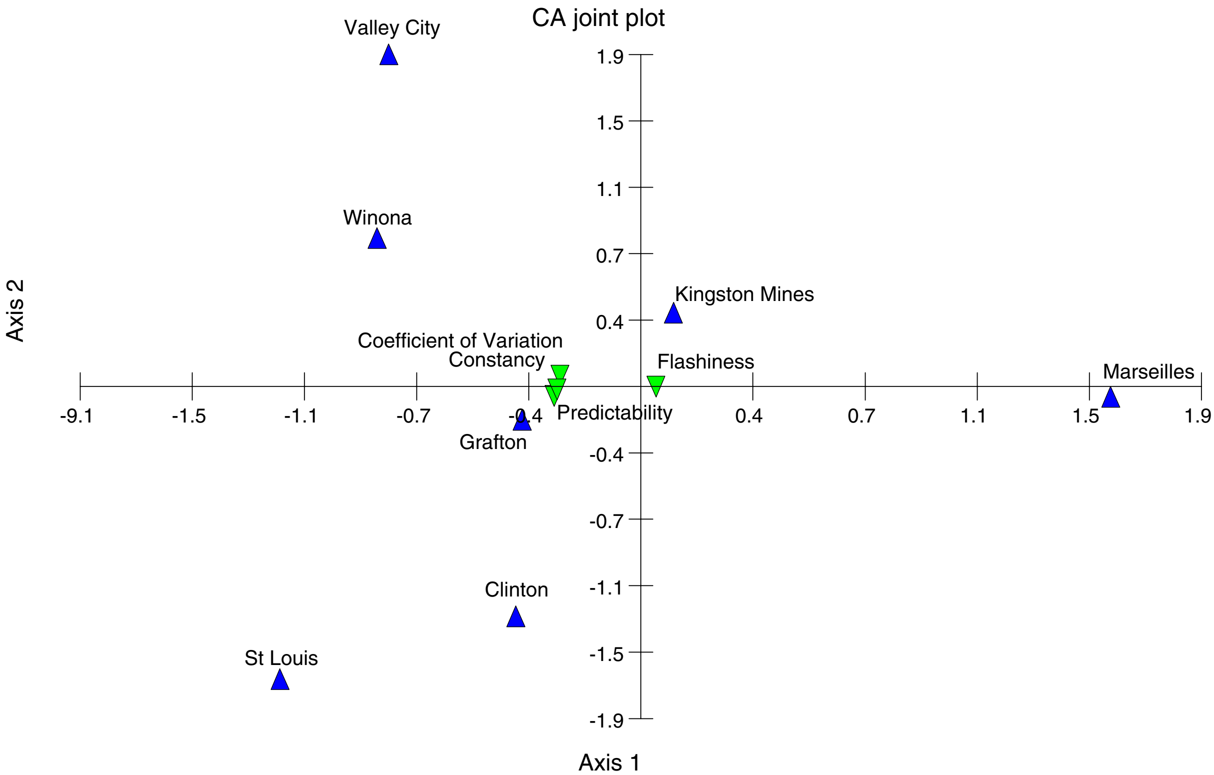


Fig. 11 Correspondence analysis scatter plot of Upper Mississippi River discharge gage records against coefficient of variation predictability, constancy, and flashiness parameters

Table 10 IHA parameter and calculated values used in discharge correspondence analysis

Discharge gauge	Coefficient of variation	Predictability	Constancy	Flashiness
Winona	0.77	0.54	0.81	9
Clinton	0.67	0.57	0.82	10
Grafton	0.70	0.52	0.83	10
St Louis	0.65	0.55	0.85	8
Marseilles	0.78	0.55	0.87	23
Kingston Mines	0.74	0.50	0.86	12
Valley City	0.79	0.49	0.82	9

possible to consider the spread of gages in the CA plot as similar to the within-pool hydrology plot (see Fig. 10) with all the upper pool medians skewed to the right, the mid-pool medians in the middle and the lower pool medians skewed to the left.

A final CA was conducted using all the data above and a data set of contemporary flow with the dams modeled out at three locations in Geomorphic Reach 3. The combined analysis was conducted to test the utility of these methods to differentiate across a wider range of conditions. In this case, pre-impact data, discharge data, and modeled data (Table 14) represent a less disturbed hydrologic reference. These sites all fall below axis 1 and mostly to the right of axis 2 (Fig. 15). They generally have lower predictability, less constancy, and less flashiness. Post-dam data and within-pool gages represent different degrees of hydrologic alteration. The hydrologic gradients within pools as discussed above are evident in the plot with Lower, Mid, and Upper Pool sites in a line across the

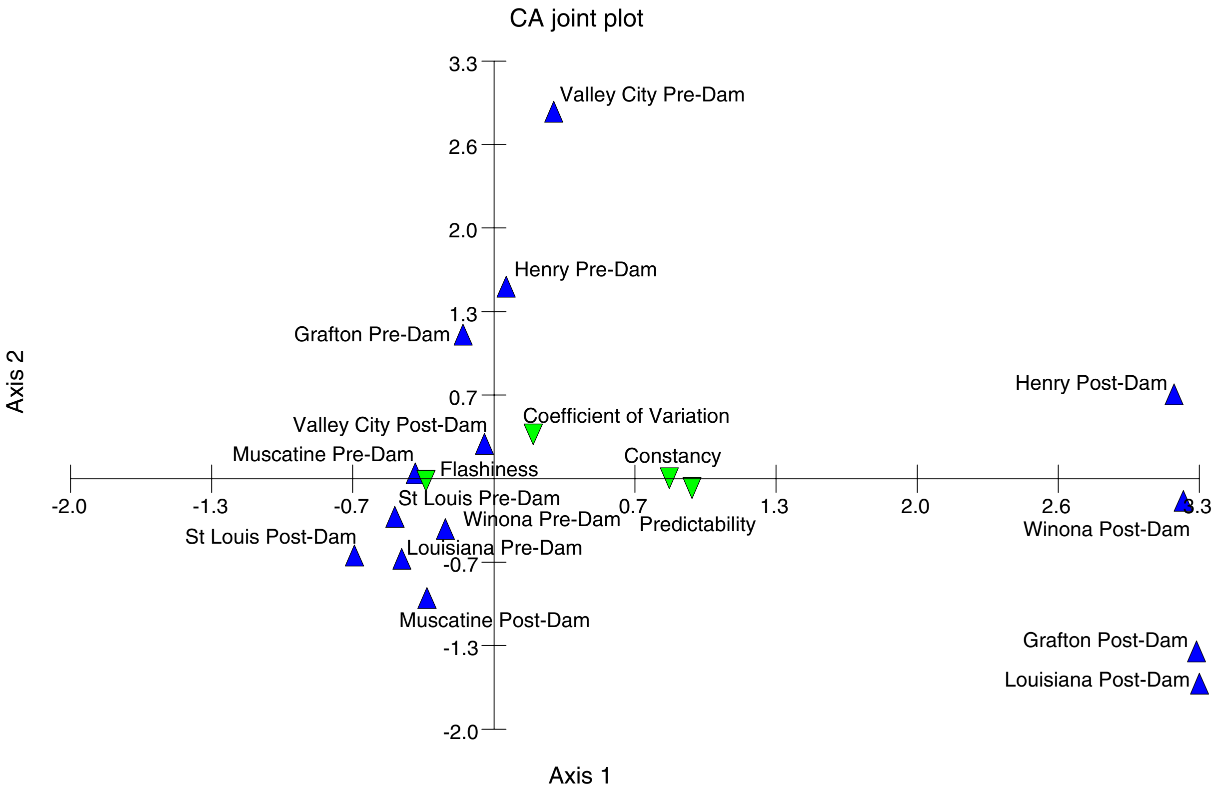


Fig. 12 Correspondence analysis scatter plot of Upper Mississippi River pre- and post-impact river stage gage records against coefficient of variation predictability, constancy, and flashiness parameters

Table 11 IHA parameter and calculated values used in pre- and post-impact correspondence analysis

Elevation gauge	Coefficient of variation	Predictability	Constancy	Flashiness
Winona pre-dam	0.36	0.69	0.91	6
Winona post-dam	0.16	0.80	0.94	0
Muscatine pre-dam	0.47	0.63	0.88	7
Muscatine post-dam	0.31	0.76	0.92	7
Louisiana pre-dam	0.39	0.70	0.90	8
Louisiana post-dam	0.11	0.84	0.96	0
Grafton pre-dam	0.52	0.56	0.88	5
Grafton post-dam	0.12	0.84	0.96	0
St Louis pre-dam	0.45	0.65	0.85	8
St Louis post-dam	0.48	0.61	0.87	11
Henry pre-dam	0.51	0.62	0.84	4
Henry post-dam	0.19	0.78	0.96	0
Valley City pre-dam	0.56	0.55	0.84	3
Valley City post-dam	0.43	0.73	0.92	5

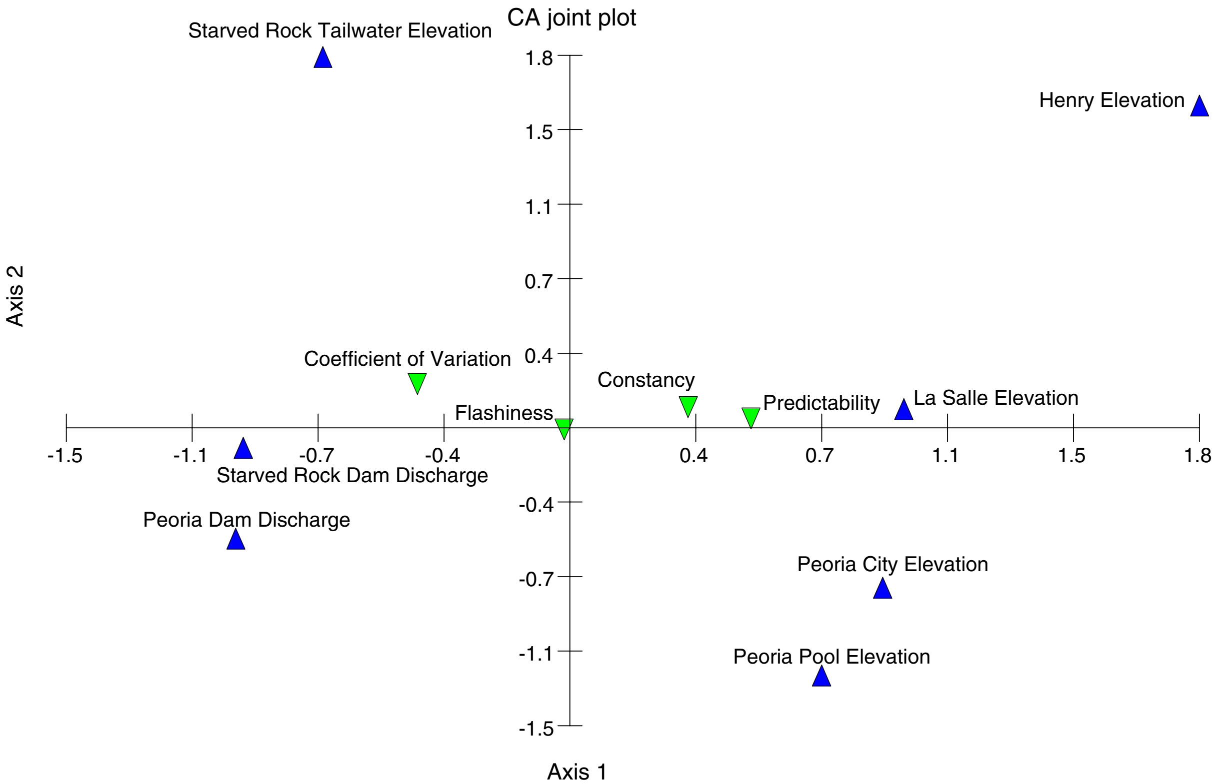


Fig. 13 Correspondence analysis scatter plot of Upper Mississippi River Peoria Pool river stage gage records against coefficient of variation predictability, constancy, and flashiness parameters

Table 12 IHA parameter and calculated values used in Peoria Pool, within pool correspondence analysis

Elevation gauge	Coefficient of variation	Predictability	Constancy	Flashiness
Starved Rock Dam discharge	0.98	0.43	0.80	33
Peoria Dam discharge	1.00	0.44	0.80	36
Starved Rock Tailwater elevation	0.85	0.43	0.80	23
La Salle elevation	0.25	0.77	0.95	19
Henry elevation	0.17	0.78	0.96	14
Peoria City elevation	0.20	0.80	0.96	21
Peoria Pool elevation	0.21	0.80	0.96	23

center of the plot. The post-dam gauges at the control points are the extreme outliers on the predictability/constancy axis (axis 2).

Discussion: implications for ecosystem management

It is important to understand the drivers responsible for ecosystem condition, so that restoration and management actions can be targeted at the "most important" drivers. Hydrology is a key driver in river systems (Welcomme, 1979; Vannote et al., 1980; Ward & Stanford, 1983; Poff et al., 1997; Sparks et al., 1998; and many others). Water level management is routine in wetland (Cross & Vohs, 1988) and reservoir management (Ploskey, 1983) applications, and the concepts can be applied on regulated floodplain rivers as well. Relating hydrologic and hydraulic changes caused by human activity at river,

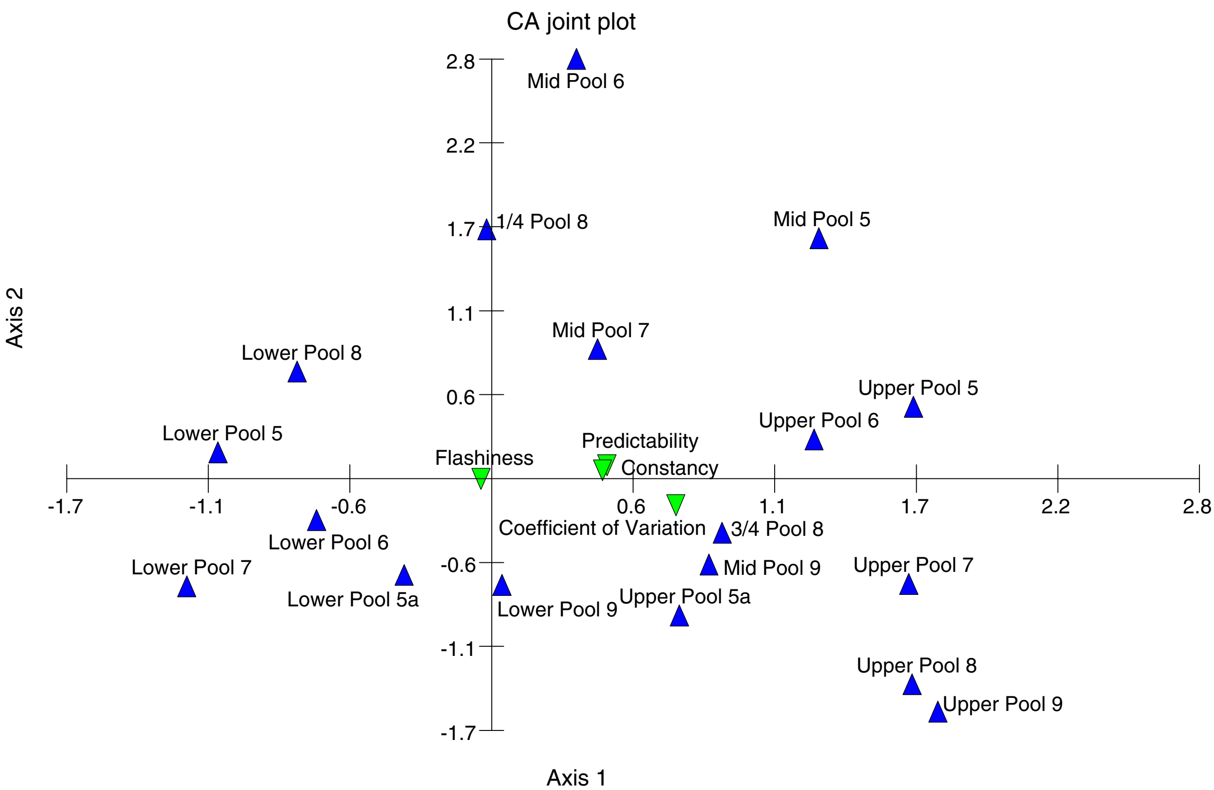


Fig. 14 Correspondence analysis scatter plot of Upper Mississippi River Geomorphic Reach 3 (Pools 5–9) river stage gage records against coefficient of variation predictability, constancy, and flashiness parameters

floodplain, and basin scales were important aspects of this paper; levees, dams, diversions, and channelization have had profound effects on the UMRS and similar rivers world-wide. Our intent here was to synthesize river hydrology in terms of regional and local hydrologic characteristics and hydrologic response to development. In this case study, we documented the degree to which water levels of impounded river reaches have been raised and stabilized to become more predictable due to increased constancy (i.e., loss of low river stage). We also document a post-dam within-pool hydrologic gradient that creates repeating patterns of riverine, backwater, and impounded aquatic habitat conditions in the Upper Impounded Reach. Our synthesis demonstrated through literature review and new analyses that hydrologic alterations were expressed differently on the landscape in at least four distinct river reaches (Lubinski, 1999; WEST Consultants, 2000). These differences, summarized briefly below, have implications for the type of responses to development that have occurred and the types and likely success of management actions among river reaches. Lower pool drawdowns are being evaluated for their utility to increase emergent aquatic plant production (Landwehr et al., 2004; Kenow et al., 2007). Our results can help set drawdown depth objectives based on historic water level variation. Low profile island construction can replace habitat lost to island erosion in impounded areas by recreating structural diversity in open water habitats. Knowledge about the degree of impoundment effects through a pool reach helps determine island size, shape, and spacing.

The Upper Impounded Reach (between Pools 1 and Pool 13) exhibits increased lower pool surface water areas that created large shallow impounded areas (see Fig. 5). The altered hydrodynamic environment in lower pool impounded locations induced wind-generated waves that rapidly (in geologic time) eroded alluvial features (e.g., ridges, levees, and terraces for example) that remained as islands above

Table 13 IHA parameter and calculated values used in Geomorphic Reach 3, within pool correspondence analysis

Elevation gauge	Coefficient of variation	Predictability	Constancy	Flashiness
Upper pool 5	0.50	0.76	0.89	13
Mid pool 5	0.41	0.75	0.92	14
Lower pool 5	0.14	0.73	0.97	51
Upper pool 5a	0.56	0.75	0.89	19
Lower pool 5a	0.45	0.71	0.96	32
Upper pool 6	0.50	0.76	0.91	15
Mid pool 6	0.24	0.80	0.93	19
Lower pool 6	0.34	0.72	0.96	39
Upper pool 7	0.54	0.67	0.90	13
Mid pool 7	0.39	0.75	0.94	20
Lower pool 7	0.26	0.73	0.98	67
Upper pool 8	0.57	0.65	0.88	13
3/4 pool 8	0.51	0.72	0.90	17
1/4 pool 8	0.26	0.74	0.96	23
Lower pool 8	0.18	0.72	0.96	37
Upper pool 9	0.55	0.60	0.85	12
Mid pool 9	0.54	0.75	0.91	18
Lower pool 9	0.50	0.72	0.95	26

Table 14 IHA parameter and calculated values used in modeled data correspondence analysis

	Annual C. V.	Flow predictability	Constancy	Flashiness
Prescott w/o Dam	0.51	0.60	0.82	6.2
Winona w/o Dam	0.72	0.47	0.75	5.8
L&D 9 w/o Dam	0.54	0.57	0.84	5.1

the increased water levels. In one well documented situation, islands in lower Pool 8 eroded in less than 50 years following impoundment (USGS, 1999). Recent fisheries investigations indicate a preferred recreational fishery was supported in the less altered upper pool reach of Pool 8 compared to lower Pool 8 (Knights et al., 2008). Forest diversity was reduced by elimination of flood intolerant species because of the elevated water table in impounded reaches (Nelson et al., 1996; Yin et al., 1997; Sparks et al., 1998).

The Lower Impounded Reach (between Pools 14 and 26) does not show dramatic planform change in surface water area or distribution (see Fig. 5), but the reach exhibits the same within-pool hydrologic zonation detected upstream. Lower pool regions and large island interiors, which were previously seasonal wetlands, were permanently flooded by the dams. The new aquatic areas are subject to excessive sedimentation from the highly developed watershed, and the sediments remain flocculent because they are not exposed and dried during summer low flow conditions as they were in an unregulated condition. Fine sediments are easily resuspended by wind-generated waves to block light transmittance through the water column. The floodplain in the Lower Impounded Reach is more than 50% leveed and drained for agriculture, so isolated floodplain wetlands are largely absent or degraded.

The Unimpounded Mississippi River below St. Louis differs greatly from the rivers upstream because of the influence of the combined flow from three great rivers. The Missouri River in particular nearly doubles the flow and its bimodal hydrologic signal is expressed on the Mississippi River below the confluence. The floodplain is highly developed for

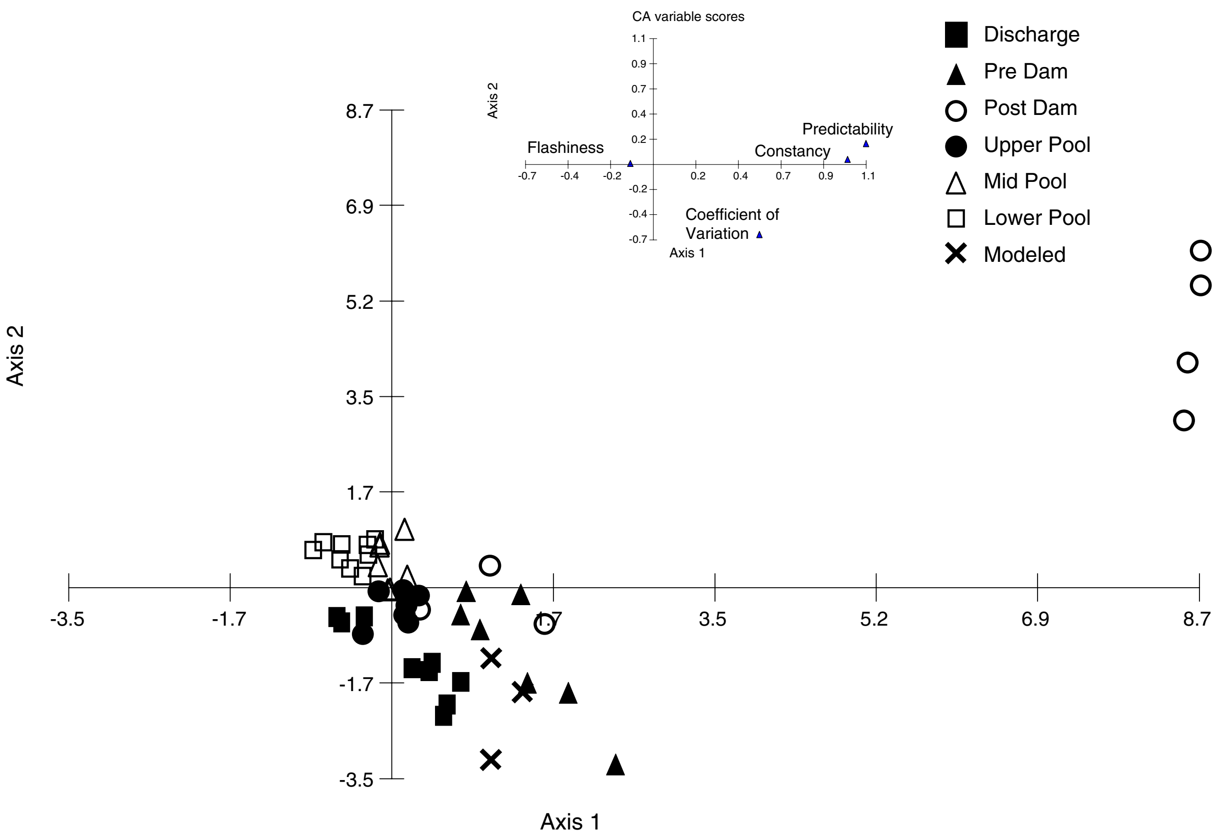


Fig. 15 Correspondence analysis scatter plot of a variety of Upper Mississippi River stage, discharge, and modeled gage records against coefficient of variation predictability, constancy, and flashiness parameters

agriculture behind levees isolating 83% of the floodplain. Wetlands have been drained and leveled. Flood flows rarely reach the 8–10 mile (13–16 km) wide floodplain with the current flood control structures, and when they do it is a catastrophic event (Changnon, 1996). Hydrologic variables examined in this analysis are most similar for St. Louis pre- and post-impact comparisons, but the St. Louis gage is the longest record on the river and it can be parsed in many ways that were not explored here (Pinter et al., 2000). It is apparent there is a wider range of hydrologic variation now than in the past (see Fig. 6). Increases in the range of hydrologic variation are caused by extensive flood protection and increased discharge and magnitude of extreme events over the period of record (Changnon, 1983; Knox, 1993; Wlosinski 1999; Zhang & Schilling, 2006). Decreased low flow river stage was caused by main channel downcutting from channelization activities (Chen & Simmons, 1986; Wlosinski, 1999; Pinter & Heine, 2005; Remo & Pinter, 2007). Decreased river stages result in more frequent isolation of secondary channels, alluvial wetland drainage, and water table drawdown.

Impacts from hydrologic alteration on the Lower Illinois River differ from the Mississippi because of the low gradient of the river and the large diversion of flow into the system from Lake Michigan. The low gradient channel and level floodplain allowed water from the diversion to spread broadly to form large shallow lakes along the entire river in areas that had been seasonal wetlands. Dams stabilized the increased stage and prevented seasonal drying of wetlands and backwaters. As in the Lower Impounded Reach on the Mississippi River, the large open water areas were degraded by large sediment loads that remain flocculent and easily resuspended in their aqueous state. Floodplain development is most prominent in the LaGrange and Alton Pools where the floodplain is 60% isolated by levee and drainage districts and converted to agriculture. While the median hydrologic patterns seem comparable, there is increased variability and small fluctuations that are worthy of more detailed analysis. Vegetated backwaters that once supported millions of migratory waterfowl (Havera, 1999) are now sparsely vegetated because of poor water clarity that inhibits submersed aquatic plants and fluctuating water levels that inhibit growth of emergent aquatic plants on mudflats (Moore et al., 2010).

Hydrologic drivers were investigated because of their fundamental importance in UMRS ecosystem function and process. Hydrologic alteration is responsible for much of the ecological change in the UMRS, ranging from obvious direct effects of impounded surface waters, restricted flood flows, regulated flow patterns in channels, and altered hydraulic residence time in backwaters, to more subtle effects like altered water quality (Houser & Richardson, 2010), vegetation distribution (Moore et al., 2010), forest community structure (Romano, 2010), and invertebrate and fish community distribution. Ecological conditions can be managed by adjusting key drivers, and hydrology and hydraulics are highly responsive to management actions that can be achieved at reasonable cost. On the UMRS for example, islands are constructed at a local scale to break up wind and currents in open water impounded areas subject to wind-generated waves that resuspend fine sediment. Water level drawdowns at the dams or in managed backwaters are used to promote emergent and submersed aquatic vegetation in shallow floodplain aquatic areas at a larger scale. Innovation and refinement of restoration techniques in the field for more than 20 years have set the foundation for a more active adaptive environmental assessment and management framework for the UMRS. The techniques described here can help target and assess restoration measures to the most appropriate hydrologic condition. Future analyses will expand the variable set to incorporate floodplain inundation area (i.e., lateral connectivity) at various flood stages and geomorphic parameters.

Upper Mississippi River System hydrology presented a good model of how multiple time periods and modeled scenarios (i.e., multiple reference conditions, Nestler et al., 2010) can be used to characterize and compare environmental parameters. The stepwise exploratory analyses and final combined correspondence analysis showed where each site falls among other sites in multivariate space. A desirable condition can be defined any number of ways, but once it is determined, the distance of any other value from it can be measured in multivariate space and absolute value as described. The IHA software provides a simple user interface that could easily be used in a stakeholder setting for many regulatory, emergency management, flood protection, and restoration planning purposes (Hickey & Dunn, 2004). This analytical approach could be easily exported to other systems with similar data, of which most Federal projects have in abundance because of engineering and operating requirements.

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