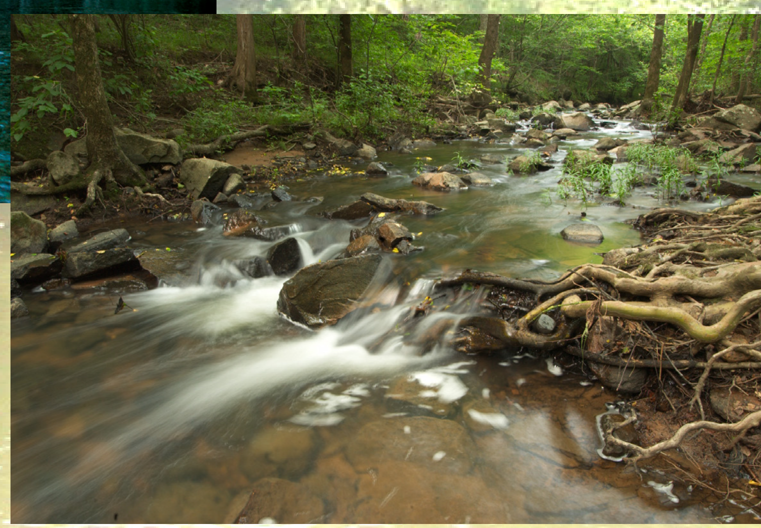
In cooperation with the Missouri Department of Conservation and the U.S. Fish and Wildlife Service

Application of the Hydroecological Integrity Assessment Process for Missouri Streams

By Jonathan G. Kennen, James A. Henriksen, John Heasley, Brian S. Cade, and James W. Terrell



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Cover photos. Background photo—Locust Creek, Sullivan County, MO, Perennial runoff stream (Photo by Matt Matheney, Missouri Department of Conservation); Left inset—Meramec River, MO, Perennial groundwater stream (Photo by Jim Rathert, Missouri Department of Conservation); Right inset—Turkey Creek, Madison County, MO, Intermittent stream (Photo by Jim Rathert, Missouri Department of Conservation).

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Conversion Factors

Multiply	By	To obtain
centimeter (cm)	0.3937	inch (in.)
kilometer (km)	0.6214	mile (mi)
meter (m)	3.281	foot (ft)
cubic meters per second (m^3/s)	35.31	cubic feet per second (ft^3/s)
square kilometer (km^2)	0.3861	square mile (mi^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32.

Abbreviations and symbols used in this report:

Abbreviation	Description
ANOVA	Analysis of Variance
DFA	Discriminant-Function Analysis
FWS	U.S. Fish and Wildlife Service
HIP	Hydroecological Integrity Assessment Process
HIT	Hydrologic Indices Tool
HAT	Hydrologic Assessment Tool
HRIs	Hydroecologically-Relevant Indices
IDH	Intermediate Disturbance Hypothesis
MDC	Missouri Department of Conservation
MOHAT	Missouri Hydrologic Assessment Tool
MOSCT	Missouri Stream Classification Tool
MOWSC	Missouri Water Science Center
NATHAT	National Hydrologic Assessment Tool
NWIS	National Water Information System
PCA	Principal Components Analysis
POR	Hydrologic Time Period of Record
RCC	River Continuum Concept
SCT	Stream Classification Tool
UPGMA	Un-weighted Pair Group Method Analysis
USGS	U.S. Geological Survey
>	Greater than
<	Less than

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Abstract

Natural flow regime concepts and theories have established the justification for maintaining or restoring the range of natural hydrologic variability so that physiochemical processes, native biodiversity, and the evolutionary potential of aquatic and riparian assemblages can be sustained. A synthesis of recent research advances in hydroecology, coupled with stream classification using hydroecologically relevant indices, has produced the Hydroecological Integrity Assessment Process (HIP). HIP consists of (1) a regional classification of streams into hydrologic stream types based on flow data from long-term gaging-station records for relatively unmodified streams, (2) an identification of stream-type specific indices that address 11 subcomponents of the flow regime, (3) an ability to establish environmental flow standards, (4) an evaluation of hydrologic alteration, and (5) a capacity to conduct alternative analyses. The process starts with the identification of a hydrologic baseline (reference condition) for selected locations, uses flow data from a stream-gage network, and proceeds to classify streams into hydrologic stream types. Concurrently, the analysis identifies a set of non-redundant and ecologically relevant hydrologic indices for 11 subcomponents of flow for each stream type. Furthermore, regional hydrologic models for synthesizing flow conditions across a region and the development of flow-ecology response relations for each stream type can be added to further enhance the process. The application of HIP to Missouri streams identified five stream types ((1) intermittent, (2) perennial runoff–flashy, (3) perennial runoff–moderate baseflow, (4) perennial groundwater–stable, and (5) perennial groundwater–super stable). Two Missouri-specific computer software programs were developed: (1) a Missouri Hydrologic Assessment Tool (MOHAT) which is used to establish a hydrologic baseline, provide options for setting environmental flow standards, and compare past and proposed hydrologic alterations; and (2) a Missouri Stream Classification Tool (MOSCT) designed for placing previously unclassified streams into one of the five pre-defined stream types.

Introduction

Maintaining and restoring the ecological integrity of streams, that is, the native biodiversity and physiochemical processes that result in self-sustaining productivity, can be difficult goals to achieve for many State water and land-use regulatory, management, and planning programs. While some State water-quality programs are well developed, most existing State laws, regulations, and policies addressing the quantity of water in a stream are often inadequate to establish meaningful flow management programs (Annear and others, 2004). Furthermore, State agencies with the authority and responsibility for protecting and managing stream resources are often confronted with four problematic issues when they attempt to develop or apply standards or requirements for environmental flow (that is, a flow regime of a particular magnitude, duration, frequency, timing, and rate of change which is necessary to ensure that a river system remains ecologically, environmentally, economically, and socially healthy; also called instream flow). State agencies and decision makers responsible for water development may be under the assumption that:

- The environmental flow necessary to protect stream resources commonly described using terms such as aquatic habitat, fishery resources, aquatic assemblages, or ecological integrity, is known or easily quantified by the State regulatory agency for every stream reach within its authority.
- Regardless of the extent of previous hydrologic alterations of the flow (that is, cumulative impact on streamflow) a sufficient quantity remains available for an additional water use.
- The environmental flow standard developed by a State management agency is simple and compliance with the standard can easily be attained.
- And finally, streamflow alteration is perceived to result primarily from direct diversion (for example, municipal water supply), or regulation of flow (for example, hydropower), not from land-use changes. In other words, water development and land use may not be perceived to be competing for the same water resources.

These assumptions may not be accurate.

The Missouri Department of Conservation (MDC) and the U.S. Fish and Wildlife Service (FWS) have broad responsibilities through various regulatory and planning programs for managing water and land resources, while concurrently protecting and restoring stream and riverine resources. Consequently, the MDC and FWS initiated a cooperative agreement with the U.S. Geological Survey (USGS) to apply the HIP methodology to Missouri streams and develop supporting computer software tools for use in environmental flow management.

The purpose of this report is to describe the results of the Hydroecological Integrity Assessment Process (HIP) as applied to the streams in the State of Missouri. Two Missouri-specific computer software tools have been developed: (1) a Missouri Hydrologic Assessment Tool (MOHAT) which is used to establish a hydrologic baseline, to provide options for setting environmental flow standards, and to compare past and proposed streamflow alterations (a National HAT has also been developed and is available at *http://www.fort.usgs.gov/Products/Software/NATHAT/*); and (2) a Missouri Stream Classification Tool (MOSCT) designed for placing previously unclassified streams into pre-defined stream types. Multivariate response models including principal component, cluster, and discriminant-function analyses aided in the development of software and application of HIP for Missouri streams. Ultimately, this process should provide greater understanding of the effects of anthropogenic changes on hydrologic variability and help planners and resource managers balance current and future water requirements and ecological needs.

Seminal Hydroecological Research

A brief overview of several stream ecological concepts is presented here to provide a scientific basis for understanding the foundation upon which HIP is established. Figures 1 and 2 provide generalized views of a stream ecosystem and the components that influence stream biotic assemblages. Both figures emphasizes the important role that the flow regime, and the associated inter- and intra-annual hydrologic variability, plays in influencing and affecting distribution, abundance, and diversity of stream assemblages, that is, stream biotic integrity.

Five highly-interrelated components (hydrology, geomorphology, biology, water quality, and connectivity) are listed below in five conceptual models of stream structure and function:

- River Continuum Concept
- Intermediate-Disturbance Hypothesis
- Flood Pulse Concept
- Hierarchical Framework for Stream Habitat
- Natural Flow Regime Paradigm

Each model is described briefly below following Kennen and others (2007).

The **River Continuum Concept** (RCC) (fig. 3) presents a generalized description of fluvial systems as a continuously integrating series of physical gradients and associated biotic adjustments as a river flows from the headwater to the

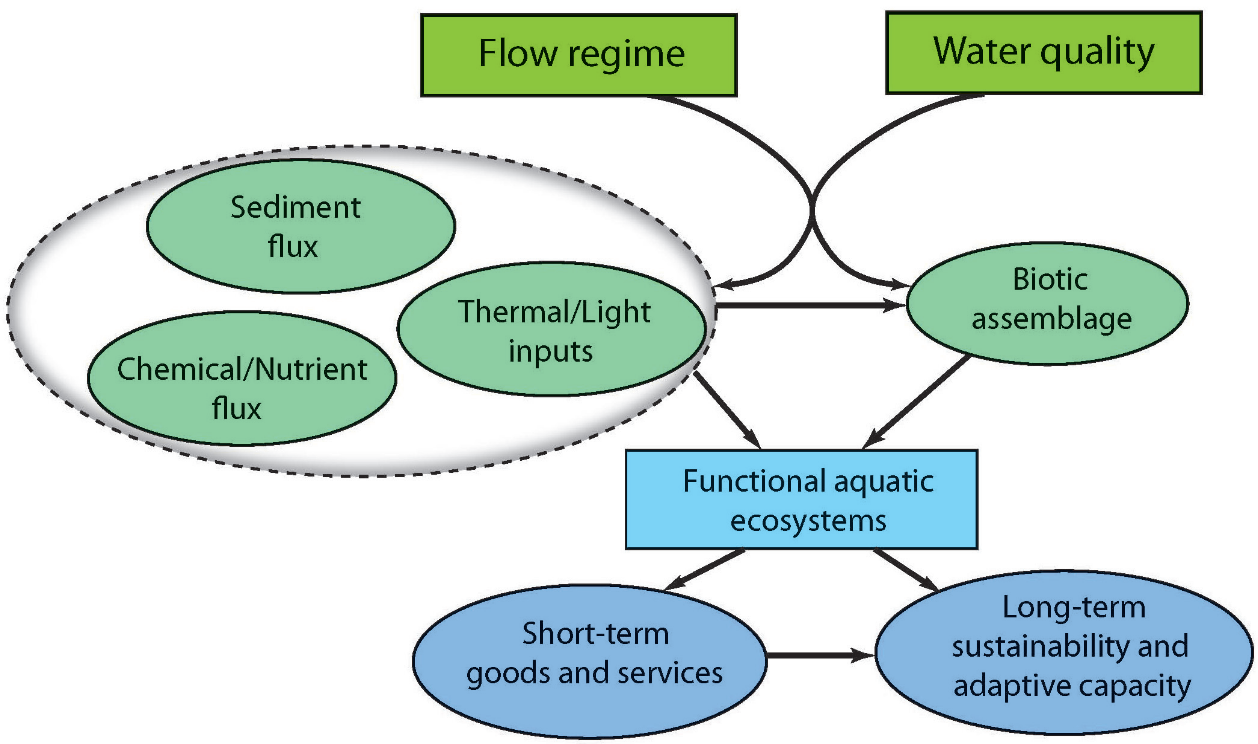

Figure 1. Conceptual model of the major driving forces that influence freshwater ecosystems. From Baron and others, 2002.

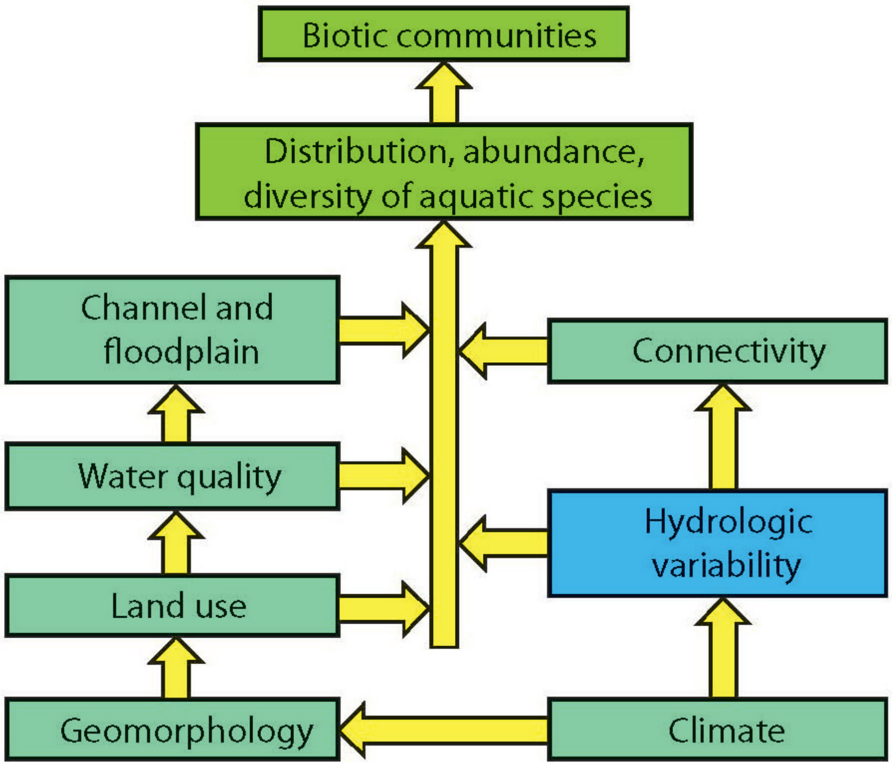

Figure 2. Conceptual view of the interrelations between the physical environment and biotic assemblages (source unknown).

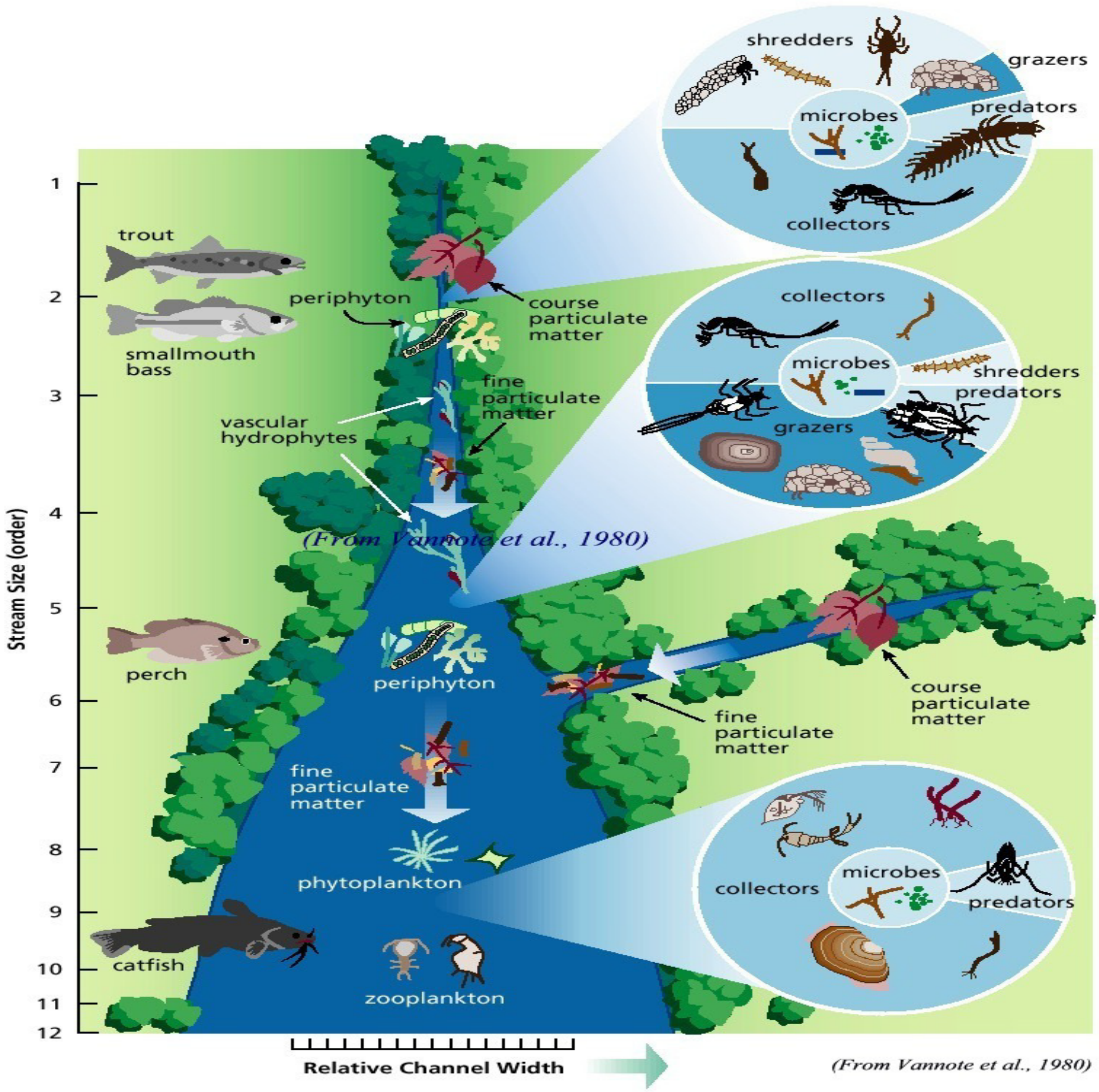

Figure 3. Generalized view of the River Continuum Concept. From Vannote and others, 1980.

mouth (Vannote and others, 1980). The RCC is derived from data that established that the size of the stream and its location along the gradient from the headwaters to the mouth influences the type and distribution of the aquatic fauna. It is well established that stream order, discharge, and watershed area are highly correlated. Furthermore, energy inputs along this gradient have significant effects on the structure and function of the consumer assemblages, especially those organisms that differ in their dependence on allochthonous (derived from outside of the stream, for example, leaves and sticks) and autochthonous (derived from within the lotic system, for example, algae) sources, and those organisms that are responsible for the processing (the breaking down of coarse organic matter into smaller particles) of organic matter in the flowing water along the river continuum. In the context of environmental flows, hydrologic variability and, subsequently, the stream biota are highly dependent on their longitudinal location along the continuum.

One conclusion that can be drawn from the RCC is that as the physical environment and aquatic-assemblage structure and function change from the headwaters (stream orders 1 and 2), to middle reaches (stream orders 3 through 5), to the lower reaches (stream orders 6 through 10) there is a concomitant change in the flow regime. Consequently, understanding the extent of hydrologic change is important in estimating its effect on the structural and functional integrity of aquatic ecosystems. Therefore, it is necessary to identify which components of the hydrologic regime (for example, magnitude, frequency, duration) are the most influential and what hydrologic measures (that is, statistics and indices) are best suited to describe the degree of alteration.

The **Intermediate-Disturbance Hypothesis** (IDH) predicts that biotic diversity is greatest in assemblages subjected to moderate levels of disturbance (for example, small floods with relatively short return intervals). This hypothesis is consistent with patterns of diversity observed in natural and altered lotic ecosystems (Ward and Stanford, 1983; Pickett and White, 1985; Resh and others, 1988). The general view is that diversity is enhanced by the spatial-temporal heterogeneity resulting from an intermediate level of disturbance, which maintains the assemblages in a nonequilibrium state. The disturbance can be biotic or abiotic or both, and can fluctuate from severe, to moderate, to no disturbance. Furthermore, even the sequence of these disturbances influence diversity. Ultimately, assemblage structure is shaped by a myriad of physical, chemical, and biological processes acting synergistically (Ward and Stanford, 1983).

An important conclusion can be drawn from the IDH: To maintain biodiversity, a ”moderate” level of disturbance is necessary. To apply this concept in a way that assists with ecological flow evaluation, it is important to determine what a ”moderate” level of disturbance represents for a stream or class of streams and how it can be measured in terms of magnitude and duration of flow events. One could also ask how frequently a moderate disturbance event occurs, whether the timing of the event is important in terms of life cycle cues (see Lytle and Poff, 2004), and how such a disturbance affects the life history of longer-lived species.

The **flood pulse concept** (Wood, 1951; Gosselink and Turner, 1978; Brinson and others, 1980; Odum, 1984; Junk and others, 1989; and Ward, 1989;) recognizes the importance of lateral exchange of water, nutrients and organisms between the stream channel and the connected floodplain. It focuses on how pulsing hydrology affects the organisms and specific processes in the floodplain. Hydrologic pulsing enhances biological productivity, efficiency of nutrient use, movement of detritus and sediments, and maintains biodiversity in aquatic systems. Bayley (1991) presents the idea that the flood pulse should not be viewed as a disturbance; rather, only significant departures from the average hydrologic regime, such as the prevention of floods, should be regarded as a disturbance. This perspective is consistent with Ward and Stanford’s (1983) suppositions regarding the IDH. Floods are inextricably part of the natural hydrologic process and should be considered integral when developing any ecologically based flow methods.

The **hierarchical framework for stream habitat** classification presented by Frissell and others (1986) indicates that structure, operation, and other aspects of the organization and development of stream assemblages are largely determined by the physical stream habitat, together with the pool of species available for colonization. The hierarchical framework itself entails an organized view of the spatial and temporal variation among and within stream systems. Stream systems can be defined as hierarchically organized systems with successively linked lower levels –stream segment, reach, pool/riffle, and microhabitat (fig. 4).

At each level in the hierarchy, systems can develop and persist predominantly at a specified spatiotemporal scale. The authors conclude: "…by viewing streams as hierarchically organized systems, the approach focuses on a small set of variables at each level that most determine system behaviors and capacities within the relevant spatiotemporal frame" (Frissell and others, 1986, p. 212). This framework represents an integral part of the HIP because it emphasizes the role that physical processes play in determining watershed characteristics at different scales, and how the flow regime determines the relative suitability of habitats for different organisms which ultimately affects their distribution, abundance, and diversity.

The final concept examined, the **Natural Flow Regime Paradigm** (Poff and others, 1997), synthesizes existing scientific knowledge to argue that the natural-flow regime plays a critical role in sustaining native biodiversity and ecosystem integrity in rivers. Decades of observation of the effects of human alteration of natural flow regimes have resulted in well-established scientific findings indicating that altering the hydrologic regimes in rivers can be ecologically deleterious (for example, Arthington and others, 1991; Castelberry and others, 1996; Hill and others, 1991; Johnson and others, 1976; Richter and others, 1996, 1997; Sparks 1995; Stanford and others, 1996; Toth, 1995; Tyus, 1990). These authors argue that streamflow quantity and timing are critical components affecting the ecological integrity of river systems. Furthermore, streamflow, which is strongly correlated with many critical physiochemical characteristics of rivers, can be considered a "master variable" that limits the distribution and abundance of riverine species (fig. 2). In addition, riverflow regimes show regional patterns determined by the size of the river, geographic variation in climate, geography, and topography. Thus, the five components of the flow regime outlined by Poff and others (1997): Magnitude, frequency, duration, timing, and rate of change, should be considered explicitly to characterize the entire range of flows and specific hydrologic phenomena that are critical to maintaining the integrity of river ecosystems. Finally, the authors present a table with 52 representative studies that document the ecological responses to alterations of the natural flow regime. Examples include fish life cycle disruption, encroachment of vegetation, loss of sensitive invertebrate species, and loss of fish access to backwaters and wetlands.

The Natural Flow Regime Paradigm's approach to flow variability effectively incorporates several concepts that are vital to preserving hydroecological integrity. These concepts are:

- The structure and function of riverine ecosystems varies spatially (longitudinally and laterally) and temporally and is strongly influenced by hydrologic variability in terms of magnitude, frequency, duration, timing, and rate of change.
- River ecosystems consist of three templates: physical, chemical, and biological, emphasizing the dynamic spatial and temporal interactions between abiotic and biotic factors.
- Natural flow regimes show regional patterns, and these patterns represent a gradient of ecological processes that influence the structure and function of the aquatic, plant, and animal assemblages.
- Magnitude, frequency, duration, timing, and rate of change for flow can be used to characterize streams, their entire range of flows, as well as the specific hydrologic events critical to maintaining the integrity of river ecosystems.

The choice of biological response(s), which may be tied to hydrologic variability, will determine which specific statistics, indices, and (or) parameters best describe the hydrologic variability of an unaltered flow regime. Biological responses to streamflow regimes may show regional patterns

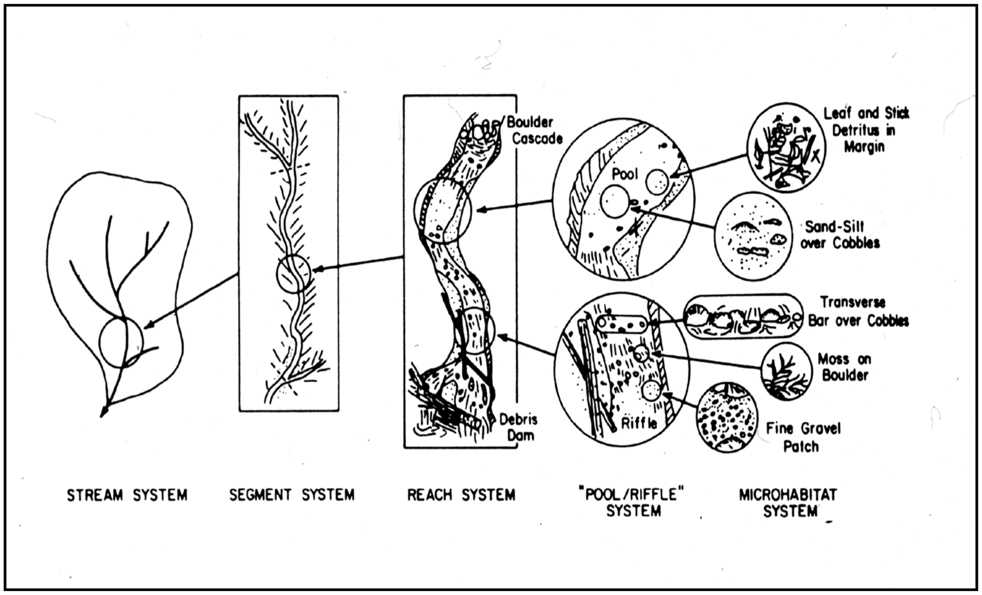

Figure 4. Hierarchical organization of a stream system and its habitat subsystem. From Frissell and others, 1986.

that are determined largely by stream size, variation in climate, geology, topography, vegetation, and land use, so the statistics, indices, and parameters that best link hydrologic variability to biological responses may also vary by such factors as climate and geology.

Poff and Ward (1989) investigated streamflow variability and assemblage structure at the regional level. The authors concluded that patterns of diversity of all major lotic assemblages, including fish, invertebrates, algae, and macrophytes are related to patterns of temporal variation in flow. Furthermore, there is a substantial body of evidence indicating that high-flow and low-flow disturbances have a central role in structuring stream assemblages (for example, Ward and Stanford, 1983). Different combinations of streamflow variation result in different degrees of physical control over biotic organizations.

Poff and Ward's (1989) research developed an objective and a general quantitative characterization of streamflow variability and predictability. They used 11 summary statistics (three addressing overall flow variability, six addressing the pattern of the flood regime, and two addressing the extent of flow intermittency) of long-term daily-discharge records from 78 streams across the conterminous United States to classify streams into nine hydrologically distinct stream types. Thus, the analysis assessed hydrologic similarity between streams using components of the flow regime with ecological significance. They use flow variability, flood patterns, and extent of flow intermittency to develop their conceptual model (fig. 5) of stream types. They also recognized that more benign or predictable flow environments are more conducive to stronger biotic interactions. The authors note, however, that in most lotic systems streamflow regimes are intermediate between these extremes and consequently, abiotic and biotic factors influence assemblage structure at various degrees at various times. The authors concluded that long-term, daily flow records are valuable sources of information with which to evaluate temporal and spatial patterns of lotic environmental variability and disturbances across physiographic and ecographic regions. Thus, evaluation of the long-term patterns in flow variability needs to be an integral part of the development of any hydrologically-based flow methodology.

Poff (1996) continued to build on and expand this research using ecologically relevant hydrologic measures (that is, streamflow indices) to classify streams and examine relations between hydrologic variability and population- and

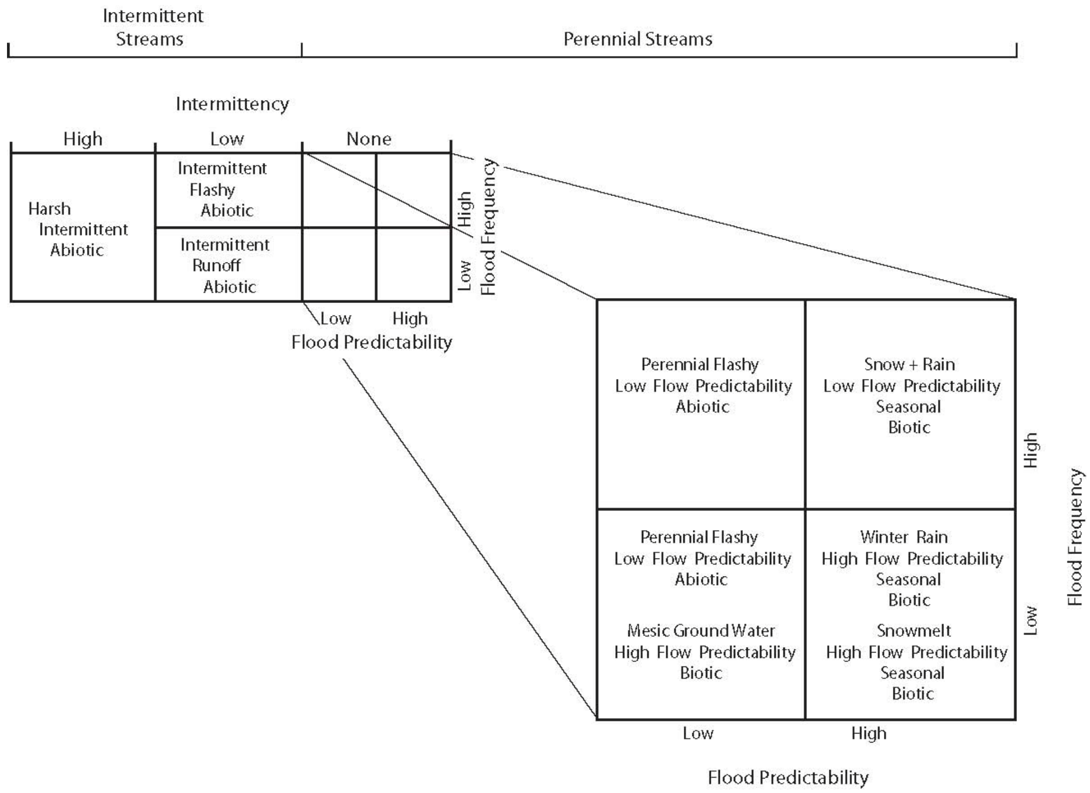

Figure 5. Conceptual model of classification of stream clusters based on hierarchical ranking of four temporal components of discharge regime. From Poff and Ward, 1989.

assemblage-level processes and patterns. He used long-term daily and peak-flow gaging records (>36 yrs) from 420 relatively undisturbed streams in the conterminous United States to classify streams according to variation in 10 ecologically relevant hydrological characteristics (only five of those measures differed from that of Poff and Ward (1989)). Cluster analysis was used to identify 10 distinctive stream types which included seven permanent and three intermittent types. This study established that there are distinct patterns in the hydrological regimes of streams across the United States based on geographical distribution. Such patterns can be used to identify similar streams for the purpose of engaging in regional, comparative ecological research.

Many studies have used pre-selected hydrological variables and flow data from either unclassified or classified streams to seek out biological relations. For example, Clausen and Biggs (1997) selected 34 hydrological variables and biological data from 83 New Zealand streams. Four of the thirty-four hydrologic variables were significantly correlated with periphyton biomass, whereas twenty-four variables were correlated with periphyton diversity. Conversely, 24 of the hydrological variables were correlated with total invertebrate density, whereas only four variables were correlated with diversity. Monk and others (2006) classified 83 river basins in England and Wales into five classes using a suite of 201 flow-regime descriptors. They found significant correlations with macroinvertebrate assemblage metrics, primarily with two of the variables associated with the magnitude of the flow regime. This relation was consistent for all sites and a sub-set of the flow-regimes classes. Poff and Allan (1995) evaluated fish assemblages and hydrologic data from 34 Wisconsin and Michigan streams. They found strong hydrologic-assemblage relations which may indicate that hydrologic factors significantly influence fish assemblage structure.

Hydroecological studies such as those discussed above, indicate statistical connections between hydrologic variability and aquatic-assemblage structure for the three ecosystem templates (physical, chemical, and biological). The transferability of these connections to altered time periods and (or) locations cannot be assumed because causal mechanisms are undefined. In addition, the ability to address the dynamic spatial and temporal interactions known to occur between abiotic and biotic factors remains largely unknown. Poff (Colorado State University, personal commun., 2006) also recognizes that species have differing, and often opposing, environmental requirements. Therefore, it may not be possible to determine a single environmental optimum for all individual species or an assemblage (see also Stalnaker, 1990; Poff and others, 1997; and Doyle and others, 2005). In addition, it is important to recognize that the sequence of inter- and intra-annual hydrologic events influence the significance of abiotic/biotic interactions. Consequently, fluctuations between favorable and unfavorable environmental conditions (that is, hydrologic variability) through space and time helps sustain the ecological integrity of a stream ecosystem.

Olden and Poff (2003) recognized that the overarching goal of streamflow characterization and classification is to select hydrologic indices that account for streamflow variability characteristics that are "biologically relevant". Researchers, however, have used many different ways to characterize streamflow, generally taking a multivariable approach. Moreover, "…although the use of single indices has been criticized as being overly simplified and lacking adequate biological relevance, stream ecologists are now faced with the difficult task of choosing from the plethora of available hydrologic indices" (Olden and Poff, 2003, p. 102), many of which are highly intercorrelated.

One of the primary goals of the Olden and Poff (2003, p. 102) article was to answer the question: "Which minimum subset of available hydrologic indices is required to adequately describe the main aspects of the flow regime?" The authors answered this question by reclassifying the same 420 stream gages (>20 years, unregulated, flow records) analyzed in the Poff (1996) study by using 171 published hydrologic indices that were found to be biologically relevant. This reclassification identified six distinctive stream types. It identified patterns of redundancy among hydrologic indices, and provided a number of statistically- and ecologically-based recommendations for the selection of a reduced set of indices that adequately represent all five critical elements of the flow regime (that is, magnitude, frequency, duration, timing, and rate of change) by stream type. Olden and Poff (2003) state that their research provides a statistically-based framework that can guide researchers in the selection of nonredundant hydrologic indices that fully characterize the flow regime. Thus, one can reduce the population of indices to a minimal set that incorporates all critical components of the flow regime (for example, table 1) for all Missouri stream types. Table 1 represents the quantification of the natural flow regime, for Missouri streams, as defined in Poff and others (1997).

A number of ecologically important streamflow characteristics constitute the natural flow regime, including the seasonal patterning of flows; timing of extreme flows; the frequency, predictability, and duration of floods, droughts, and intermittent flows; daily and seasonal, and annual flow variability; and rates of change (Poff and others, 1997). These hydrologic indices must be derived from an adequate period of record. Consequently, if, using biological metrics, a stream reach's integrity is declared to be 'healthy' or 'acceptable' currently, or at some previous point in time, it can be attributed in large part to the preceding historic flow regime.

To address stream integrity, the importance of stream ecosystem theory and hydrologic-ecologic principles should be recognized. Streams should be classified, at a minimum, based on ecologically relevant indices that incorporate all dimensions of hydrologic variability including magnitude, frequency, duration, timing, and rate of change.

Study Area Description

Missouri is a physiographically and biologically diverse State situated in the east-central United States (fig. 6). Two great rivers, the

Table 1. Hydrologic indices with the largest absolute loading on each of the first three through five significant principal component axes for each of the 11 subcomponents of the flow regime for each of the three primary and four secondary Missouri stream types. (Refer to appendix 2 for definitions of hydrologic indices.)

[Some indices can appear more than once in the table and in succession because they are the most highly loaded variable on PCA axis one, two, three, and so forth, for a given flow component. These indices represent surrogates for the primary index listed. In some cases, for example, low-flow conditions for an intermittent stream, no surrogate indices were identified]

	STREAM CLASS							
Flow component	**Intermittent**	**Perennial/ runoff (PR)**	**PR flashy**	**PR Moderate baseflow**	**Perennial/ Groundwater (PG)**	**PG Stable**	**PG Super stable**	**All streams**
Magnitude of flow events:								
Average flow conditions	MA35, MA42, MA37,	MA35, MA3, MA44, MA39	MA3, MA35, MA39, MA11, MA44	MA35, MA37, MA42	MA3, MA44, MA42, MA11	MA35, MA42, MA45, MA43, MA37	MA37, MA45, MA45, MA39, MA43	MA3, MA42, MA39, MA3, MA11
Low–flow conditions	ML18, ML20, ML20,	ML20, ML18, ML20, ML18	ML18, ML20, ML20, ML20, ML18	ML18, ML18, ML20	ML20, ML18, ML18, ML18	ML20, ML18, ML18, ML18, ML20	ML18, ML20, ML18, ML18, ML18	ML20, ML20, ML18, ML20, ML20
High–flow conditions	MH13, MH19, MH18,	MH16, MH18, MH13, MH16	MH14, MH13, MH13, MH16, MH19	MH14, MH18, MH19	MH16, MH13, MH18, MH13	MH16, MH16, MH18, MH18, MH19	MH14, MH13, MH18, MH18, MH19	MH16, MH13, MH18, MH13, MH19
Frequency of flow events:								
Low–flow conditions	FL1, FL1, FL1,	FL2, FL1, FL1, FL1	FL1, FL2, FL1, FL1, FL2	FL1, FL2, FL2	FL2, FL2, FL1, FL1	FL2, FL1, FL1, FL1, FL1	FL1, FL1, FL2, FL1, FL1	FL2, FL2, FL1, FL1, FL2
High–flow conditions	FH2, FH8, FH11,	FH2, FH5, FH5, FH11	FH5, FH8, FH11, FH11, FH10	FH8, FH10, FH10	FH8, FH8, FH11, FH5	FH8, FH11, FH5, FH8, FH11	FH10, FH11, FH5, FH10, FH11	FH8, FH2, FH10, FH10, FH5
Duration of flow events:								
Low–flow conditions	DL17, DL9, DL3,	DL3, DL18, DL16, DL16	DL18, DL16, DL16, DL16, DL16	DL9, DL18, DL10	DL3, DL9, DL17, DL16	DL3, DL10, DL16, DL18, DL9	DL3, DL16, DL16, DL17, DL17	DL10, DL17, DL18, DL17, DL16
High–flow conditions	DH16, DH6, DH3,	DH17, DH18, DH6, DH15	DH3, DH15, DH6, DH19, DH3	DH15, DH18, DH3	DH21, DH18, DH24, DH19	DH21, DH19, DH19, DH23, DH6	DH19, DH22, DH21, DH15, DH6	DH15, DH16, DH23, DH6, DH18

Timing of flow events:								
Average flow conditions	TA2, TA3, TA2	TA2, TA2, TA2, TA2	TA2, TA2, TA2, TA2, TA2	TA2, TA3, TA3	TA2, TA2, TA3, TA3	TA2, TA2, TA2, TA2, TA3	TA2, TA3, TA2, TA3, TA2	TA2, TA2, TA2, TA2, TA2
Low–flow conditions	TL2, TL1, TL3	TL1, TL4, TL4, TL2	TL4, TL4, TL4, TL1, TL2	TL1, TL4, TL4	TL1, TL2, TL4, TL2	TL1, TL2, TL2, TL4, TL2	TL4, TL1, TL1, TL4, TL4	TL1, TL2, TL4, TL4, TL2
High–flow conditions	TH3, TH1, TH1	TH2, TH3, TH1, TH3	TH3, TH2, TH3, TH2, TH2	TH3, TH2, TH3	TH2, TH1, TH3, TH2	TH1, TH3, TH2, TH3, TH3	TH3, TH2, TH1, TH3, TH3	TH1, TH1, TH2, TH3, TH2
Rate of change in flow events	RA4, RA8, RA5,	RA8, RA4, RA4, RA5	RA5, RA9, RA8, RA4, RA9	RA5, RA4, RA4	RA8, RA4, RA8, RA4	RA9, RA9, RA8, RA5, RA5	RA4, RA9, RA5, RA4, RA8	RA9, RA8, RA7, RA6, RA9

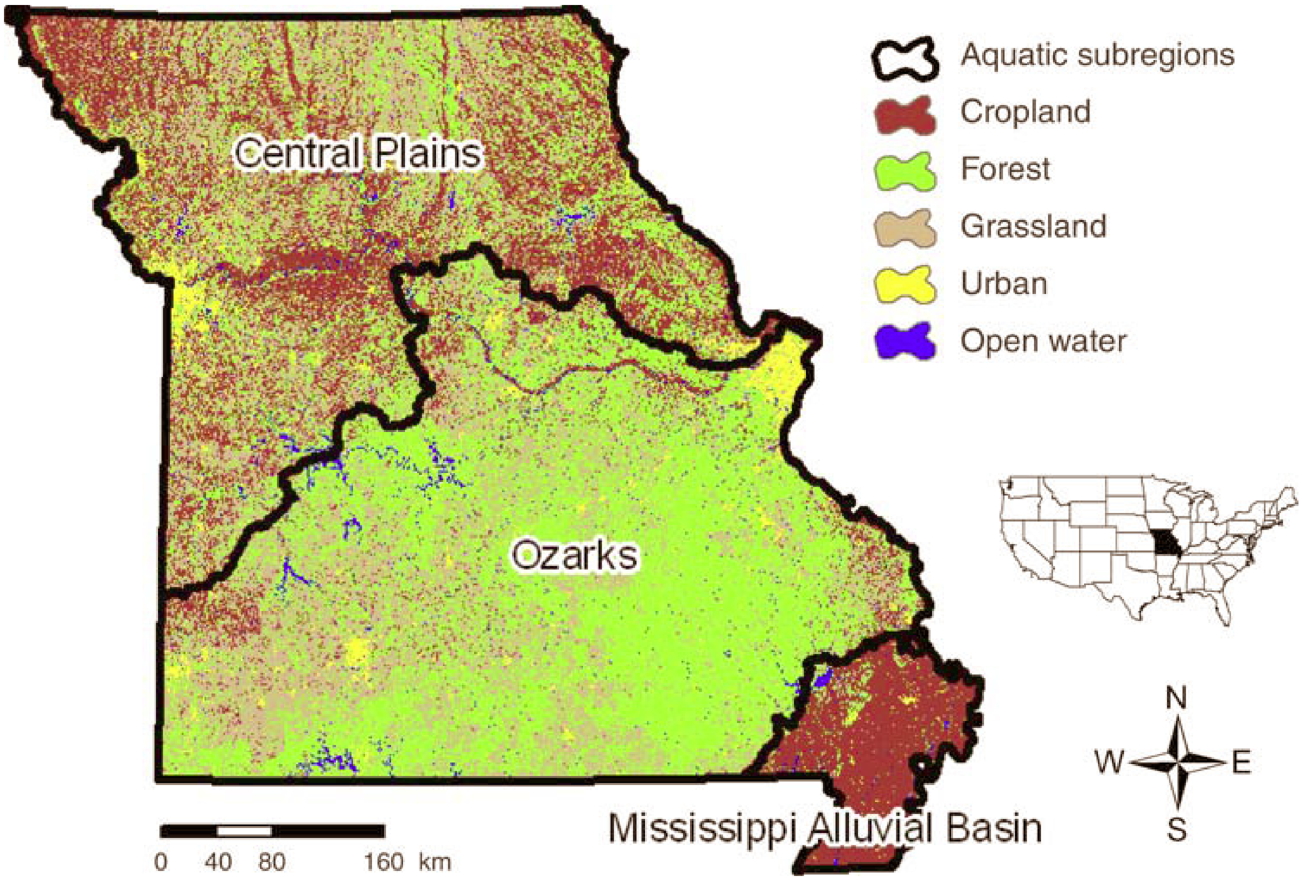

Figure 6. Map of Missouri showing 2003 land cover (from Sowa and others, 2007) and the three aquatic subregions (Central Plains, Ozarks, and Mississippi Alluvial Basin) that account for major differences in instream habitat and freshwater assemblages across the state. These three aquatic subregions are complementary to established Missouri physiographic sections. That is, the Central Plains is equivalent to the combination of the Dissected Till Plains and the Osage Plain physiographic sections; the Ozarks is equivalent to the Springfield-Salem Plateaus, and the Mississippi Alluvial Basin is equivalent to the Mississippi Alluvial Plain.

Mississippi and the Missouri, and the fauna that inhabit them have given the state a unique identity. Missouri has a humid continental climate with an average annual temperature of 13°C (Sowa and others, 2005). Average annual temperatures are lowest in the northwest (11°C) and highest in the southeast (15°C). Average annual precipitation is 97 cm, of which 71 cm are lost to evaporation and plant use (Vandike, 1995). A total of 364 native freshwater animal species and subspecies (32 crayfishes, 56 snails, 65 mussels, and 211 fishes) have been identified within Missouri (Sowa and others, 2005). Few States in the United States contain a higher number of freshwater species. This diversity is primarily the result of the Missouri and Mississippi River basin ecosystems, which acted as refugia for aquatic fauna during Pleistocene glaciation (Matthews, 1998), and the Ozark Highlands, which is an unglaciated landscape that that has allowed divergent evolutionary processes to proceed for millions of years (Pflieger, 1971, 1996; Sowa and others, 2005). Three distinct aquatic subregions have been identified in Missouri: Central Plains, Ozarks, and Mississippi Alluvial Basin (fig. 6) (Pflieger, 1971, 1989; Sowa and others, 2005). Boundaries of these subregions tend to follow major drainage divides that correspond with transitions in topography, geology, soils, land cover, and groundwater influences. Sowa and others (2005, 2007) provide a detailed description of these three subregions. However, only a brief overview of their distinct physical and biological characteristics is presented here.

The **Central Plains** is influenced by the Pleistocene glaciation that has largely shaped this subregion. The typography of the landscape is mainly flat to gently sloping with an average land slope of 5 percent and local relief from 5 to 60 m (Sowa and others, 2005). Average stream gradients range from 10.3 m/km (headwaters) to 0.3 m/km (large rivers). Base flows in this subregion tend to be quite low and streams with low dissolved-oxygen concentrations are common (Smale and Rabeni, 1995a, b). Much of the native grasslands have been converted to cropland or pastureland and riparian forests have been largely removed (fig. 6). Many streams have also been channelized and tend to be more turbid, have lower dissolved oxygen concentrations, less predictable base flows, and wider temperature fluctuations than in pre-European settlement times (Rabeni and Sowa, 1996, Sowa and others, 2005).

The **Ozarks** is an uplifted and unglaciated region and represents one of the oldest regions of the world (Steyermark, 1959). This subregion generally consists of older bedrocks, higher elevations, and greater local relief than the other two subregions (Sowa and others, 2005). The region is topographically diverse and ranges from very flat to very uneven with an average land slope of 9 percent. Many streams are spring fed and carry little suspended sediment and the average stream gradient ranges from 17.3 m/km (headwaters) to 0.5 m/km (large rivers). In general, Ozark streams have undergone less anthropogenic disturbance than the other aquatic subregions in Missouri. Some of the poorest water quality in the state, however, can be found in the Ozarks in areas downstream from metropolitan St. Louis, and in stream segments downstream from lead mines (Cieslewicz, 2004; Sowa and others, 2005).

The **Mississippi Alluvial Basin** is a nearly flat plain that is underlain by Cretaceous and Tertiary deposits of clay, sand, and gravel. Historically, this subregion was one of the most heavily timbered regions of Missouri (Pflieger, 1971). The majority of this subregion (nearly 95 percent) has been drained and converted to farmland (Nigh and Schroeder, 2002). Average annual runoff ranges from 46 to 51 cm, which is the highest in the State (Sowa and others, 2005). The flat topography and shallow aquifers of this subregion contribute to the relatively stable hydrographs and high base-flow of streams and ditches (Pflieger, 1971). Springs and natural streams are relatively scarce. However, there are numerous ditches which vary substantially in terms of discharge, turbidity, flow, substrate, and aquatic and riparian vegetation (Pflieger, 1971; Sowa and others, 2005). Channel gradients are significantly lower in the Mississippi Alluvial Basin than in the other two subregions. Despite these low stream gradients, erosion is still a substantial problem upstream from channelized sections (Boone, 2001).

Stream Classification and Selection of Indices

Implementation of the Hydroecological Integrity Assessment Process (HIP) involves a sequence of four major steps (see also Kennen and others, 2007, p. 9) that can also be represented as stages of development and application (fig. 7). Each of these steps are more fully described in the sections that follow. A narrative outline is presented here as a general overview of the approach.

1. **Perform a hydrologic classification of streams** in the selected geographic area using a selected subset of long-term gaging records representing relatively-unmodified streams. Calculate 171 hydroecologically relevant indices (HRIs) for each gage and reduce data complexity by eliminating known inter-correlations among HRIs following the approach presented by Olden and Poff (2003). Employ an unweighted pair-group method analysis (UPGMA; McCune and Medford, 1999; McCune and Grace, 2002), or use a comparable hierarchical-clustering method, on the reduced subset of hydrologic indices to

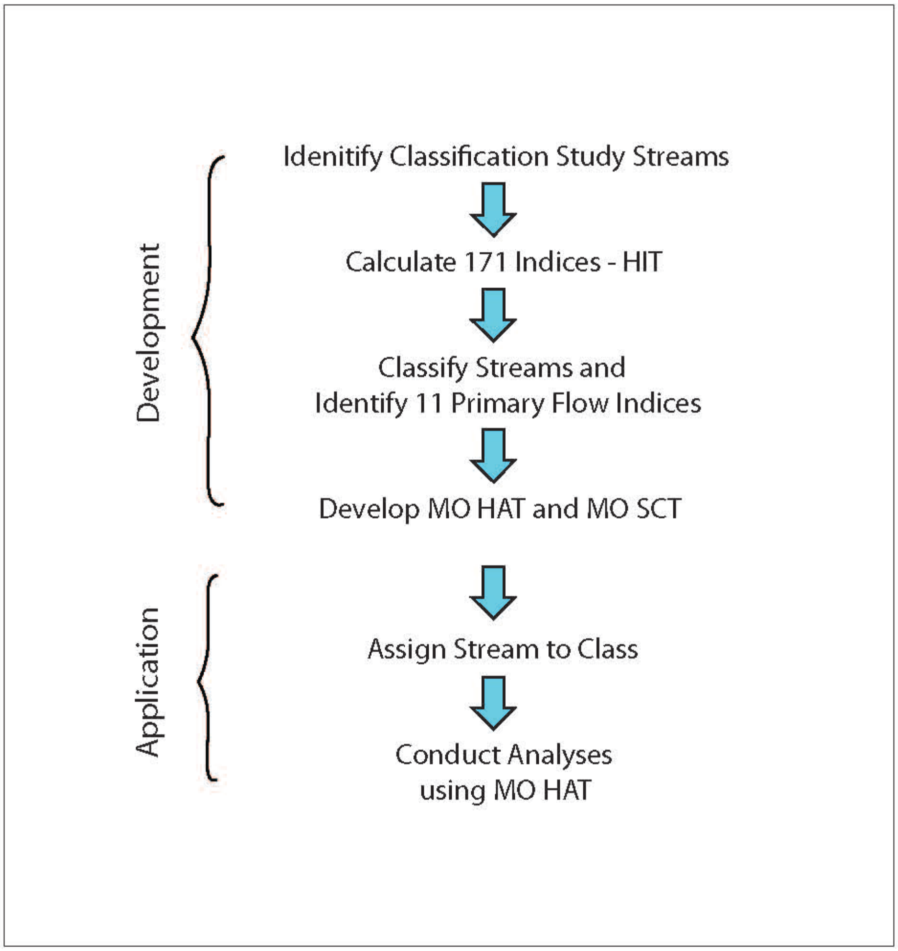

Figure 7. Generalized flow chart of sub steps taken to develop and apply a regional Hydroecological Integrity Assessment Process (HIP) for Missouri streams.

group streams into regionally or state-specific stream types. Bayesian hierarchical clustering may be another useful option (see Heller and Ghahramani, 2005, or Kennard and others, 2009).

2. **Identify statistically significant, non-redundant, HRIs** (surrogate indices are also identified) associated with the five major flow components (a total of 11 primary indices) of the flow regime for each classified stream type using Principal Components analysis (SAS Institute Inc., 1989). The most significant HRI for each principal component is extracted for each flow component and for each of the major stream types (refer to table 1 for the full set of significant HRIs and their surrogates). This suite of extracted HRIs should adequately characterize the flow regime for each stream type (Olden and Poff, 2003).

3. **Develop an area-specific stream classification (computer software) Tool** (SCT) for placing unclassified streams (that is, streams not placed into a specific stream type as part of the initial classification analysis; unclassified streams typically fall into two categories: ungaged streams, or streams with known flow modification) into one of the identified stream types. This soft-

ware tool, which is developed specifically for use in Missouri streams (that is, MOSCT), uses linear discriminant-function analyses (SYSTAT, 2004) to match a stream with one of the specified stream types based on the level of concordance among a subset of significant HRIs. DFA is used explicitly to provide the classification functions for the MOSCT software tool.

4. **Develop an area-specific Hydrologic Assessment Tool** (HAT). This Missouri-specific software tool (that is, MOHAT) can be used to (a) establish a hydrologic baseline (that is, a reference time period), (b) provide options for setting environmental flow standards, and (c) evaluate past and proposed hydrologic modifications for a stream reach. These two software tools (MOSCT and MOHAT) are custom tailored for Missouri streams and have been furnished to the Missouri Department of Conservation as part of the cooperative agreement. Details on the application of these software tools are provided in the Users' manual for the Hydroecological Integrity Assessment Process software (Henriksen and others, 2006).

Selection of Streamflow Data

The steps used for selection of Missouri streams for use in the HIP excluded streams that either were not representative of "least impaired" conditions, did not have a continuous period of record long enough to be considered appropriate for analysis, were not free flowing, that is, had man-made structures (dams, impoundments, reservoirs, and so forth) that greatly impeded natural flow, or had known withdrawals. These steps included a site-selection process that incorporated visual and best professional judgment procedures. First, all candidate Missouri stream gages (154) with a period of record (POR) of at least 20 years (where possible) were identified (36 gages used in the analysis did have a POR < 20 years; see appendix 1). Second, the flow records were used to establish a minimum background flow profile based on the available POR. The flow profile was used to help identify any flow-related anomalies or identify whether any major changes in flow processes have occurred over the established POR. Least impaired sites, that is, sites that had minimal flow regulation or a POR reflecting a time period prior to major flow alteration were identified. In addition, gage records affected by major impoundments or withdrawals were excluded to reduce the influence of man-made structures on the analysis. Best professional judgment, which relied upon the experience and knowledge of Missouri Water Science Center and Missouri Department of Conservation personnel, was extensively utilized as part of this evaluation.

Ecologically Relevant Hydrologic Indices

The hydrologic index tool (HIT) is a standalone program that calculates 171 HRIs by using daily-mean and peak-flow discharge values (Henriksen and others, 2006). The USGS conducted a series of tests to verify that the computer code in the Hydroecological Integrity Assessment Process computer programs (HIT and MOHAT) correctly applies the definitions and the formulas for the calculation of the 171 HRIs (for example, Hersh and Maidment, 2006; Kennen and others, 2007). The results of these tests are presented in appendix 6 of Henriksen and others (2006) and in appendix 5 of Kennen and others (2007). HIT, which calculates 171 HRIs, is primarily used in conjunction with the classification analysis of any geographic area (for example, Missouri, or a selected state, province, or geographic region). Prior to using HIT, a researcher would select all stream gages within a geographic area of interest using the POR that provides the least-altered streamflow record. These gage records should have an acceptable POR with a recommended minimum of 10 yrs; however, 25 yrs is preferred where possible (Interagency Advisory Committee, 1981). Daily mean discharge and peak-flow data (if available) would be processed using HIT; that is, the program would calculate all 171 indices for each stream. If peak flow data are not available, then eight frequency, duration, and timing HIT indices (that is, FH11, DH22, DH23, DH24, TA3, TH3, TL3, and TL4) are not calculated. Daily mean discharges and peak annual flows; however, are necessary to run a complete HIT analysis. These data can be downloaded directly from the USGS Website, NWIS Web Data for the Nation available at: *http://waterdata.usgs.gov/nwis/*. The daily mean discharge values could also be acquired by simulating daily flow data (for example, Kennen and others, 2008), but the format should be consistent with that of USGS continuous gaging records (Henriksen and others, 2006).

Following calculation of 171 indices for the initial candidate stream gages, it was observed that 14 gages had too few data points for analysis. Seven harshly intermittent streams with a large number of zero-flow days (defined here as a stream with a median annual flow equal to zero) were excluded because “NC” (not calculated) values were returned for numerous indices. In addition, six Mississippi Alluvial Basin streams, with known alterations too great to be considered least altered, and one outlier, were excluded. Combined, these eliminations reduced the number of candidate streams in Missouri from 154 to 140 (Appendix 1).

Five hydrologic indices also were found to not be fully populated. For example, the original calculation for ML18 (see appendix 2) produced some missing values. To complete the dataset, the missing values were replaced with estimates derived from a predictive equation based on index RA6, which was the index most strongly correlated with ML18. One missing value for DL9 (see appendix 2) was predicted from the fully populated ML18 data. In addition, it was observed that a few indices (MA6, MA7, and MA8) returned “NC” values for some gages. These indices are defined as the ratios of $10^{th}/90^{th}$, $20^{th}/80^{th}$, and $25^{th}/75^{th}$ percent exceedance flows, respectively. Intermittent streams and some small perennial streams in Missouri have enough zero flow days to produce a zero value in the denominator(s); consequently, the ratio for these indices would be undefined and would return “NC” values. In an attempt to address this issue, the indices were modified by inverting the ratios. However, MA6, MA7, and MA8 were excluded during the redundancy analysis and ultimately did not affect the stream classification. Therefore, to maintain consistency with the index definitions in the national hydrologic assessment Tool (NATHAT; Henriksen and others, 2006), the modifications were not implemented in the MOHAT program. When using MOHAT, however, such changes could be done post hoc to accommodate evaluation of sites or flow alternatives that return ”NC” values for MA6, MA7, or MA8.

Statistical Analyses for Stream Classification

This section describes a series of procedural steps that identifies a set of gages on minimally impaired Missouri stream sites, and (1) calculates 171 HRIs for a minimally impaired period of record for 140 stream gages, (2) presents a statistical process to reduce the amount of redundancy among the hydrologic indices based on work by Olden and Poff (2003), and (3) groups these stream sites into distinct stream types based on hydroecologically relevant indices (HRIs). The HRIs characterize the magnitude, frequency, duration, timing, and rate of change in flow events (table 1). The reduced set of indices is used to cluster the streams into stream types and Principal Components Analysis (PCA) is used to identify the most significant hydrologic indices for each of the stream types.

Stream types in Missouri were defined by classifying the 140 stream gage-sites that met the minimum criteria established above, that is, a sufficiently long POR associated with minimal anthropogenic disturbance in the catchment. In this analysis, the POR selected for each of the 140 stream gages was assumed to represent the “least impaired” portion of the gaging record and was subsequently analyzed using the Hydroecological Indices Program (HIP) to generate 171 hydroecologically relevant indices (Richter and others, 1997; Olden and Poff, 2003) for each stream site. By focusing on sites with a least impaired POR, the resulting HRIs are thought to be indicative of what would be expected for a relatively unmodified aquatic system. The results of the HIP analyses were validated against available published USGS streamflow records and by a series of validation techniques presented in Henriksen and others

(2006). All 171 HRIs were calculated for the 140 stream sites.

Principal Components Analysis (PCA) (SAS Institute Inc., 1989) in combination with collinearity assessment (Spearman's rho), was used to reduce the number of HRIs and to isolate a subset of indices that accounted for the greatest proportion of variance while minimizing redundancy (Olden and Poff, 2003). PCA is well suited to decreasing the dimensionality of complex data sets (Digby and Kempton, 1987; Manly, 1994) and was used to minimize HRI inter-correlation. Distributions of all HRIs were evaluated for normality. Those HRIs that were strongly correlated with drainage area and total flow (for example, DL3 and DH3 in appendix 1) were standardized by dividing by drainage area (square miles). PCA was conducted on the correlation matrix and the significance of principal components was evaluated using the broken stick method (Jackson, 1993). The broken stick method is used to determine statistically significant principal component axes by comparing the observed eigenvalues to the eigenvalues from random data. In addition, use of the correlation matrix ensured that all HRIs contributed equally to the PCA and that the contributions were scale-independent (Legendre and Legendre, 1998; Olden and Poff, 2003). Loadings (the level of correlation between the HRIs and principal components) of the HRIs on each significant principal component were used to identify indices explaining the dominant patterns of variation among a full suite of intercorrelated indices. Indices with the strongest loadings (minimum cutoff was set at 0.6000) along significant primary components were retained for additional analysis. Spearman's correlations were then used to further diminish redundancy and the combination of these two approaches reduced the number of significant HRIs from 171 to 53. Indices that were standardized by drainage area had such reduced variance that most never loaded strongly on any of the primary principal components.

The reduced set of HRIs were then used to classify the 140 stream sites into distinct stream types using the unweighted pair-group average method (UPGMA, that is, a clustering technique that is also known as average linkage or group average). UPGMA is a hierarchical clustering technique where the similarity between clusters is calculated using the average of all Euclidean distances for all pairs of individuals (McCune and Grace, 2002). Prior to the cluster analysis, HRIs were normalized (to mean = 0, and variance = 1) to reduce the effect of scale and the UPGMA was carried out using PRIMER 6 (Clarke and Gorley, 2006). The UPGMA cluster analysis separated the 140 streams based on the strength of the associations between the 53 indices into three primary stream types (intermittent (INT), perennial runoff (PR), and perennial groundwater (PG); table 1) and four secondary stream types (perennial runoff–flashy (PRF), perennial runoff–moderate baseflow (PRMB), perennial groundwater–stable (PGS), and perennial groundwater–super stable (PGSS); see appendix 1). One gage was found to be an outlier (that is, it did not classify with any of the other stream types because it is on a losing stream), and rather than create a separate stream type for a single site, it was omitted from further analysis. The three primary stream types were found to be highly distinct and the sensitivity of the clusters was validated using a jackknifing procedure (for example, Ibarra and Stewart, 1989; Kennen and others, 2002). This analysis requires a sequential deletion of sites and calculation of percent persistence of each cluster division. This analysis indicated 80- to 95-percent persistence for the three primary stream types.

Following the cluster analysis, PCA was conducted to identify the HRIs that best exemplify the 11 sub-components of the flow regime (that is, low, average, and high flow magnitude; frequency of low and high flows; duration of low and high flows; timing of low, average, and high flows; and average rate of change; see table 1) for each of the stream types. The stream types are ordered in table 1 to represent a continuum from intermittent to perennial groundwater–super stable groundwater. A matrix was produced (table1) by identifying, for each stream type, the indices that were most significant for each of the 11 subcomponents of the flow regime. Significant indices were derived by assessing the loading pattern on significant principal components for each stream type separately, and that is why there may be a different number of significant axes for each stream type. Loadings of the hydroecological indices on each significant principal component were used to identify indices that explain dominant patterns of hydrologic variation. Because principal component axes by definition are orthogonal, indices from significant secondary and tertiary principal component axes also were selected to ensure that the chosen indices were relatively independent from one another and to identify surrogate indices for later comparisons (Olden and Poff, 2003). Surrogate indices represent other indices within each flow sub-component that are not collinear with the indices of interest (Henriksen and others, 2006). The primary and surrogate indices for each stream type are listed in table 1. Box plots of selected HRIs that best distinguished the five stream types are presented in figures 8–12. The among stream variation in the hydrologic indices depicted by the box plots is a measure of spatial variability in indices that are either temporal averages or measures of temporal variability of flow characteristics within a stream.

Analysis of variance (ANOVA) was performed to highlight differences in hydrologic index score among the five stream types (SAS Institute Inc., 1989) of (1) intermittent (INT), (2) perennial runoff – flashy (PRF), (3) perennial runoff–moderate baseflow (PRMB), (4) perennial groundwater–stable (PGS), and (5) perennial groundwater–super stable (PGSS). The null hypothesis (H_0) evaluated was that the mean hydrologic index score among the five stream types was equal. If the null hypothesis was rejected, Tukey's honestly significant difference test (Tukey's test) was performed to determine which mean index scores differed. Null hypothesis testing was performed at the 95-percent confidence level ($\alpha = 0.05$). Tukey results are presented as letters A through D on the box plots and represent significant differences in mean hydrologic index score. The selected HRIs presented in figures 8–12 were chosen based on a series of steps that incorporated statistical significance (that is, results from PCA (table 1) and ANOVA), were capable of distinguishing between intermittent and other stream types, and represented the continuum from intermittent to super stable groundwater (Del Lobb, Missouri Department of Conservation, written commun., Feb. 4, 2009). The box plots are particularly useful for visually and statistically comparing the distributions of HRIs among stream types and can be used to assist HIP users in Missouri identify specific HRIs, in addition to those presented in table 1, that have the highest statistical probability of differentiating among stream types.

Statistical Analysis for Classifying Unclassified Streams

Linear discriminant-function analyses (DFA) were used to find a parsimonious model that best separated the means of the three primary stream types (intermittent, perennial runoff, and perennial groundwater) in a multivariate space represented by the streamflow indices. The classification functions produced by the DFA were used in the Missouri Stream Classification Tool (MOSCT) to provide a method for classifying streams not included in our original sample. Several steps were taken to select variables for the final model: (1) Backwards elimination of variables (based on F-ratio P-value of 0.15, which is equivalent to reduction in Akaike Information Criteria) in separate DFA were performed using the 53 variables identified from the principal components analysis (PCA) and cluster analysis for each of the main groupings of indices: magnitude of flow events, frequency of flow events, duration of flow events, timing of flow events, and rate of change in flow events. (2) This led to a reduced set of variables that were then considered simultaneously in another DFA that used backward elimination of variables. The philosophy of this approach was to try and eliminate any residual redundancy while allowing all 5 types of indices to potentially contribute to the final model.

We also excluded indices that were dependent on peak flow records (FH11, DH23, TL4, TH3) if doing so did not reduce the classification accuracy. This allows streams without peak flow records to be classified. The final model included four flow magnitude variables (MA3, MA45, ML18, MH14), five frequency of flow variables (FL1, FL2, FH2, FH8, FH10), seven duration of flow variables (DL9, DL10, DL16, DL17, DH3 [standardized by DA], DH18, DH19), and three

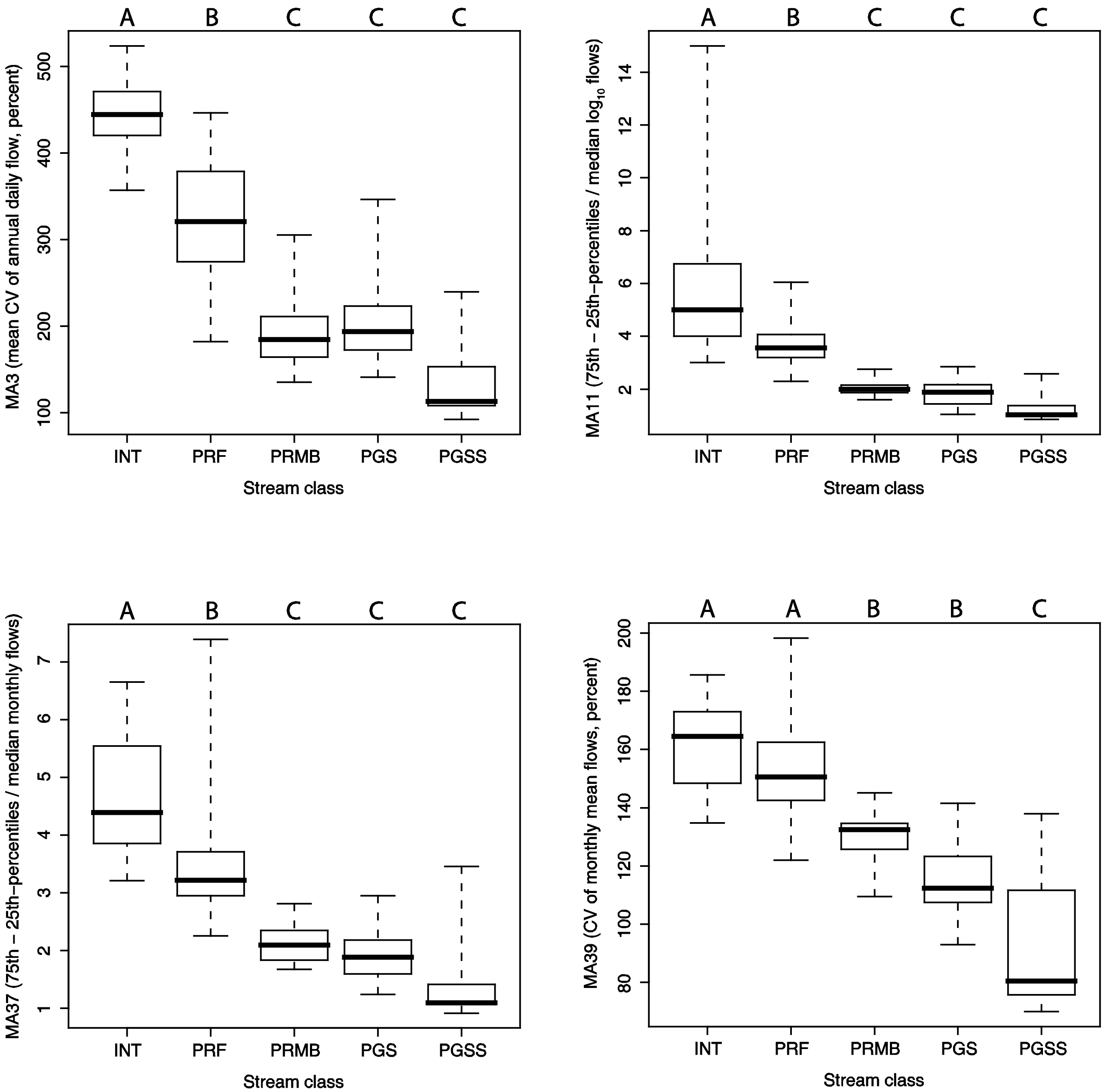

Figure 8. Box plots of selected flow magnitude indices (center line is median, box is 25^{th} to 75^{th} percentiles, and whiskers extend to minimum and maximum) that distinguish five stream types: intermittent (INT), perennial runoff–flashy (PRF), perennial runoff–moderate baseflow (PRMB), perennial groundwater–stable (PGS), and perennial groundwater–super stable (PGSS). Results of Tukey's test are represented by letters A through C; hydrologic indices with the letter A have the highest mean or median index score whereas hydrologic indices with letters B and C have successively lower index scores. Stream types with letters in common have means that do not differ significantly. Refer to appendix 2 for definitions of hydrologic indices. CV; coefficient of variation.

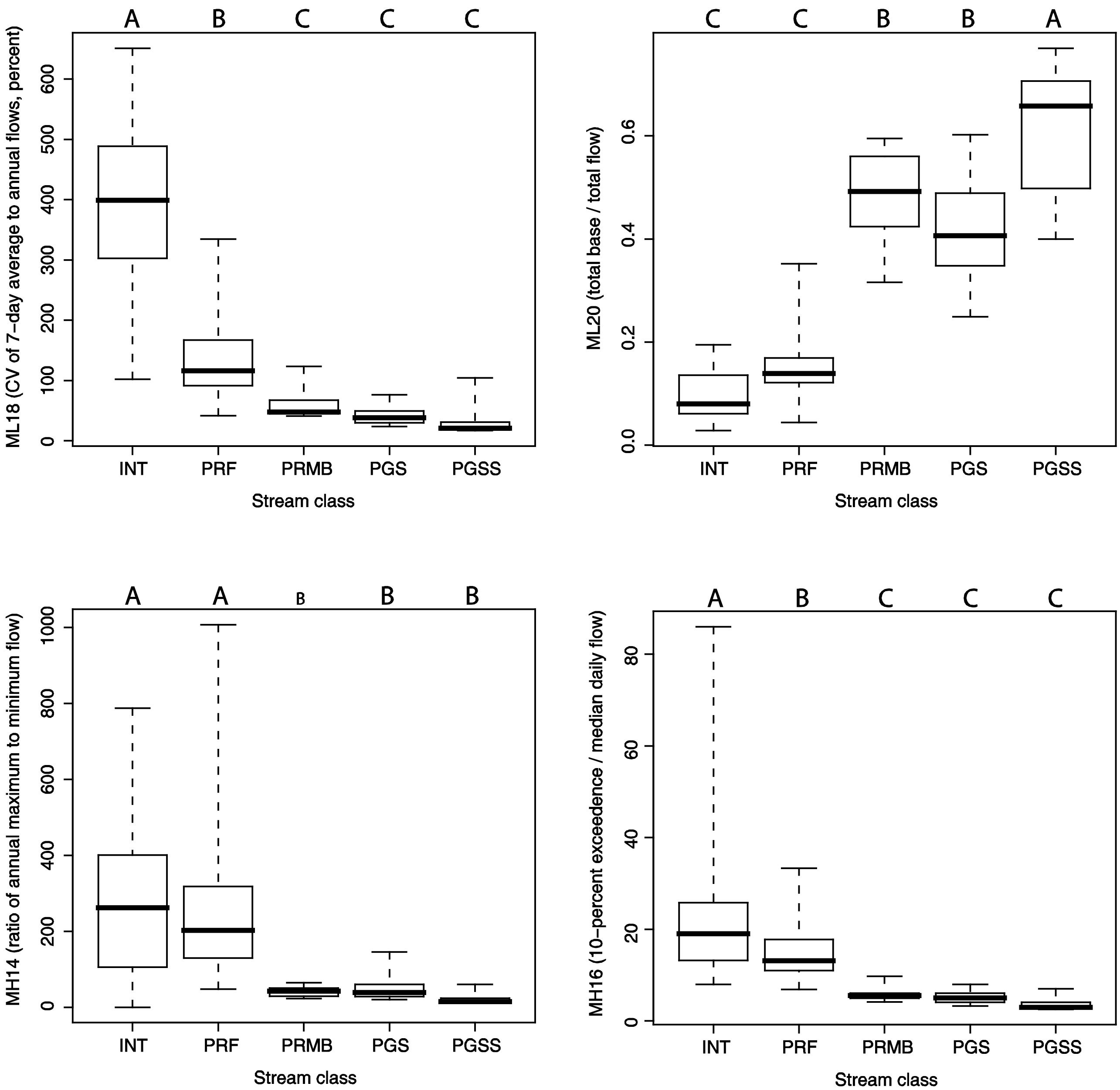

Figure 9. Box plots of selected low and high magnitude of flow indices (center line is median, box is 25th to 75th percentiles, and whiskers extend to minimum and maximum) that distinguish five stream types: intermittent (INT), perennial runoff–flashy (PRF), perennial runoff–moderate baseflow (PRMB), perennial groundwater–stable (PGS), and perennial groundwater–super stable (PGSS). Results of Tukey's test are represented by letters A through C; hydrologic indices with the letter A have the highest mean or median index score whereas hydrologic indices with letters B and C have successively lower index scores. Stream types with letters in common have means that do not differ significantly. Refer to appendix 2 for definitions of hydrologic indices. CV; coefficient of variation.

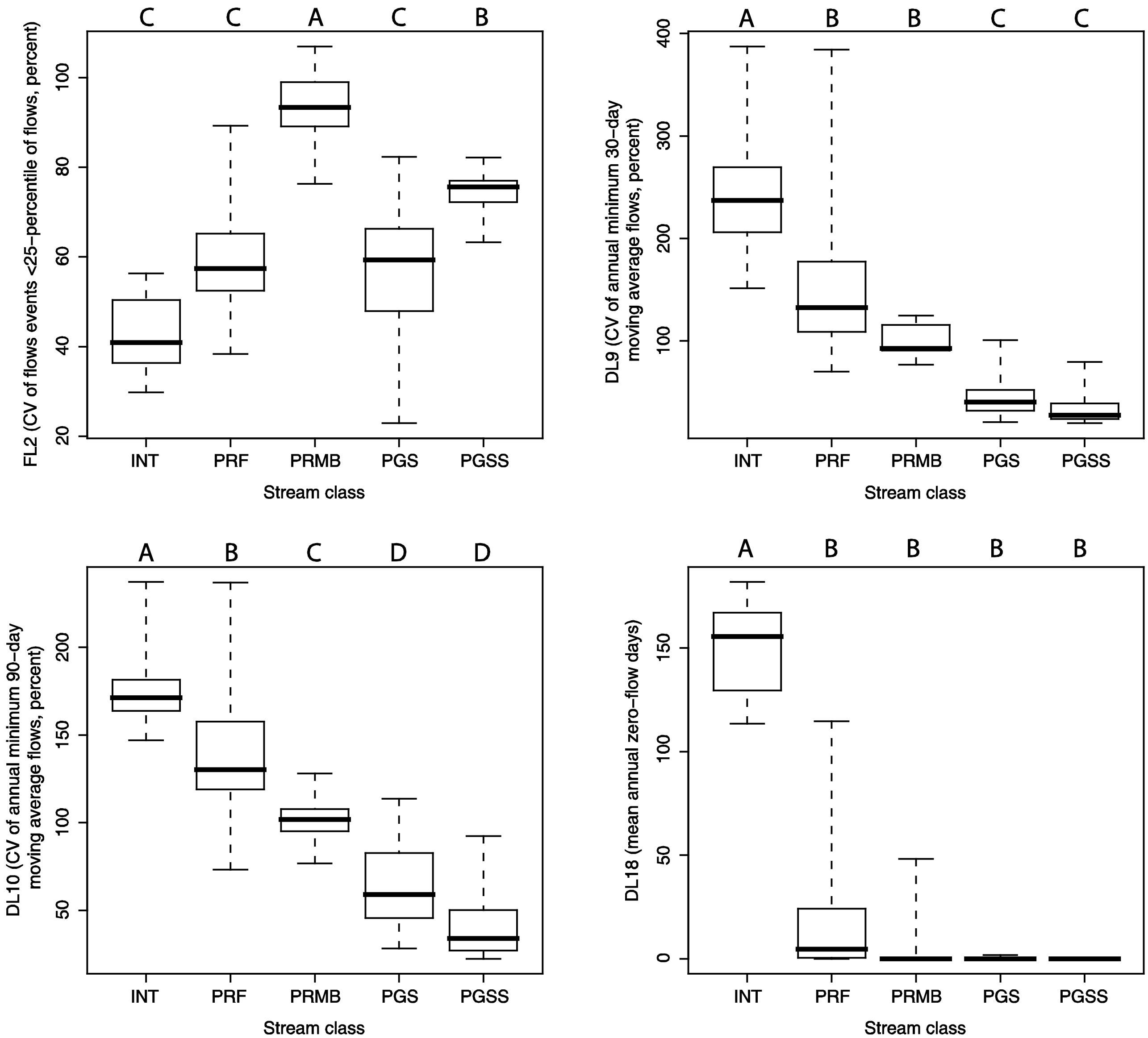

Figure 10. Box plots of selected frequency and duration of low flow indices (center line is median, box is 25th to 75th percentiles, and whiskers extend to minimum and maximum) that distinguish five stream types: intermittent (INT), perennial runoff–flashy (PRF), perennial runoff–moderate baseflow (PRMB), perennial groundwater–stable (PGS), and perennial groundwater–super stable (PGSS). Results of Tukey's test are represented by letters A through D; hydrologic indices with the letter A have the highest mean or median index score whereas hydrologic indices with letters B through D have successively lower index scores. Stream types with letters in common have means that do not differ significantly. Refer to appendix 2 for definitions of hydrologic indices. CV; coefficient of variation.

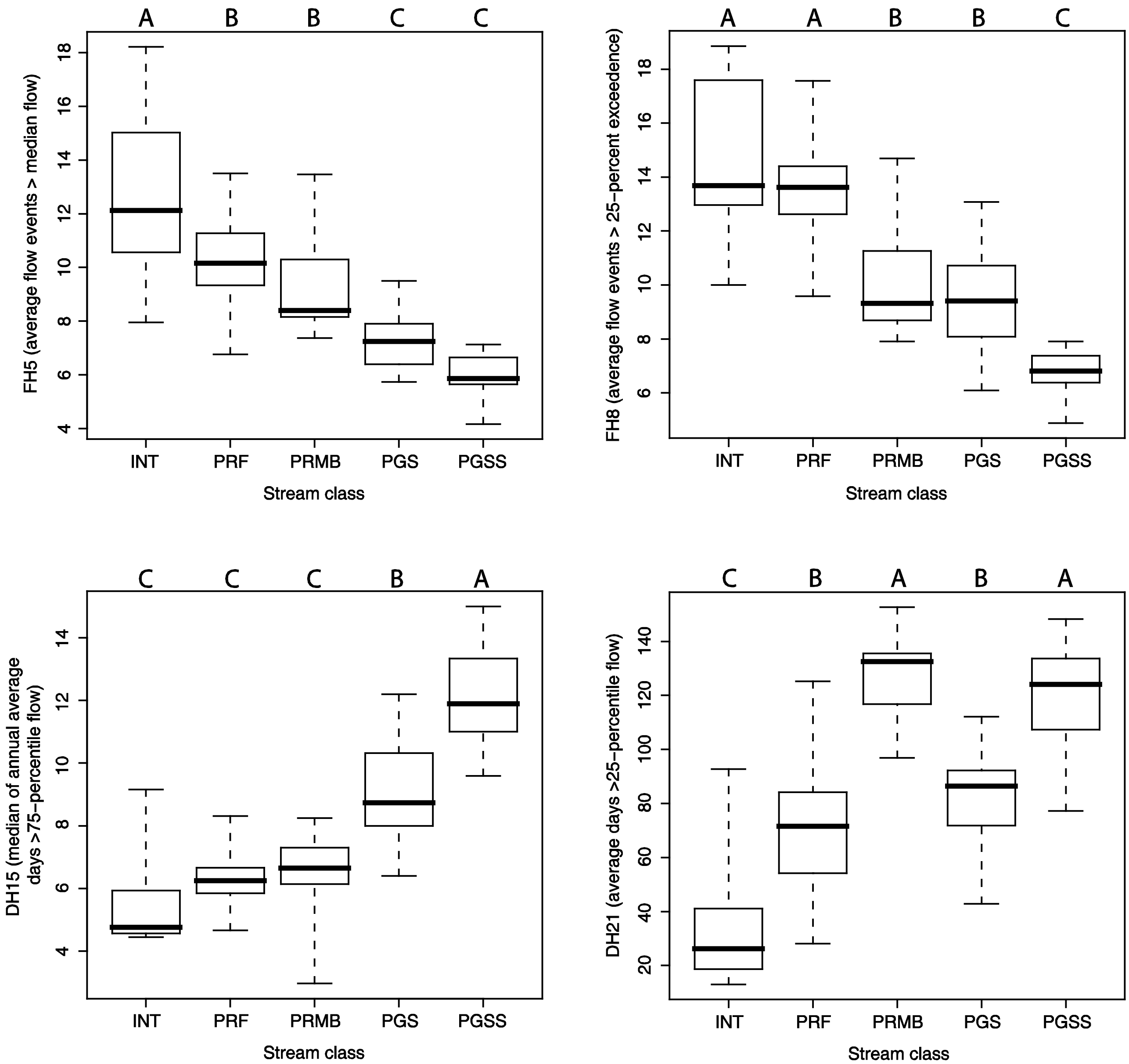

Figure 11. Box plots of selected frequency and duration of high flow indices (center line is median, box is 25th to 75th percentiles, and whiskers extend to minimum and maximum) that distinguish five stream types: intermittent (INT), perennial runoff–flashy (PRF), perennial runoff–moderate baseflow (PRMB), perennial groundwater–stable (PGS), and perennial groundwater–super stable (PGSS). Results of Tukey's test are represented by letters A through C; hydrologic indices with the letter A have the highest mean or median index score whereas hydrologic indices with letters B and C have successively lower index scores. Stream types with letters in common have means that do not differ significantly. Refer to appendix 2 for definitions of hydrologic indices.

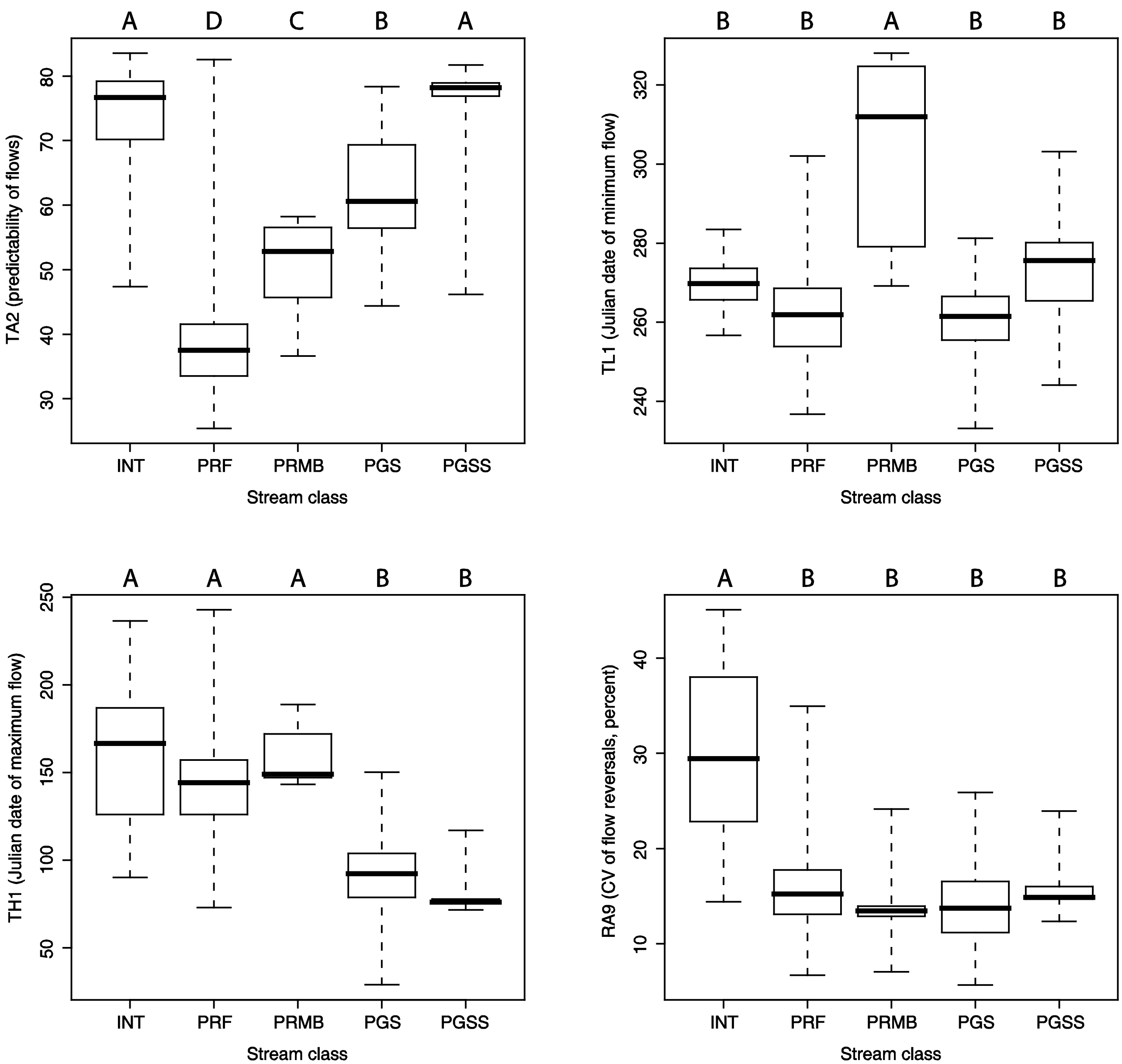

Figure 12. Box plots of selected timing and rate of change flow indices (center line is median, box is 25th to 75th percentiles, and whiskers extend to minimum and maximum) that distinguish five stream types: intermittent (INT), perennial runoff–flashy (PRF), perennial runoff–moderate baseflow (PRMB), perennial groundwater–stable (PGS), and perennial groundwater–super stable (PGSS). Results of Tukey's test are represented by letters A through D; hydrologic indices with the letter A have the highest mean or median index score whereas hydrologic indices with letters B through D have successively lower index scores. Stream types with letters in common have means that do not differ significantly. Refer to appendix 2 for definitions of hydrologic indices. CV; coefficient of variation.

timing of flow events (TA2, TL2, TH1). This model had an overall jackknifed classification accuracy of 99 percent (raw optimistic classification accuracy was also 99 percent) based on the final DFA with the 19 variables on n = 140 stream sites. Prior probabilities in the classification function were based on relative sample sizes of the 3 groups (n = 11 for intermittent, n = 82 for perennial runoff, and n = 47 for perennial groundwater).

Linear discriminant-function analyses (DFA) also were used to find a parsimonious model that best separated the means of the two subclasses of perennial runoff (flashy and moderate baseflow) streams in a multivariate space represented by the streamflow indices. Similar steps as above were taken to select variables for the final model. The final model included one flow magnitude variable (MA11), two frequency of flow indices (FL2, FH2), and three duration of flow indices (DL3 [standardized by drainage area], DL10, DH16). This model had an overall jackknifed classification accuracy of 100 percent (raw optimistic classification accuracy was 100 percent) based on the final DFA with the six variables on n = 82 stream sites classified as perennial runoff. Prior probabilities in the classification function were based on relative sample sizes of the two groups (n = 73 for flashy and n = 9 for moderate base flow).

Linear discriminant-function analyses (DFA) were used to find a parsimonious model that best separated the means of the two subclasses of perennial groundwater (stable and super stable) streams in a multivariate space represented by the streamflow indices. Similar steps as above were taken to select variables for the final model. The final model included two flow magnitude variables (MH13, MH18), four duration of flow indices (DL3 [standardized by DA], DL9, DH17, DH19) and two timing of flow indices (TA2, TH2). This model had an overall jackknifed classification accuracy of 96 percent (raw optimistic classification accuracy was 100 percent) based on the final DFA with the nine variables on n = 47 streams classified as perennial groundwater. Classification accuracy was lowest (78 percent) for the super stable subclass. Prior probabilities in the classification function were based on relative sample sizes of the two groups (n = 38 for stable, and n = 9 for super stable).

It is important to understand a limitation of the classification functions. Because the gages for harshly intermittent streams (n = 7) were not included in the classification analyses, any unclassified streams with harshly intermittent flow characteristics would not be classified reasonably with our discriminant-function classifications. The geographic locations for all classified gages is shown in figure 13, and for intermittent streams in figure 14, perennial runoff streams in figure 15, and perennial groundwater streams in figure 16.

Hydroecological Integrity Assessment Software

The Natural Flow Regime Paradigm (Poff and others, 1997) is the conceptual basis for the HIP (Henriksen and others, 2006; Kennen and others, 2007). As implemented here it evaluates the degree of alteration of 11 primary flow indices (out of a total of 171) that address the five major components of streamflow (Richter and others, 1997; Olden and Poff, 2003). Commonly, however, the "natural flow regime" is assumed to require a lengthy flow record pre-dating any anthropogenic water or land-use alteration. Such a period of record is rarely available and usually not necessary to apply the HIP tools. In most cases, the user will be limited to either an existing streamflow record or a synthesized period of record (synthesized hydrographs can be derived through flow modeling; Kennen and others, 2008) documenting the flow history. In addition, regardless of what POR is recommended (for example, Poff and others, 1997), the user should determine whether a stream's biotic integrity can be considered "healthy" or "acceptable" in its current condition or at some prior point in time for the available POR. If stream biotic integrity (user defined) is found to be acceptable, then the recent historic POR (alternatively, a time frame in the POR when the stream's integrity was considered acceptable) can be used as the baseline condition. Ultimately, the biotic condition of a stream reach should be derived from biological metrics from monitoring programs (for example, Missouri Department of

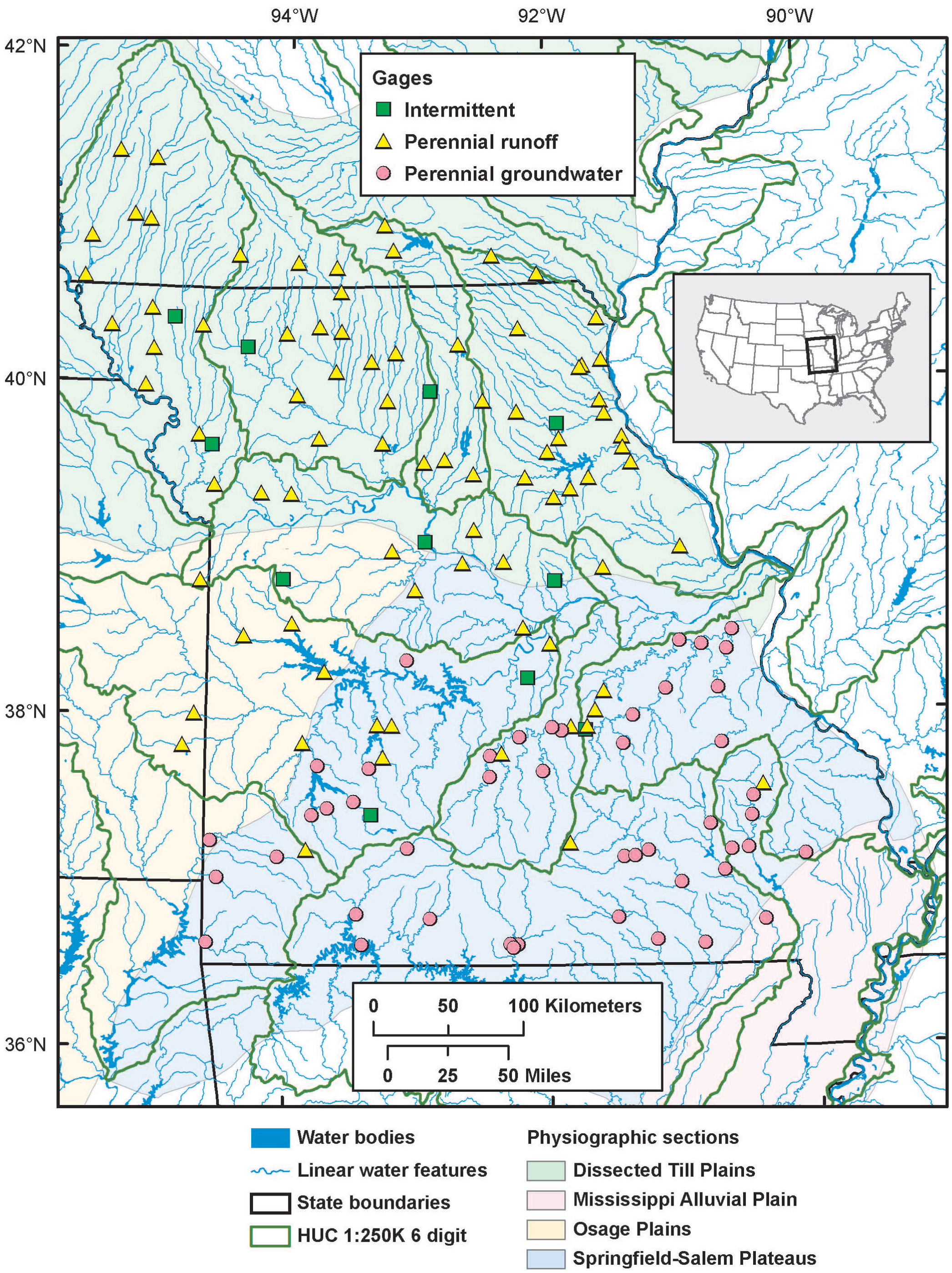

Figure 13. Location of physiographic sections and streamflow sites used to classify the three primary stream types in Missouri. Each symbol represents a U.S. Geological Survey streamflow-gaging station and is color coded to indicate a primary stream type as referenced in appendix 1.

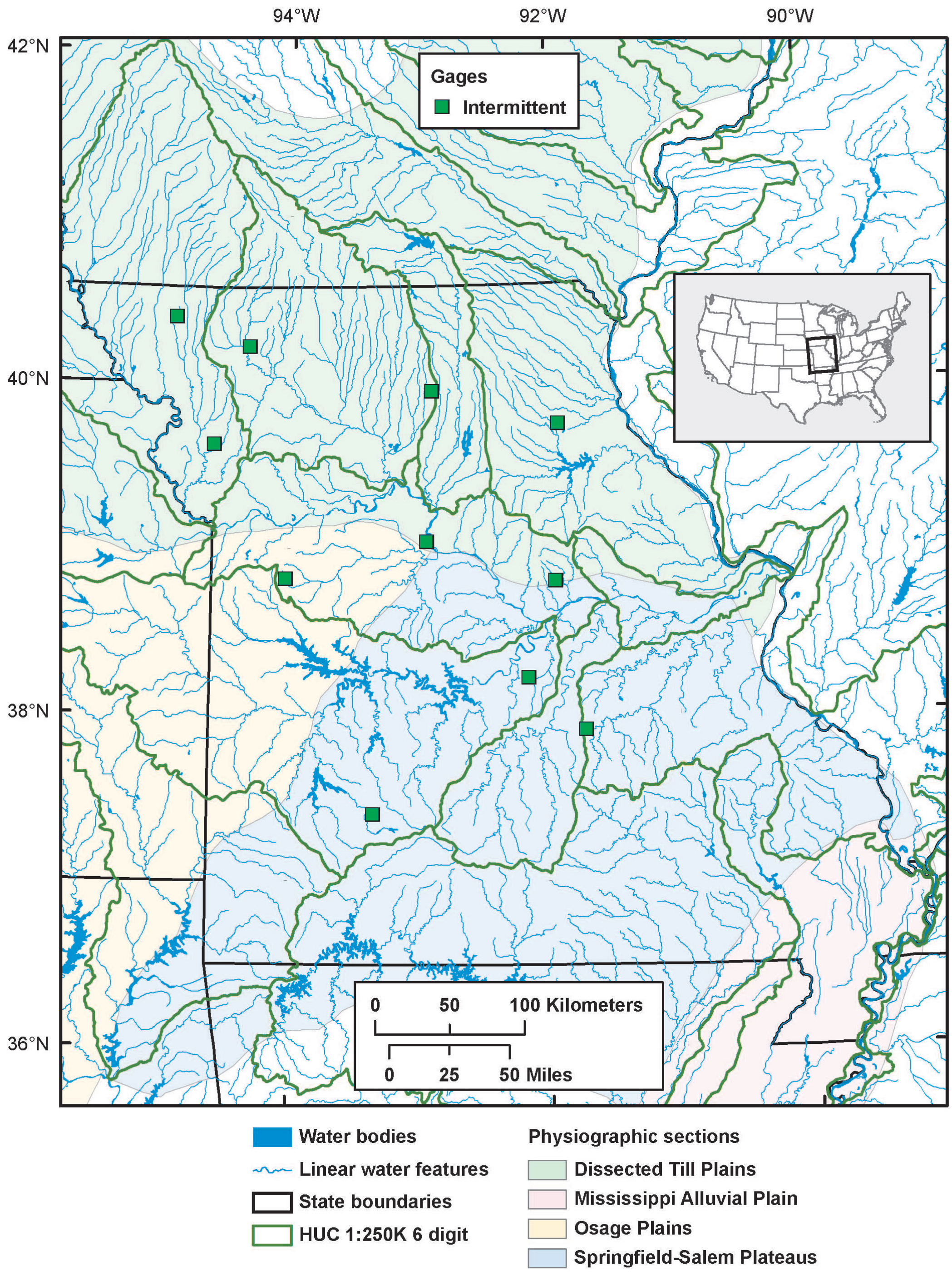

Figure 14. Location of physiographic sections and Missouri streamflow sites classified as intermittent. Each symbol represents a U.S. Geological Survey streamflow-gaging station and is coded (green square) indicating the stream was classified as intermittent based on cluster analysis. Refer to appendix 1 for stream names and gaging station characteristics.

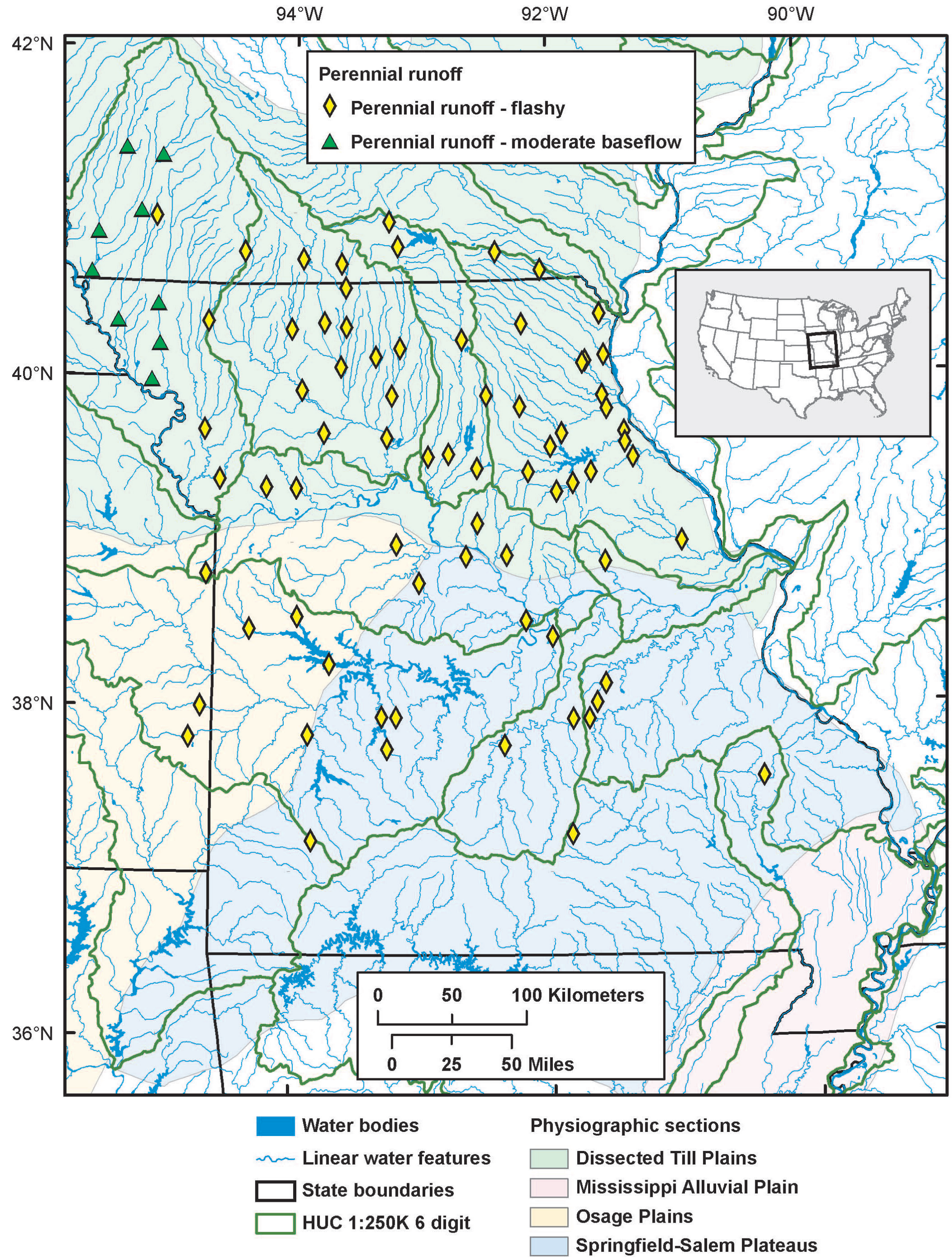

Figure 15. Location of physiographic sections and Missouri streamflow sites classified as perennial/runoff dominated. Each symbol represents a U.S. Geological Survey streamflow-gaging station and is coded to reflect the two perennial runoff subtypes: Perennial runoff–flashy (yellow diamonds); Perennial runoff–moderate baseflow (green triangles). Refer to appendix 1 for stream names and gaging station characteristics.

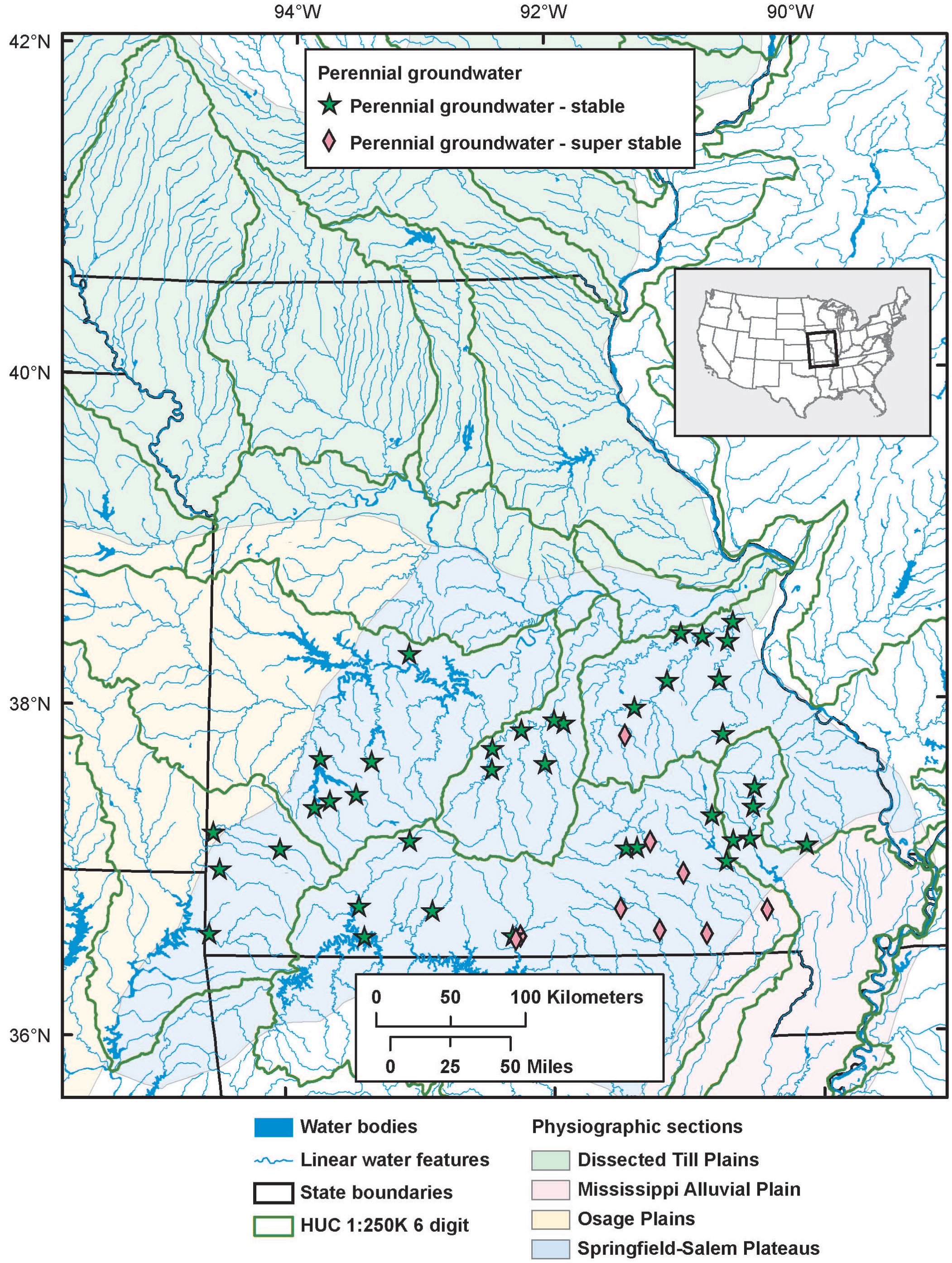

Figure 16. Location of physiographic sections and Missouri streamflow sites classified as perennial groundwater dominated. Each symbol represents a U.S. Geological Survey streamflow-gaging station and is coded to reflect the two perennial groundwater subtypes: Perennial groundwater–stable (green stars); Perennial groundwater–super stable (pink diamonds). Refer to appendix 1 for stream names and gaging station characteristics.

Natural Resources biological monitoring program, see Sarver and others, 2002) or rapid stream assessment tools (for example, U.S. Environmental Protection Agency's Rapid Assessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Bentic Macroinvertebrates, and Fish, see Barbour and others, 1999). Hereafter, the term baseline hydrologic condition will be used as a surrogate for the natural flow regime.

The primary purpose of the MOHAT (or any version of HAT developed for a specific State or geographic area) is to assist decision makers (water resource managers, planners, or regulatory agencies) with the comparison of baseline hydrologic conditions to either current conditions or proposed hydrologic changes through the evaluation of HRIs. HRIs account for characteristics of streamflow variability that are known to be 'biologically relevant', that is, they are important in shaping ecological processes in streams (Olden and Poff, 2003; Richter and others, 1997). The basic premise is that if one or more stream-type specific index is significantly altered due to past or proposed streamflow alterations, the alteration will have a significant effect, directly or indirectly, on biodiversity, physical processes, habitat, or production. It is anticipated that HRIs will be used by regulatory agencies to establish environmental flow standards and criteria that are assumed to protect, maintain, or restore stream biotic integrity.

MOHAT can be applied to an unlimited number of flow scenarios to assess the flow regime of the stream system that has been or is going to be altered. One possible application of MOHAT would be the assessment of a proposed or existing diversion (for example, water treatment facility intake, reservoir, or groundwater extraction) in a watershed. For a proposed diversion, the goal could be to establish environmental flow standards that address the 11 primary flow components (for example, Kennen and others, 2007 p. 15–23). In the case of an existing diversion, the purpose would be to determine if the agency established standard is being violated for any of the 11 primary indices derived using the HIP methodology. If so, operational changes could be recommended that limit the diversion and reduce or eliminate the violation(s). If not, then a moratorium could be placed on any future proposed flow alterations that would exacerbate existing violation(s). For either case, adaptive management (a type of natural resource management that implies making decisions as part of an on-going process) of environmental flows can be effectively applied for determining the ecologically compatible withdrawal rate necessary to protect biotic integrity (Richter and others, 2006).

MOHAT can be used to compare a variety of water development or hydrologic infrastructure scenarios by directly varying the streamflow and (or) the project's operating procedures. For example, if a proposed water development project consists of an intake on stream (x) and the facilities require (y) amount of water per day, an environmental flow standard could be established to meet the most stringent level (worst case scenario) or be adjusted monthly or seasonally to set flow regimes during the most ecologically sensitive time of the year (for example, during fish spawning or migration periods). The proposed diversion could also be adjusted to meet seasonal demands or the project could be revised to include storage that reduces reliance on diversions during specific times of the year.

Another application of the MOHAT is to evaluate the effects of anthropogenic changes that have occurred over a longer period of time for a given stream. Assuming that a stream-gaging record or a streamflow POR is available or can be developed for a fairly long period of time (for example > 20 years), MOHAT can be used to evaluate the effects that historical hydrologic alteration associated with land-use changes may have had during that time frame. This would provide managers and decision makers with the ability to compare the relative affects of differing approaches for proposed water-development projects which may allow for better management choices if streamflow restoration is warranted. MOHAT also can be used to evaluate trends in streamflow for the entire POR or for segments of the record. Again, such analysis can give the user a more comprehensive understanding of the variability in flow characteristics for the stream being investigated.

Establishing a Baseline Time Period

It is important to determine the appropriate baseline hydrological conditions so that the extent of alteration to the hydrology is accurate and environmental flow standards can be established. A hydrologic baseline represents the "relatively unimpaired" or "natural conditions" that embody natural flow variability (Poff and others, 1997) and represent the foundation of environmental flow management. In this document we take an approach that incorporates direct visual evaluation of stream hydrographs to identify least impaired streams or portions of the hydrograph that represent the least impaired time period. In addition, professional judgment incorporating extensive institutional knowledge was used to identify specific time periods or overlooked water development processes (including withdrawals, dams, diversions, and inter-basin transfers) in the POR that would affect the baseline conditions or skew the results of statistical comparisons. This worked well for this study, however, there are many other statistical processes and hydrologic criteria that can also be used to establish baseline hydrographs and we encourage other investigators to seek out and evaluate methods that are best suited for their watershed, region, Province, or State of interest. Such approaches could include modeling flow duration curves (Seelbach and Wiley, 1997; Wiley and others, 1998), quantile regression (Cade and Noon, 2003), hydrologic trends, the use of simulated hydrographs (Kennen and others, 2008), or regression approaches (Sanborn and Bledsoe, 2006; Stuckey, 2006) to identify hydrographic anomalies, hydrologic inflection points, statistical differences in trend-line slopes, back-projected baseline conditions using hydrologic modeling, or predicted stream baselines, respectively.

Establishing Environmental Flow Standards

The scientific field of "environmental flows" has resulted in greater than 207 "methods" that have been grouped into four categories: hydrological rules, hydraulic rating methods, habitat simulation methods, and holistic methodologies (Tharme, 2003). Many of these methods address arbitrary "minimum" flows and are recognized as being inadequate to protect freshwater biodiversity and maintain essential goods and services (Naiman and others, 2002; Postel and Richter, 2003). HIP is established based on the principles of hydroecology and the Natural Flow Regime paradigm (Poff and others, 1997), and to maintain biodiversity and overall stream integrity, it takes into account natural flow variability. This is achieved by addressing the magnitude, frequency, duration, timing, and rate of change for streamflow. However, translating hydrologic-ecological principles and knowledge into specific environmental flow standards remains a challenge (Poff and others, 2003).

Adaptive management is an example of a collaborative approach that has been used to address scientific uncertainties by implementing carefully planned long-term adaptive-management experiments and developing appropriate management actions (for example, Grand Canyon flow release, Rubin and others 2002; Snowy River flow restoration program, Pigram, 2000). In addition, adaptive management procedures have been successfully used in environmental flow restoration of impounded rivers with substantial flow control (Richter and others, 2006; see also TNCs Sustainable Rivers Program web page, accessed May 9, 2008 at: *http://www.nature.org/ success/dams.html*). It is yet to be seen, however, whether adaptive management processes can be used for management of short-term water-development projects or whether there is enough time in such circumstances to implement strategic, incremental actions to reduce policy uncertainties. Water managers are more commonly faced with the situation where no additional experimentation is possible, there is limited regulatory control of most flow processes except low flow, and once the proposed water development project is approved, there is no possibility to retract or amend the decision either through incremental revision or stakeholder participation without eliciting legal or regulatory concerns. It is apparent that due to the high risk of being unable to restore stream biodiversity and stream integrity once management options are foregone, and because in most situations time is of the essence, that stringent environmental flow standards should be given full consideration as early on in the process as possible.

Fortunately, a few approaches have been put forth to bridge the gap between simplistic hydrological low flow standards and long-term, empirically developed, environmental flow assessments.

As discussed in the "Stream Classification and Selection of Indices" section of this report, the first step for instituting environmental flow standards is to identify stream reaches considered to be in a non-impaired "healthy" condition. Ideally, biotic condition can be evaluated in these streams by using long-term biomonitoring or rapid assessment methods that address the status of environmental components deemed important by decision makers, that is, key aquatic assemblages, instream habitat, and biological and geomorphological processes. Once established, the management objective would be to protect, maintain, or restore the stream to a desired condition. Accordingly, the manager would use the 11 primary (or secondary) ecologically-relevant hydrologic indices from HIP that are associated with a specific stream type (that is, table 1). The 11 primary indices, however, may be supplemented or substituted with surrogate hydrologic indices that have been identified and in some cases validated with empirical biological data. For example, Kennen and Ayers (2002) established that hydrologic instability associated with urban development was significantly related to impairment of fish, invertebrate, and algae assemblages in New Jersey streams. Specifically, the 2-yr peak flow event was identified as accounting for a significant proportion of the variability in aquatic-assemblage structure (Kennen and Ayers, 2002). Thus, under a similar scenario for Missouri, flow index FH11 (that is, frequency of high flow events) could potentially be substituted for FH10 as the primary index for the intermittent stream type even though it was listed as a tertiary index in table 1. Likewise, FH11 is identified as a surrogate index for perennial runoff and perennial groundwater stream types in MOHAT (table 1), and therefore, based on empirical results, could justifiably be used to replace the primary index (FH8) for both stream types.

Richter and others (1997) recommended that environmental flow standards address hydrologic variability by suggesting that the mean or median (depending on the index in question) of selected hydroecologically relevant indices be maintained within the 25th to 75th percentile range. The 25th to 75th percentile was presented by Richter as a range in flow processes that could be used to maintain stream biotic integrity while still allowing some management flexibility to accommodate human uses. A water regulatory agency, however, has the option of using more restrictive standards which would be assumed to provide a higher level of protection of biotic integrity. For example, a 40th to a 60th percentile range would be narrower and therefore, would represent a more restrictive standard. Some HRIs available in MOHAT may have even broader regulatory applicability if the standards take into consideration dry, average, and wet water seasons or years. Hoffman and Rancan (2007) recommend a variety of possible flow statistics that can be generated by MOHAT as guidelines for setting low flow standards. For example, the statistics associated with MA12–23 (median monthly flow values) provide information on monthly median flows. The 25th percentile value represents a median flow which is exceeded three years out of four. These values could be used to set monthly flow standards. A flow standard based on the 25th percentile of median monthly flows would thus require more frequent reduction in withdrawals. Consider a similar standard associated with ML1–12 (monthly low flow values), for example, the 25th percentile value of ML1–12 would provide less protection of streamflow while requiring less frequent withdrawal reductions. The MOHAT provides for novel, flexible, and innovative approaches to selecting alternate indices (beyond the 11 primary indices identified in MOHAT) that allow water managers to apply meaningful and enforceable regulatory standards that take into consideration inherent natural hydrologic variability and presumably differences in level of assemblage impairment associated with that change in variability. This application requires, however, that the water managers analyze tradeoffs between reliability of the stream as a water source and greater protection of streamflow.

A holistic flow management approach that incorporates essential aspects of the natural flow variability shared among stream types was presented by Arthington and others (2006). This approach challenges water scientists to establish and validate thresholds for individual ecologically relevant hydrologic indices using empirical biological data from natural or "reference" streams and flow-altered streams. This validation process is not trivial. Arthington and others (2006) suggestion that flow-ecological response relations be developed for each ecological index across a gradient of reference flow regimes to modified flow regimes for each streamflow variable and stream type has not been done for Missouri streams. Therefore, the relations between ecological response and streamflow should be assumed to be highly variable due both to temporal and spatial scale differences among streamflow indices and ecological responses, and because factors other than streamflow may affect ecological responses. The HIP approach described in this report is based on the identification of specific stream types in Missouri and supports the recommendations proposed by Arthington and others (2006) for classifying streams based on key attributes of flow variability. Our approach attempts to balance the need for managing streams based on the unique hydrologic variability of specific stream types and on generalized ecological attributes (described herein as stream-type specific HRIs). Arthington and others (2006) describe a series of steps for characterizing streams and provide two critical "risk levels" or "benchmarks" which can be used to establish or guide the setting of environmental flow standards. This approach shows much promise in (1) validating the indices used to assess hydrologic alteration, and (2) refining the threshold and benchmark (risk level) standard.

Recently, a multi-authored paper by Poff and others (2009) was instrumental in outlining a unified framework for developing regional environmental flow standards called the Ecological Limits of Hydrologic Alteration (ELOHA; see also the ELOHA toolbox available at: *http://conserveonline.org/workspaces/eloha/*). ELOHA is designed to support comprehensive regional flow management and strives to synthesize available scientific information into ecologically based and socially acceptable goals and standards for management of environmental flows. A number of key steps are outlined to help environmental flow practitioners develop relations between flow alteration and ecological response. This includes: (1) building a sound hydrologic foundation of baseline hydrographs for ungaged streams using a flow modeling tool (for example, Kennen and others, 2008); (2) employing a set of ecologically relevant flow attributes to classify streams into distinctive flow regime types (for example, Olden and Poff, 2003; Kennen and others, 2007; Armstrong and others, 2008; Kennard and others, 2009); (3) determining the deviation of current-condition flows from baseline-condition flows (for example, Esralew and others, 2008); and (4) developing flow-ecological response relations for each stream type. The HIP is highly consistent with ELOHA and specifically incorporates steps one through three, however, step four is implied. Completion of the final step outlined in ELOHA of directly establishing relations between streamflow and ecological response is likely as elusive as establishing relations between aquatic habitat measures and ecological response (for example, Fayram and Mitro, 2008). It may be possible, however, to conduct such an analysis where overlapping ambient aquatic-assemblage data is available at classified stream sites. Once established, these relations can be further used to enhance the applicability of the HIP by providing stream-type specific empirical results to better guide the implementation of HAT indices. Ultimately, such relations will better inform water resource managers, planners, and policy makers on the best suite of HAT indices to use for setting environmental flow standards.

Summary

This report documents the application of the Hydroecological Integrity Assessment Process (HIP) in Missouri streams which includes a hydroecological classification of streams and the development of two custom-tailored software tools: MOSCT, for classifying previously unclassified Missouri streams; and, MOHAT for evaluating baseline (reference) time periods, conducting hydrologic-alteration analyses, evaluating past and proposed hydrologic modifications of streams, and establishing environmental-flow standards.

Previously developed HIT (for calculating 171 HRIs to aid in stream classification) and NATHAT (for doing nationally-based hydrologic assessment) are also discussed. Refer to Henriksen and others (2006) "Users' manual for the Hydroecological Integrity Assessment Process software" for a more thorough description of how these tools are applied. The HIP was specifically designed to assist State and watershed resource planners with making sound and scientifically defensible management decisions by providing reference points which can be used as a basis for comparing pre- and post-watershed conditions or evaluating the effects of planned water development projects (for example, Kennen and others, 2007). This procedure used a robust modeling approach that included multivariate techniques and incorporated more than two decades of hydroecological research. The methodology can be applied in any State, region, or Province where additional flow-based water management processes are needed. This methodology uses a hydroecological stratification of stream types and assumes that hydrology is the "master variable" that directly and indirectly affects the distribution and abundance of riverine species (Poff and others, 1997). However, the degree of linkage between the HRIs described in this report and the distribution and abundance of riverine species is largely unknown.

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Appendix 1. Stream type and characteristics of gaging stations representing relatively unimpaired basins used to classify Missouri streams.

[DA; drainage area, in square miles; INT, intermittent; PRF, perennial/runoff—flashy; PRMB, perennial/runoff—moderate baseflow; PGS, perennial/groundwater—stable; PGSS, perennial/groundwater—super stable; POR, period of record; Color-coded station numbers correspond to symbols in figure 13 that represent the three primary stream classes (intermittant, perennial runoff, and perennial groundwater]

Station number	Station name	DA	Stream type	Start date	End date	POR (years)
5503000	Oak Dale Branch near Emden, MO	3	INT	9/1/1955	10/2/1975	20.1
6820000	White Cloud Creek near Maryville, MO	6	INT	10/1/1948	7/31/1970	21.8
6821000	Jenkins Branch at Gower, MO	3	INT	5/1/1950	9/30/1976	26.4
6896500	Thompson Branch near Albany, MO	6	INT	10/1/1955	9/30/1972	17.0
6902500	Hamilton Branch near New Boston, MO	3	INT	10/1/1955	9/30/1972	17.0
6906600	Burge Branch near Arrow Rock, MO	1	INT	10/1/1959	9/30/1973	14.0
6907500	South Fork Blackwater River near Elm, MO	17	INT	6/1/1954	10/9/1979	25.4
6918700	Oak Grove Branch near Brighton, MO	1	INT	8/1/1956	9/30/1975	19.2
6926200	Van Cleve Branch near Meta, MO	1	INT	9/1/1956	9/30/1972	16.1
6927200	Big Hollow near Fulton, MO	4	INT	3/1/1957	9/30/1972	15.6
7011500	Green Acre Branch near Rolla, MO	1	INT	12/1/1947	9/30/1975	27.9
6925200	Starks Creek at Preston, MO	4	PRF	8/1/1956	10/26/1976	20.3
6928200	Laquey Branch near Hazlegreen, MO	2	PRF	6/1/1958	9/30/1972	14.3
7012000	Behmke Branch near Rolla, MO	1	PRF	8/1/1948	9/30/1959	11.2
7035500	Barnes Creek Near Fredericktown, MO	4	PRF	10/1/1955	11/6/1975	20.1
7185500	Stahl Creek near Miller, MO	4	PRF	7/1/1950	10/18/1976	26.3
5494300	Fox River at Bloomfield, IA	88	PRF	10/1/1957	9/30/1973	16.0
5494500	Fox River at Cantril, IA	161	PRF	8/28/1940	9/30/1951	11.1
5495000	Fox River at Wayland, MO	400	PRF	3/1/1922	9/30/1987	65.6
5496000	Wyaconda River above Canton, MO	393	PRF	10/1/1932	9/30/1972	40.0
5497000	North Fabius River at Monticello, MO	452	PRF	3/1/1922	9/30/2004	82.6
5497500	Middle Fabius River near Baring, MO	185	PRF	10/1/1935	9/30/1960	25.0
5498000	Middle Fabius River near Monticello, MO	393	PRF	10/1/1945	9/30/2004	59.0
5500000	South Fabius River near Taylor, MO	620	PRF	1/1/1935	9/30/2004	69.8

5501000	North River at Palmyra, MO	373	PRF	1/1/1935	9/30/2004	69.8
5502000	Bear Creek at Hannibal, MO	31	PRF	10/1/1938	9/30/1959	21.0
5502300	Salt River at Hagers Grove, MO	365	PRF	9/1/1974	9/30/2004	30.1
5503500	Salt River near Hunnewell, MO	626	PRF	4/1/1931	9/30/1940	9.5
5503800	Crooked Creek near Paris, MO	80	PRF	10/1/1979	9/30/2004	25.0
5505000	South Fork Salt River at Santa Fe, MO	298	PRF	10/1/1939	9/30/1968	29.0
5506000	Youngs Creek near Mexico, MO	67	PRF	10/1/1936	6/30/1982	35.0
5506800	Elk Fork Salt River near Madison, MO	200	PRF	10/1/1968	9/30/2004	36.0
5507600	Lick Creek at Perry, MO	104	PRF	10/1/1979	9/30/2004	25.0
5508805	Spencer Ck below Plum Creek near Frankford, MO	206	PRF	1/6/1976	9/30/2004	27.4
5514500	Cuivre River near Troy, MO	903	PRF	3/1/1922	9/30/2004	53.0
6818750	Platte River near Diagonal, IA	217	PRF	4/1/1968	9/30/1991	23.5
6818900	Platte River at Ravenwood, MO	486	PRF	9/1/1958	9/30/1971	12.2
6893080	Blue River near Stanley, KS	46	PRF	9/20/1974	9/30/1985	11.0
6894500	East Fork Fishing River at Excelsior Springs, MO	20	PRF	2/1/1951	11/30/1972	21.8
6895000	Crooked River near Richmond, MO	159	PRF	3/1/1948	9/30/1970	22.6
6897000	East Fork Big Creek near Bethany, MO	95	PRF	4/1/1934	9/30/1971	37.5
6897950	Elk Creek near Decatur City, IA	53	PRF	10/1/1967	9/30/1994	27.0
6898100	Thompson Rover at Mount Moriah, MO	891	PRF	9/1/1960	9/30/1977	17.1
6898400	Weldon River near Leon, IA	104	PRF	10/1/1958	9/30/1991	33.0
6898500	Weldon River near Mercer, MO	246	PRF	10/1/1939	9/30/1959	20.0
6899000	Weldon River at Mill Grove, MO	494	PRF	4/3/1929	9/30/1972	43.5
6899700	Shoal Creek near Braymer, MO	391	PRF	10/1/1957	10/19/1977	20.1
6900000	Medicine Creek near Galt, MO	225	PRF	10/1/1921	12/31/1990	67.2
6901000	Locust Creek near Milan, MO	225	PRF	10/1/1921	9/30/1933	12.0
6901500	Locust Creek near Linneus, MO	550	PRF	4/1/1929	9/30/2004	47.5
6903400	Chariton River near Chariton, IA	182	PRF	10/1/1965	9/30/2004	39.0
6903700	South Fork Chariton River near Promise City, IA	168	PRF	10/1/1967	9/30/2004	37.0
6906000	Mussel Fork near Musselfork, MO	267	PRF	10/1/1962	9/30/1989	27.0
6906150	Long Branch Creek near Atlanta, MO	23	PRF	7/7/1995	9/30/2004	9.2
6907000	Lamine River at Clifton City, MO	598	PRF	7/1/1922	9/30/1971	49.3
6908000	Blackwater River at Blue Lick, MO	1,120	PRF	7/1/1922	9/30/2004	68.6
6909500	Moniteau Creek near Fayette, MO	81	PRF	4/1/1948	9/30/1968	20.5
6910000	Petite Saline Creek near Boonville, MO	182	PRF	4/1/1948	9/30/1967	19.5
6910230	Hinkson Creek at Columbia, MO	70	PRF	10/1/1966	9/30/1980	14.0
6910750	Moreau River near Jefferson City, MO	561	PRF	12/1/1947	9/30/1973	25.8

6917000	Little Osage River at Fulton, KS	295	PRF	11/9/1948	9/30/2004	55.9
6917380	Marmaton River near Marmaton, KS	292	PRF	5/1/1971	9/30/2000	29.4
6919500	Cedar Creek near Pleasant View, MO	420	PRF	4/22/1923	9/30/2004	19.0
6921200	Lindley Creek near Polk, MO	112	PRF	5/1/1957	9/30/2004	43.4
6921500	Pomme De Terre River at Hermitage, MO	655	PRF	10/1/1921	9/30/1958	37.0
6921590	South Grand River at Archie, MO	356	PRF	10/1/1969	10/9/1986	17.0
6921720	Big Creek near Blairstown, MO	414	PRF	8/1/1960	10/8/1974	14.2
6922000	South Grand River near Brownington, MO	1,660	PRF	7/24/1921	9/30/1971	50.2
6927000	Maries River at Westphalia, MO	257	PRF	1/1/1948	9/30/1969	21.8
6931500	Little Beaver Creek near Rolla, MO	6	PRF	12/1/1947	9/30/1975	27.9
6935500	Loutre River at Mineola, MO	202	PRF	12/1/1947	9/30/1967	19.8
7015000	Bourbeuse River near St. James, MO	21	PRF	11/26/1947	1/13/1982	34.2
7015720	Bourbeuse River near High Gate, MO	135	PRF	7/1/1965	9/30/2004	37.3
7064500	Big Creek near Yukon, MO	8	PRF	6/1/1949	10/15/1975	26.4
5508000	Salt River near New London, MO	2,480	PRF	10/1/1922	9/30/1977	55.0
6811840	Tarkio River at Stanton, IA	49	PRF	10/1/1957	9/30/1991	34.0
6820500	Platte River near Agency, MO	1,760	PRF	10/1/1924	9/30/2004	77.6
6821150	Little Platte River at Smithville, MO	234	PRF	6/1/1965	9/30/1977	12.3
6897500	Grand River near Gallatin, MO	2,250	PRF	10/1/1920	9/30/2004	84.1
6899500	Thompson River at Trenton, MO	1,720	PRF	10/1/1928	9/30/2004	76.0
6902000	Grand River near Sumner, MO	6,880	PRF	10/1/1924	9/30/2004	80.1
6904500	Chariton River at Novinger, MO	1,370	PRF	10/1/1930	9/30/1967	37.0
6905500	Chariton River near Prairie Hill, MO	1,870	PRF	4/9/1929	9/30/1967	38.5
6906300	East Fork Little Chariton River near Huntsville, MO	220	PRF	10/1/1962	9/30/1976	14.0
6807410	West Nishnabotna River at Hancock, IA	609	PRMB	10/1/1959	9/30/2004	45.0
6808500	West Nishnabotna River at Randolph, IA	1,326	PRMB	6/1/1948	9/30/2004	56.4
6809210	East Nishnabotna River near Atlantic, IA	436	PRMB	10/1/1960	9/30/2004	44.0
6809500	East Nishnabotna River at Red Oak, IA	894	PRMB	10/1/1937	9/30/2004	67.0
6810000	Nishnabotna River above Hamburg, IA	2,806	PRMB	10/1/1929	9/30/2004	75.0
6813000	Tarkio River at Fairfax, MO	508	PRMB	4/1/1922	12/31/1990	68.8
6816000	Mill Creek at Oregon, MO	5	PRMB	8/1/1950	9/30/1976	26.2
6817500	Nodaway River near Burlington Junction, MO	1,240	PRMB	4/1/1922	10/28/1983	61.6
6817700	Nodaway River near Graham, MO	1,380	PRMB	10/22/1982	9/30/2004	20.0
6922800	Big Buffalo Creek near Stover, MO	24	PGS	3/1/1965	9/30/1977	11.7
6919000	Sac River near Stockton, MO	1,160	PGS	7/21/1921	9/30/1966	45.2
7186000	Spring River near Waco, MO	1,164	PGS	4/25/1924	9/30/2004	80.5

6918740	Little Sac River near Morrisville, MO	237	PGS	9/1/1968	9/30/2004	32.1
6921070	Pomme de Terre River near Polk, MO	276	PGS	10/1/1968	9/30/2004	32.0
6927800	Osage Fork Gasconade River at Drynob, MO	404	PGS	8/1/1962	12/11/1981	19.4
6928000	Gasconade River near Hazelgreen, MO	1,250	PGS	10/1/1928	9/30/1970	42.0
6928500	Gasconade River near Waynesville, MO	1,680	PGS	10/1/1914	10/6/1971	57.1
6930000	Big Piney River near Big Piney, MO	560	PGS	10/1/1921	9/30/1982	61.0
6933500	Gasconade River at Jerome, MO	2,840	PGS	4/12/1925	9/30/2004	79.0
7013000	Meramec River near Steelville, MO	781	PGS	10/1/1922	9/30/2004	82.1
7014500	Meramec River near Sullivan, MO	1,475	PGS	10/1/1921	9/30/2004	73.1
7016500	Bourbeuse River at Union, MO	808	PGS	6/7/1921	9/30/2004	69.4
7017000	Meramec River at Robertsville, MO	2,673	PGS	10/1/1939	9/30/1951	12.0
7017200	Big River at Irondale, MO	175	PGS	7/1/1965	9/30/2004	39.3
7018100	Big River near Richwoods, MO	735	PGS	4/28/1949	9/30/2004	53.5
7018500	Big River at Byrnesville, MO	917	PGS	5/10/1922	9/30/2004	80.4
7019000	Meramec River near Eureka, MO	3,788	PGS	10/1/1903	9/30/2004	53.0
7021000	Castor River at Zalma, MO	423	PGS	1/1/1920	9/30/2004	75.9
7035800	St. Francis River near Mill Creek, MO	505	PGS	2/5/1987	9/30/2004	15.7
7036100	St. Francis River near Saco, MO	664	PGS	6/10/1983	9/30/1997	14.3
7037500	St. Francis River near Patterson, MO	956	PGS	6/16/1921	9/30/1939	18.3
7037700	Clark Creek near Piedmont, MO	4	PGS	10/1/1956	9/30/1976	20.0
7050580	James River near Strafford, MO	165	PGS	10/1/1973	11/3/1986	13.1
7052500	James River at Galena, MO	987	PGS	10/1/1921	9/30/1960	39.0
7053000	White River near Reeds Spring, MO	3,617	PGS	3/1/1938	9/30/1952	14.6
7054080	Beaver Creek at Bradleyville, MO	298	PGS	7/23/1994	9/30/2004	10.0
7061500	Black River near Annapolis, MO	484	PGS	3/23/1939	9/30/1961	22.5
7065495	Jacks Fork at Alley Spring, MO	298	PGS	3/25/1993	9/30/2004	11.5
7189000	Elk River near Tiff City, MO	872	PGS	10/1/1939	9/30/2004	65.0
6918440	Sac River near Dadeville, MO	257	PGS	6/1/1966	9/30/2004	34.4
6918460	Turnback Creek above Greenfield, MO	252	PGS	9/1/1965	9/30/2004	35.1
6932000	Little Piney Creek at Newburg, MO	200	PGS	11/1/1928	9/30/2004	76.0
7058000	Bryant Creek near Tecumseh, MO	570	PGS	10/1/1944	9/30/2004	50.2
7063000	Black River at Poplar Bluff, MO	1,245	PGS	10/1/1936	9/30/1946	10.0
7066000	Jacks Fork at Eminence, MO	398	PGS	11/1/1921	9/30/2004	83.0
7185700	Spring River at Larussell, MO	306	PGS	5/1/1957	12/31/1981	23.0
7187000	Shoal Creek above Joplin, MO	427	PGS	10/1/1941	9/30/2004	63.0
7010350	Meramec River at Cook Station, MO	199	PGSS	10/1/1965	1/15/1982	16.3

7070500	Eleven Point River near Thomasville, MO	361	PGSS	10/1/1950	11/9/1976	26.1
7057500	North Fork River near Tecumseh, MO	561	PGSS	10/1/1944	9/30/2004	60.0
7058500	North Fork River at Tecumseh, MO	1,157	PGSS	10/1/1921	9/30/1941	20.0
7062500	Black River at Leeper, MO	987	PGSS	6/15/1921	9/30/1946	25.3
7066500	Current River Near Eminence, MO	1,272	PGSS	8/24/1921	3/18/1976	54.6
7067000	Current River at Van Buren, MO	1,667	PGSS	6/18/1921	9/30/2004	83.3
7068000	Current River at Doniphan, MO	2,038	PGSS	6/14/1921	9/30/2004	83.4
7071500	Eleven Point River near Bardley, MO	793	PGSS	10/1/1921	9/30/2004	83.1

Appendix 2. Definitions for the 171 Hydrologic Indices

Explanation—The following information for the 171 hydrologic indices is from Olden and Poff (2003). The USGS revised a limited number of the formulas and (or) definitions when deemed appropriate for a given study (for example, MA6, MA7, and MA8). The Olden and Poff (2003) article contains 12 additional references from which the indices were derived. Two of these articles are referenced here (Colwell, 1974; Poff, 1996) because they provide examples and additional explanation for complex indices.

The alphanumeric code preceding each definition refers to the category of the flow regime (magnitude, frequency, duration, timing, and rate of change) and type of flow event (A, average; L, low; and H, high) the hydrologic index was developed to describe. Indices are numbered successively within each category. For example, MA1 is the first index describing magnitude of the average flow condition.

Following each definition, in parentheses, are (1) the units of the index, and (2) the type of data, temporal or spatial data, from which the upper and lower percentiles limits (for example, 75/25) are derived. Temporal data are from a multiyear daily flow record from a single stream gage. For example, index MA1, mean for the entire flow record, uses 365 mean daily flow values for each year in the flow record to calculate the mean for the entire flow record. Consequently, there are 365 values for each year to calculate upper and lower percentile limits. However, formulas for 60 of the indices do not produce a range of values from which percentile limits can be calculated. MA5 (skewness), for example, the mean for the entire flow record divided by the median for the entire record results in a single value, and thus, upper and lower percentile limits cannot be directly calculated. MOHAT uses available spatial data, values for each stream gage for all the streams within a stream type, to compute limits. Upper and lower percentile limits are calculated, for example, from the 38 MA3 values from the 38 stream-gage sites that were identified from the classification analysis as perennial groundwater–stable (see appendix 1).

Exceedence and percentile are used in the calculation for a number of indices. Note the difference; a 90 percent exceedence means that 90 percent of the values are equal to or greater than the 90 percent exceedence value, while a 90th percentile means that 10 percent of the values are equal to or greater than the 90th percentile value.

MA#	Magnitude, average flow event
ML#	Magnitude, low flow event
MH#	Magnitude, high flow event
FL#	Frequency, low flow event
FH#	Frequency, high flow event
DL#	Duration, low flow event
DH#	Duration, high flow event
TA#	Timing, average flow event
TL#	Timing, low flow event
TH#	Timing, high flow event
RA#	Rate of change, average event

Code	Definition
MA1	Mean of the daily mean flow values for the entire flow record (cubic feet per second–temporal).
MA2	Median of the daily mean flow values for the entire flow record (cubic feet per second–temporal).
MA3[3]	Mean (or median–Use Preference option) of the coefficients of variation (standard deviation/mean) for each year. Compute the coefficient of variation for each year of daily flows. Compute the mean of the annual coefficients of variation (percent–temporal).
MA4	Standard deviation of the percentiles of the entire flow record divided by the mean of percentiles. Compute the 5th, 10th, 15th, 20th, 25th, 30th, 35th, 40th, 45th, 50th, 55th, 60th, 65th, 70th, 75th, 80th, 85th, 90th, and 95th percentiles for the entire flow record. Percentiles are computed by interpolating between the ordered (ascending) flow values. Compute the standard deviation and mean for the percentile values. Divide the standard deviation by the mean to get MA4. (percent–spatial)
MA5	The skewness of the entire flow record is computed as the mean for the entire flow record (MA1) divided by the median (MA2) for the entire flow record (dimensionless–spatial).
MA6	Range in daily flows is the ratio of the 10-percent to 90-percent exceedence values for the entire flow record. Compute the 5-percent to 95-percent exceedence values for the entire flow record. Exceedence is computed by interpolating between the ordered (descending) flow values. Divide the 10-percent exceedence value by the 90-percent value (dimensionless–spatial).
MA7	Range in daily flows is computed like MA6 except using the 20-percent and 80-percent exceedence values. Divide the 20-percent exceedence value by the 80-percent value (dimensionless–spatial).
MA8	Range in daily flows is computed like MA6 except using the 25-percent and 75-percent exceedence values. Divide the 25-percent exceedence value by the 75-percent exceedence value (dimensionless–spatial).
MA9	Spread in daily flows is the ratio of the difference between the 90th and 10th percentile of the flow data to median of the entire flow record. Compute the 5th, 10th, 15th, 20th, 25th, 30th, 35th, 40th, 45th, 50th, 55th, 60th, 65th, 70th, 75th, 80th, 85th, 90th, and 95th percentiles for the entire flow record. Percentiles are computed by interpolating between the ordered (ascending) flow values. Compute MA9 as (90th–10th) /MA2 (dimensionless–spatial).
MA10	Spread in daily flows is computed like MA9 except using the 20th and 80th percentiles (dimensionless–spatial).
MA11[3]	Spread in daily flows is computed like MA9 except using the 25th and 75th percentiles (dimensionless–spatial).
MA12–MA23	Means (or medians–Use Preference option) of monthly flow values. Compute the means for each month over the entire flow record. For example, MA12 is the mean of all January flow values over the entire record (cubic feet per second–temporal).
MA24–MA35[3]	Variability (coefficient of variation) of monthly flow values. Compute the Standard deviation for each month in each year over the entire flow record. Divide the standard deviation by the mean for each month. Average (or median–Use Preference option) these values for each month across all years (percent– temporal).

Code	Definition
MA36	Variability across monthly flows. Compute the minimum, maximum, and mean flows for each month in the entire flow record. MA36 is the maximum monthly flow minus the minimum monthly flow divided by the median monthly flow (dimensionless–spatial).
MA37[3]	Variability across monthly flows. Compute the first (25th percentile) and the third (75th percentile) quartiles (every month in the flow record). MA37 is the third quartile minus the first quartile divided by the median of the monthly means (dimensionless–spatial).
MA38	Variability across monthly flows. Compute the 10th and 90th percentiles for the monthly means (every month in the flow record). MA38 is the 90th percentile minus the 10th percentile divided by the median of the monthly means (dimensionless–spatial).
MA39[3]	Variability across monthly flows. Compute the standard deviation for the monthly means. MA39 is the standard deviation times 100 divided by the mean of the monthly means (percent–spatial).
MA40	Skewness in the monthly flows. MA40 is the mean of the monthly flow means minus the median of the monthly means divided by the median of the monthly means (dimensionless–spatial).
MA41	Annual runoff. Compute the annual mean daily flows. MA41 is the mean of the annual means divided by the drainage area (cubic feet per second/square mile–temporal).
MA42[3]	Variability across annual flows. MA42 is the maximum annual flow minus the minimum annual flow divided by the median of mean annual flows (dimensionless–spatial).
MA43[3]	Variability across annual flows. Compute the first (25th percentile) and third (75th percentile) quartiles and the 10th and 90th percentiles for the annual means (every year in the flow record). MA43 is the third quartile minus the first quartile divided by the median of the annual means (dimensionless–spatial).
MA44[3]	Variability across annual flows. Compute the first (25th percentile) and third (75th percentile) quartiles and the 10th and 90th percentiles for the annual means (every year in the flow record). MA44 is the 90th percentile minus the 10th percentile divided by the median of the annual means (dimensionless–spatial).
MA45[3]	Skewness in the annual flows. MA45 is the mean of the annual flow means minus the median of the annual means divided by the median of the annual means (dimensionless–spatial).
ML1–ML12	Mean (or median–Use Preference option) minimum flows for each month across all years. Compute the minimum daily flow for each month over the entire flow record. For example, ML1 is the mean of the minimums of all January flow values over the entire record (cubic feet per second–temporal).
ML13	Variability (coefficient of variation) across minimum monthly flow values. Compute the mean and standard deviation for the minimum monthly flows over the entire flow record. ML13 is the standard deviation times 100 divided by the mean minimum monthly flow for all years (percent-spatial).
ML14	Mean of annual minimum annual flows. ML14 is the mean of the ratios of minimum annual flows to the median flow for each year (dimensionless–temporal).
ML15	Low flow index. ML15 is the mean (or median–Use Preference option) of the ratios of minimum annual flows to the mean flow for each year (dimensionless–temporal).
ML16	Median of annual minimum flows. ML16 is the median of the ratios of minimum annual flows to the median flow for each year (dimensionless–temporal).

Code	Definition
ML17	Base flow. Compute the mean annual flows. Compute the minimum of a 7-day moving average flow for each year and divide them by the mean annual flow for that year. ML17 is the mean (or median–Use Preference option) of those ratios (dimensionless–temporal).
ML18[3]	Variability in base flow index 1. Compute the standard deviation for the ratios of minimum 7-day moving average flows to mean annual flows for each year. ML18 is the standard deviation times 100 divided by the mean of the ratios. (percent–spatial)
ML19	Base flow. Compute the ratios of the minimum annual flow to mean annual flow for each year. ML19 is the mean (or median–Use Preference option) of these ratios times 100 (dimensionless–temporal).
ML20[3]	Base flow. Divide the daily flow record into 5-day blocks. Find the minimum flow for each block. Assign the minimum flow as a base flow for that block if 90 percent of that minimum flow is less than the minimum flows for the blocks on either side. Otherwise, set it to zero. Fill in the zero values using linear interpolation. Compute the total flow for the entire record and the total base flow for the entire record. ML20 is the ratio of total base flow to total flow (dimensionless–spatial).
ML21	Variability across annual minimum flows. Compute the mean and standard deviation for the annual minimum flows. ML21 is the standard deviation times 100 divided by the mean (percent–spatial).
ML22	Specific mean annual minimum flow. ML22 is the mean (or median–Use Preference option) of the annual minimum flows divided by the drainage area (cubic feet per second/square mile–temporal).
MH1–MH12	Mean (or median–Use Preference option) maximum flows for each month across all years. Compute the maximum daily flow for each month over the entire flow record. For example, MH1 is the mean of the maximums of all January flow values over the entire record (cubic feet per second–temporal).
MH13[3]	Variability (coefficient of variation) across maximum monthly flow values. Compute the mean and standard deviation for the maximum monthly flows over the entire flow record. MH13 is the standard deviation times 100 divided by the mean maximum monthly flow for all years (percent–spatial).
MH14[3]	Median of annual maximum flows. Compute the annual maximum flows from monthly maximum flows. Compute the ratio of annual maximum flow to median annual flow for each year. MH14 is the median of these ratios (dimensionless–temporal).
MH15	High flow discharge index. Compute the 1-percent exceedence value for the entire data record. MH15 is the 1-percent exceedence value divided by the median flow for the entire record (dimensionless–spatial).
MH16[3]	High flow discharge index. Compute the 10-percent exceedence value for the entire data record. MH16 is the 10-percent exceedence value divided by the median flow for the entire record (dimensionless–spatial).
MH17	High flow discharge index. Compute the 25-percent exceedence value for the entire data record. MH17 is the 25-percent exceedence value divided by the median flow for the entire record (dimensionless–spatial).
MH18[3]	Variability across annual maximum flows. Compute the logs ($\log_{10}$) of the maximum annual flows. Find the standard deviation and mean for these values. MH18 is the standard deviation

Code	Definition
	times 100 divided by the mean (percent–spatial).
MH19[3]	Skewness in annual maximum flows. Use the equation: $$MH19 = \frac{N^2 \times sum(qm^3) - 3N \times sum(qm) \times sum(qm^2) + 2 \times (sum(qm))^3}{N \times (N-1) \times (N-2) \times stddev^3}$$ Where: N = Number of years qm = Log_{10} (annual maximum flows) stddev = Standard deviation of the annual maximum flows (dimensionless-spatial).
MH20	Specific mean annual maximum flow. MH20 is the mean (or median–Use Preference option) of the annual maximum flows divided by the drainage area (cubic feet per second/square mile–temporal).
MH21	High flow volume index. Compute the average volume for flow events above a threshold equal to the median flow for the entire record. MH21 is the average volume divided by the median flow for the entire record (days–temporal).
MH22	High flow volume. Compute the average volume for flow events above a threshold equal to three times the median flow for the entire record. MH22 is the average volume divided by the median flow for the entire record (days–temporal).
MH23	High flow volume. Compute the average volume for flow events above a threshold equal to seven times the median flow for the entire record. MH23 is the average volume divided by the median flow for the entire record (days–temporal).
MH24	High peak flow. Compute the average peak flow value for flow events above a threshold equal to the median flow for the entire record. MH24 is the average peak flow divided by the median flow for the entire record (dimensionless–temporal).
MH25	High peak flow. Compute the average peak-flow value for flow events above a threshold equal to three times the median flow for the entire record. MH25 is the average peak flow divided by the median flow for the entire record (dimensionless–temporal).
MH26	High peak flow. Compute the average peak flow value for flow events above a threshold equal to seven times the median flow for the entire record. MH26 is the average peak flow divided by the median flow for the entire record (dimensionless–temporal).
MH27	High peak flow. Compute the average peak flow value for flow events above a threshold equal to 75th percentile value for the entire flow record. MH27 is the average peak flow divided by the median flow for the entire record (dimensionless–temporal).
FL1[3]	Low flood pulse count. Compute the average number of flow events with flows below a threshold equal to the 25th percentile value for the entire flow record. FL1 is the average (or median–Use Preference option) number of events (number of events/year–temporal).
FL2[3]	Variability in low pulse count. Compute the standard deviation in the annual pulse counts for FL1. FL2 is 100 times the standard deviation divided by the mean pulse count (percent–spatial).
FL3	Frequency of low pulse spells. Compute the average number of flow events with flows below a threshold equal to 5 percent of the mean flow value for the entire flow record. FL3 is the average (or median–Use Preference option) number of events (number of events/year–temporal).
FH1	High flood pulse count. Compute the average number of flow events with flows above a threshold

Code	Definition
	equal to the 75th percentile value for the entire flow record. FH1 is the average (or median–Use Preference option) number of events (number of events/year–temporal).
FH2[3]	Variability in high pulse count. Compute the standard deviation in the annual pulse counts for FH1. FH2 is 100 times the standard deviation divided by the mean pulse count (number of events/year–spatial).
FH3	High flood pulse count. Compute the average number of days per year that the flow is above a threshold equal to three times the median flow for the entire record. FH3 is the mean (or median–Use Preference option) of the annual number of days for all years (number of days/year–temporal).
FH4	High flood pulse count. Compute the average number of days per year that the flow is above a threshold equal to seven times the median flow for the entire record. FH4 is the mean (or median - Use Preference option) of the annual number of days for all years (number of days/year–temporal).
FH5[3]	Flood frequency. Compute the average number of flow events with flows above a threshold equal to the median flow value for the entire flow record. FH5 is the average (or median - Use Preference option) number of events (number of events/year–temporal).
FH6	Flood frequency. Compute the average number of flow events with flows above a threshold equal to three times the median flow value for the entire flow record. FH6 is the average (or median–Use Preference option) number of events (number of events/year–temporal).
FH7	Flood frequency. Compute the average number of flow events with flows above a threshold equal to seven times the median flow value for the entire flow record. FH7 is the average (or median–Use Preference option) number of events (number of events/year–temporal).
FH8[3]	Flood frequency. Compute the average number of flow events with flows above a threshold equal to 25-percent exceedence value for the entire flow record. FH8 is the average (or median–Use Preference option) number of events (number of events/year–temporal).
FH9	Flood frequency. Compute the average number of flow events with flows above a threshold equal to 75-percent exceedence value for the entire flow record. FH9 is the average (or median–Use Preference option) number of events (number of events/year–temporal).
FH10[3]	Flood frequency. Compute the average number of flow events with flows above a threshold equal to median of the annual minima for the entire flow record. FH10 is the average (or median–Use Preference option) number of events (number of events/year–temporal).
FH11[1,3]	Flood frequency. Compute the average number of flow events with flows above a threshold equal to flow corresponding to a 1.67-year recurrence interval. FH11 is the average (or median–Use Preference option) number of events (number of events/year–temporal).
DL1	Annual minimum daily flow. Compute the minimum 1-day average flow for each year. DL1 is the mean (or median–Use Preference option) of these values (cubic feet per second–temporal).
DL2	Annual minimum of 3-day moving average flow. Compute the minimum of a 3-day moving average flow for each year. DL2 is the mean (or median–Use Preference option) of these values (cubic feet per second–temporal).
DL3[3]	Annual minimum of 7-day moving average flow. Compute the minimum of a 7-day moving average flow for each year. DL3 is the mean (or median–Use Preference option) of these values (cubic feet per second–temporal).
DL4	Annual minimum of 30-day moving average flow. Compute the minimum of a 30-day moving average flow for each year. DL4 is the mean (or median–Use Preference option) of these values

Code	Definition
	(cubic feet per second–temporal).
DL5	Annual minimum of 90-day moving average flow. Compute the minimum of a 90-day moving average flow for each year. DL5 is the mean (or median–Use Preference option) of these values (cubic feet per second–spatial).
DL6	Variability of annual minimum daily average flow. Compute the standard deviation for the minimum daily average flow. DL6 is 100 times the standard deviation divided by the mean (percent–spatial).
DL7	Variability of annual minimum of 3-day moving average flow. Compute the standard deviation for the minimum 3-day moving averages. DL7 is 100 times the standard deviation divided by the mean (percent–spatial).
DL8	Variability of annual minimum of 7-day moving average flow. Compute the standard deviation for the minimum 7-day moving averages. DL8 is 100 times the standard deviation divided by the mean (percent–spatial).
DL9[3]	Variability of annual minimum of 30-day moving average flow. Compute the standard deviation for the minimum 30-day moving averages. DL9 is 100 times the standard deviation divided by the mean (percent–spatial).
DL10[3]	Variability of annual minimum of 90-day moving average flow. Compute the standard deviation for the minimum 90-day moving averages. DL10 is 100 times the standard deviation divided by the mean (percent–spatial).
DL11	Annual minimum daily flow divided by the median for the entire record. Compute the minimum daily flow for each year. DL11 is the mean of these values divided by the median for the entire record (dimensionless–temporal).
DL12	Annual minimum of 7-day moving average flow divided by the median for the entire record. Compute the minimum of a 7-day moving average flow for each year. DL12 is the mean of these values divided by the median for the entire record (dimensionless–temporal).
DL13	Annual minimum of 30-day moving average flow divided by the median for the entire record. Compute the minimum of a 30-day moving average flow for each year. DL13 is the mean of these values divided by the median for the entire record (dimensionless–temporal).
DL14	Low exceedence flows. Compute the 75-percent exceedence value for the entire flow record. DL14 is the exceedence value divided by the median for the entire record (dimensionless–spatial).
DL15	Low exceedence flows. Compute the 90-percent exceedence value for the entire flow record. DL15 is the exceedence value divided by the median for the entire record (dimensionless–spatial).
DL16[3]	Low flow pulse duration. Compute the average pulse duration for each year for flow events below a threshold equal to the 25th percentile value for the entire flow record. DL16 is the median of the yearly average durations (number of days–temporal).
DL17[3]	Variability in low pulse duration. Compute the standard deviation for the yearly average low pulse durations. DL17 is 100 times the standard deviation divided by the mean of the yearly average low pulse durations (percent–spatial).
DL18[3]	Number of zero-flow days. Count the number of zero-flow days for the entire flow record. DL18 is the mean (or median–Use Preference option) annual number of zero flow days (number of days/year–temporal).

Code	Definition
DL19	Variability in the number of zero-flow days. Compute the standard deviation for the annual number of zero-flow days. DL19 is 100 times the standard deviation divided by the mean annual number of zero-flow days (percent–spatial).
DL20	Number of zero-flow months. While computing the mean monthly flow values, count the number of months in which there was no flow over the entire flow record (percent–spatial).
DH1	Annual maximum daily flow. Compute the maximum of a 1-day moving average flow for each year. DH1 is the mean (or median–Use Preference option) of these values (cubic feet per second–temporal).
DH2	Annual maximum of 3-day moving average flows. Compute the maximum of a 3-day moving average flow for each year. DH2 is the mean (or median–Use Preference option) of these values (cubic feet per second–temporal).
DH3[3]	Annual maximum of 7-day moving average flows. Compute the maximum of a 7-day moving average flow for each year. DH3 is the mean (or median–Use Preference option) of these values (cubic feet per second–temporal).
DH4	Annual maximum of 30-day moving average flows. Compute the maximum of 30-day moving average flows. Compute the maximum of a 30-day moving average flow for each year. DH4 is the mean (or median–Use Preference option) of these values (cubic feet per second–temporal).
DH5	Annual maximum of 90-day moving average flows. Compute the maximum of a 90-day moving average flow for each year. DH5 is the mean (or median–Use Preference option) of these values (cubic feet per second–temporal).
DH6[3]	Variability of annual maximum daily flows. Compute the standard deviation for the maximum 1-day moving averages. DH6 is 100 times the standard deviation divided by the mean (percent–spatial).
DH7	Variability of annual maximum of 3-day moving average flows. Compute the standard deviation for the maximum 3-day moving averages. DH7 is 100 times the standard deviation divided by the mean (percent–spatial).
DH8	Variability of annual maximum of 7-day moving average flows. Compute the standard deviation for the maximum 7-day moving averages. DH8 is 100 times the standard deviation divided by the mean (percent–spatial).
DH9	Variability of annual maximum of 30-day moving average flows. Compute the standard deviation for the maximum 30-day moving averages. DH9 is 100 times the standard deviation divided by the mean (percent–spatial).
DH10	Variability of annual maximum of 90-day moving average flows. Compute the standard deviation for the maximum 90-day moving averages. DH10 is 100 times the standard deviation divided by the mean (percent–spatial).
DH11	Annual maximum of 1-day moving average flows divided by the median for the entire record. Compute the maximum of a 1-day moving average flow for each year. DH11 is the mean of these values divided by the median for the entire record (dimensionless–temporal).
DH12	Annual maximum of 7-day moving average flows divided by the median for the entire record. Compute the maximum daily average flow for each year. DH12 is the mean of these values divided by the median for the entire record (dimensionless–spatial).

Code	Definition
DH13	Annual maximum of 30-day moving average flows divided by the median for the entire record. Compute the maximum of a 30-day moving average flow for each year. DH13 is the mean of these values divided by the median for the entire record (dimensionless–temporal).
DH14	Flood duration. Compute the mean of the mean monthly flow values. Find the 95th percentile for the mean monthly flows. DH14 is the 95th percentile value divided by the mean of the monthly means (dimensionless–spatial).
DH15[3]	High flow pulse duration. Compute the average duration for flow events with flows above a threshold equal to the 75th percentile value for each year in the flow record. DH15 is the median of the yearly average durations (days/year–temporal).
DH16[3]	Variability in high flow pulse duration. Compute the standard deviation for the yearly average high pulse durations. DH16 is 100 times the standard deviation divided by the mean of the yearly average high pulse durations (percent–spatial).
DH17[3]	High flow duration. Compute the average duration of flow events with flows above a threshold equal to the median flow value for the entire flow record. DH17 is the average (or median–Use Preference option) duration of the events (days–temporal).
DH18[3]	High flow duration. Compute the average duration of flow events with flows above a threshold equal to three times the median flow value for the entire flow record. DH18 is the average (or median - Use Preference option) duration of the events (days–temporal).
DH19[3]	High flow duration. Compute the average duration of flow events with flows above a threshold equal to seven times the median flow value for the entire flow record. DH19 is the average (or median–Use Preference option) duration of the events (days–temporal).
DH20	High flow duration. Compute the 75th percentile value for the entire flow record. Compute the average duration of flow events with flows above a threshold equal to the 75th percentile value for the median annual flows. DH20 is the average (or median–Use Preference option) duration of the events (days–temporal).
DH21[3]	High flow duration. Compute the 25th percentile value for the entire flow record. Compute the average duration of flow events with flows above a threshold equal to the 25th percentile value for the entire set of flows. DH21 is the average (or median–Use Preference option) duration of the events (days–temporal).
DH22[1,3]	Flood interval. Compute the flood threshold as the flow equivalent for a flood recurrence of 1.67 years. Determine the median number of days between flood events for each year. DH22 is the mean (or median–Use Preference option) of the yearly median number of days between flood events (days–temporal).
DH23[1,3]	Flood duration. Compute the flood threshold as the flow equivalent for a flood recurrence of 1.67 years. Determine the number of days each year that the flow remains above the flood threshold. DH23 is the mean (or median–Use Preference option) of the number of flood days for years in which floods occur (days–temporal).
DH24[1,3]	Flood-free days. Compute the flood threshold as the flow equivalent for a flood recurrence of 1.67 years. Compute the maximum number of days that the flow is below the threshold for each year. DH24 is the mean (or median–Use Preference option) of the maximum yearly no-flood days (days–temporal).

Code	Definition
TA1	Constancy. Constancy is computed via the formulation of Colwell (see example in Colwell, 1974). A matrix of values is compiled where the rows are 11 flow categories and the columns are 365 (no February 29th) days of the year. The cell values are the number of times that a flow falls into a category on each day. The categories are: log(flow) < 0.1 × log(mean flow), 0.1 × log(mean flow) ≤log(flow) < 0.25 × log(mean flow) 0.25 × log(mean flow) ≤log(flow) < 0.5 × log(mean flow) 0.5 × log(mean flow) ≤log(flow) < 0.75 × log(mean flow) 0.75 × log(mean flow) ≤log(flow) < 1.0 × log(mean flow) 1.0 × log(mean flow) ≤log(flow) < 1.25 × log(mean flow) 1.25 × log(mean flow) ≤log(flow) < 1.5 × log(mean flow) 1.5 × log(mean flow) ≤log(flow) < 1.75 × log(mean flow) 1.75 × log(mean flow) ≤log(flow) < 2.0 × log(mean flow) 2.0 ×log(mean flow) ≤log(flow) < 2.25 × log(mean flow) log(flow) ≥2.25 × log(mean flow) The row totals, column totals, and grand total are computed. Using the equations for Shannon information theory parameters, constancy is computed as: $1 - \frac{\text{(uncertainty with respect to state)}}{\log \text{(number of state)}}$ (dimensionless–spatial).
TA2[3]	Predictability. Predictability is computed from the same matrix as constancy (see example in Colwell, 1974). It is computed as: $1 - \frac{\text{(uncertainty with respect to interaction of time and state - uncertainty with respect to time}}{\log \text{(number of state)}}$ (dimensionless–spatial).
TA3[1,3]	Seasonal predictability of flooding. Divide years up into 2-month periods (that is, Oct-Nov, Dec-Jan, and so forth). Count the number of flood days (flow events with flows > 1.67-year flood) in each period over the entire flow record. TA3 is the maximum number of flood days in any one period divided by the total number of flood days (dimensionless–temporal).
TL1[3]	Julian date of annual minimum. Determine the Julian date that the minimum flow occurs for each water year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date (Julian day–spatial).
TL2[3]	Variability in Julian date of annual minima. Compute the coefficient of variation for the mean x and y components and convert to a date (Julian day–spatial).
TL3[2,3]	Seasonal predictability of low flow. Divide years up into 2-month periods (that is, Oct-Nov, Dec-Jan, and so forth). Count the number of low flow events (flow events with flows ≤5 year flood threshold) in each period over the entire flow record. TL3 is the maximum number of low flow events in any one period divided by the total number of low flow events (dimensionless–spatial).
TL4[2,3]	Seasonal predictability of non-low flow. Compute the number of days that flow is above the 5-year flood threshold as the ratio of number of days to 365 or 366 (leap year) for each year. TL4 is the maximum of the yearly ratios (dimensionless–spatial).
TH1[3]	Julian date of annual maximum. Determine the Julian date that the maximum flow occurs for each year. Transform the dates to relative values on a circular scale (radians or degrees). Compute the x

Code	Definition
	and y components for each year and average them across all years. Compute the mean angle as the arc tangent of y-mean divided by x-mean. Transform the resultant angle back to Julian date (Julian day–spatial).
TH2[3]	Variability in Julian date of annual maxima. Compute the coefficient of variation for the mean x and y components and convert to a date (Julian days–spatial).
TH3[1,3]	Seasonal predictability of nonflooding. Computed as the maximum proportion of a 365-day year that the flow is less than the 1.67-year flood threshold and also occurs in all years. Accumulate nonflood days that span all years. TH3 is maximum length of those flood-free periods divided by 365 (dimensionless–spatial).
RA1	Rise rate. Compute the change in flow for days in which the change is positive for the entire flow record. RA1 is the mean (or median–Use Preference option) of these values (cubic feet per second/day–temporal).
RA2	Variability in rise rate. Compute the standard deviation for the positive flow changes. RA2 is 100 times the standard deviation divided by the mean (percent–spatial).
RA3	Fall rate. Compute the change in flow for days in which the change is negative for the entire flow record. RA3 is the mean (or median–Use Preference option) of these values (cubic feet per second/day–temporal).
RA4[3]	Variability in fall rate. Compute the standard deviation for the negative flow changes. RA4 is 100 times the standard deviation divided by the mean (percent–spatial).
RA5[3]	Number of day rises. Compute the number of days in which the flow is greater than the previous day. RA5 is the number of positive gain days divided by the total number of days in the flow record (dimensionless–spatial).
RA6	Change of flow. Compute the $\log_{10}$ of the flows for the entire flow record. Compute the change in log of flow for days in which the change is positive for the entire flow record. RA6 is the median of these values (cubic feet per second–temporal).
RA7	Change of flow. Compute the $\log_{10}$ of the flows for the entire flow record. Compute the change in log of flow for days in which the change is negative for the entire flow record. RA7 is the median of these log values (cubic feet per second/day–temporal).
RA8[3]	Number of reversals. Compute the number of days in each year when the change in flow from one day to the next changes direction. RA8 is the average (or median - Use Preference option) of the yearly values (days–temporal).
RA9[3]	Variability in reversals. Compute the standard deviation for the yearly reversal values. RA9 is 100 times the standard deviation divided by the mean (percent–spatial).

[1]Note:1.67-year flood threshold (Olden and Poff, 2003)–For indices FH11, DH22, DH23, DH24, TA3, and TH3, compute the $\log_{10}$ of the peak annual flows. Compute the $\log_{10}$ of the daily flows for the peak annual flow days. Calculate the coefficients for a linear regression equation for logs of peak annual flow versus logs of average daily flow for peak days. Using the log peak flow for the 1.67-year recurrence interval (60th percentile) as input to the regression equation, predict the $\log_{10}$ of the average daily flow. The threshold is 10 to the $\log_{10}$ (average daily flow) power (cubic feet per second).

[2]Note:5-year flood threshold (Olden and Poff, 2003)–For TL3 and TL4, compute the $\log_{10}$ of the peak annual flows. Compute the $\log_{10}$ of the daily flows for the peak annual flow days. Calculate the coefficients for a linear regression equation for logs of peak annual flow versus logs of average daily flow for peak days. Using the log peak flow for the 5-year recurrence interval (80th percentile) as input to the regression equation; predict the $\log_{10}$ of the average daily flow. The threshold is 10 to the $\log_{10}$ (average daily flow) power (cubic feet per second).

[3]The 53 most significant HRIs identified through PCA and redundancy analysis.

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