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CLASSIFICATION OF REACHES IN THE MISSOURI AND LOWER YELLOWSTONE RIVERS BASED ON FLOW CHARACTERISTICS

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ABSTRACT

Several aspects of flow have been shown to be important determinants of biological community structure and function in streams, yet direct application of this approach to large rivers has been limited. Using a multivariate approach, we grouped flow gauges into hydrologically similar units in the Missouri and lower Yellowstone Rivers and developed a model based on flow variability parameters that could be used to test hypotheses about the role of flow in determining aquatic community structure. This model could also be used for future comparisons as the hydrological regime changes. A suite of hydrological parameters for the recent, post-impoundment period (1 October 1966–30 September 1996) for each of 15 gauges along the Missouri and lower Yellowstone Rivers were initially used. Preliminary graphical exploration identified five variables for use in further multivariate analyses. Six hydrologically distinct units composed of gauges exhibiting similar flow characteristics were then identified using cluster analysis. Discriminant analyses identified the three most influential variables as flow per unit drainage area, coefficient of variation of mean annual flow, and flow constancy. One surprising result was the relative similarity of flow regimes between the two uppermost and three lowermost gauges, despite large differences in magnitude of flow and separation by roughly 3000 km. Our results synthesize, simplify and interpret the complex changes in flow occurring along the Missouri and lower Yellowstone Rivers, and provide an objective grouping for future tests of how these changes may affect biological communities. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: human alteration; hydrology; multivariate analyses; river ecology

INTRODUCTION

Management of flow in regulated rivers and streams typically focuses on maintaining maximum, minimum and mean flows in direct response to flood control, navigation, hydropower generation, irrigation and other human demands (Poff *et al*., 1997). However, when evaluating responses of biological communities to differences in flow, it may be necessary to take a more refined approach to analyzing hydrological data (Church, 1995). Several stream flow variables have been used to describe the physical environment of streams and how organisms respond to these factors (Schlosser, 1985; Statzner and Higler, 1986; Bain *et al*., 1988; Poff and Ward, 1989; Poff, 1992; Townsend and Hildrew, 1994). Indeed, several studies have reported that hydrological factors, specifically flow variability, can influence aquatic community structure (Horwitz, 1978; Coon, 1987; Bain *et al*., 1988; Fausch and Bramblett, 1991; DiMaio and Corkum, 1995; Poff and Allan, 1995) and that this variability can occur at different temporal scales (e.g. seasonally or annually; Townsend and Hildrew, 1994).

Because of the many ways that magnitude and variability of flow can be characterized (Poff and Ward, 1989), analyzing flow variables using a multivariate approach is an effective means to determine similarities or differences among and/or within lotic systems. Hydrologically similar reaches can be grouped into homogeneous units where they can then be used as a basis for testing whether hydrology influences the biological community among the units. When relating characteristics of the biological community to hydrological conditions, it is necessary that these groupings are objectively determined and made *a priori* to assessment.

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Most previous studies characterizing and grouping lotic reaches by flow regime have focused primarily on small-order streams. Poff and Ward (1989) characterized and classified 78 streams (mean annual flows $<30\ m^3\ s^{-1}$) located across the United States using a suite of variables calculated from daily and peak flow values for each stream. They speculated on the biological significance of these different hydrological regimes, and Poff and Allan (1995) subsequently confirmed several predictions for fish communities in small and medium sized streams.

Classification of reaches exhibiting similar hydrological conditions within a system also has potential (Richter *et al.*, 1998). This may be especially important in assessing hydrological conditions in larger rivers, which are limited in number but may exhibit great variation in flow conditions from headwaters to mouth. Many large rivers, such as the Missouri, have undergone modification (e.g. impoundment and channelization) to support human demands that can influence flow characteristics (Nilsson *et al.*, 1991; Hesse and Mestl, 1993; Poff *et al.*, 1997; Parasiewicz *et al.*, 1998; Pegg, 2000). The result could potentially be several unique hydrological areas within one large river system. Furthermore, many of these changes may not necessarily be simple, linear functions of the longitudinal increase in drainage area and discharge.

The Missouri River is the longest river in the United States stretching 3768 km from western Montana to its confluence with the Mississippi River in Missouri (Figure 1). In addition to its great length, the Missouri River system also drains about one-sixth of the total area of the United States (Berner, 1951). Prior to channelization and impoundment in the early to mid-1900s, the Missouri River was characterized as a meandering, turbid river laden with islands (Funk and Robinson, 1974). After channelization, however, the Missouri River below Sioux City, Iowa, was changed into a fairly narrow and swift flowing river, resulting in a shortening of the channel by 125 km and reduction of the wetted area by nearly 64% (Whitley and Campbell, 1974). Likewise, the construction of six major reservoirs in the middle reaches of the river has changed water quality above and below the dams (Morris *et al.*, 1968) and altered the hydrology of the river (Hesse and Mestl, 1993). These major alterations have essentially divided the Missouri River into three zones, an upper zone upstream from the major alterations, a middle zone with short free-flowing reaches between reservoirs, and a zone downstream of the impoundments which is entirely channelized except for the reach between Yankton, South Dakota and Sioux City, Iowa (Figure 1).

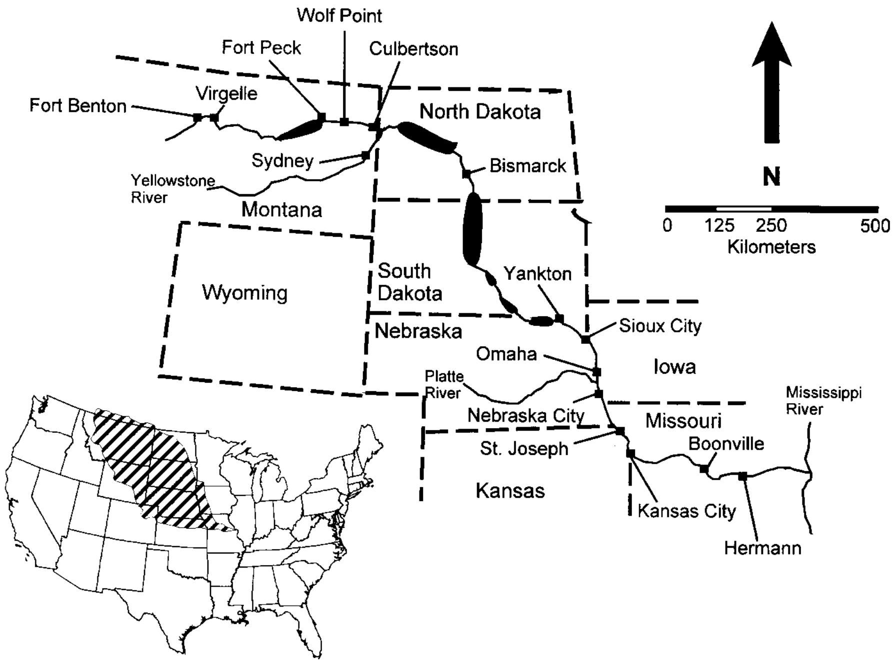

Figure 1. Location of the 15 flow gauges (■) used on the Missouri and lower Yellowstone Rivers to identify flow variability units. Inset shows location of the Missouri and Yellowstone River basins within the United States

The objective of this study was to identify hydrologically similar reaches from the Missouri and lower Yellowstone Rivers using a suite of variables calculated from daily mean flow values. These results provide an objective grouping of river reaches for future tests of how these differences affect biological communities.

METHODS

Long-term discharge records are available for several gauges along the mainstem Missouri and lower Yellowstone Rivers from the United States Geological Survey (USGS) via electronic media. These gauges yield a point measure for a given reach, providing insight into the general conditions within that river reach. For purposes of this study, we used the 15 gauges (Figure 1) with complete flow data from water year (October–September) 1967 to 1996. These dates define the years after closure of the impoundments along the mainstem Missouri River and therefore generally reflect the current, post-impoundment hydrological regime (Galat and Lipkin, 2000; Pegg, unpublished data). We also included a site on the lower Yellowstone River (Sydney, Montana) because it is a large tributary (discharge greater than the Missouri River at their confluence) that has undergone a limited amount of alteration (Benke, 1990). Thus, in terms of flow alteration, the lower Yellowstone River is similar to the Missouri River above Fort Peck Reservoir (Figure 1). Inclusion of this site provided further information from a relatively pristine zone for comparisons of flow variability with the more heavily human-influenced downstream zones of the Missouri River. We did not use gauges located within water storage areas of impoundments because we wanted to focus solely on riverine flow variability.

A suite of hydrological variables was calculated for each gauge from mean daily flow data using the Indicators of Hydrologic Alteration (IHA) methodology (Richter *et al*., 1996). Resulting data from the IHA calculations were reported by Galat and Lipkin (2000) for eleven of the fifteen gauges reported here. We calculated the IHA variables for the remaining gauges using the IHA software (Nature Conservancy, 1997). This suite of variables provides information on flow conditions (e.g. variability, predictability, magnitude) at each gauge over the period of record. The IHA method places each of these variables into one of five categories: (1) monthly flows, which focuses on the mean monthly flows; (2) magnitude and duration of extremes, giving insight into the extent and duration of both high and low flow extremes; (3) time of extreme events, giving the mean date of the extreme events; (4) characteristics of flow pulses, providing information on the number and length of flow extremes; and (5) rate of change, which gives the rate and mean number of changes in flow conditions (e.g. rising or falling) from day to day (Richter *et al*., 1996). Several other variables that further summarize conditions over the entire period of record are included in these flow summaries. Flow per unit drainage area is the ratio of daily mean discharge at the gauge to the watershed area above the gauge over all years. Coefficient of variation for mean annual flow is a dimensionless parameter that represents the ratio of standard deviation of the mean daily flow to its mean. Flow predictability is the measure of variation among successive periods (Colwell, 1974) and ranges from zero to one where high predictability values indicate low variability. Predictability is comprised of two components: (1) flow contingency and (2) flow constancy. Flow contingency is a measure of periodicity, meaning that flows can vary quite dramatically yet still have a high flow predictability score if similar flows occur at a consistent periodicity. Conversely, relatively stable flows would also have high predictability, but the major component would be constancy rather than contingency. See Colwell (1974) and Poff and Ward (1989) for further explanation and rationale of these variables.

The large number of variables calculated for a relatively small number of gauges precluded immediate application of some common multivariate procedures so we attempted to identify a meaningful subset of variables that would describe flow characteristics for each gauge. A common problem with having multiple, independent variables is that identification of variables to delineate the data is difficult and has typically been limited to pairwise comparisons of many variables (Swayne *et al*., 1998). Assessing multivariate data beyond these types of comparisons has been hindered due to the inability to identify relations beyond this two-dimensional perspective. Recent innovations in computer aided visualization have helped remedy this problem by going beyond pairwise comparisons via interactive data exploration analyses (Swayne *et al*., 1998). Therefore, we used a high dimensional, graphical data exploration application (XGobi) to identify and interpret variables that could be useful in further analyses (Swayne *et al.*, 1998). XGobi was specifically designed for interactive, multivariate data visualization and provides n-dimensional plots to assist with exploratory analyses and identification of patterns in the data. Specifically, this application provided a graphical means to simultaneously assess relations among many variables beyond two or three dimensions. Through this visualization process, we were able to identify several variables that appeared to distinguish among gauges that could be used for multivariate analyses.

Multivariate analysis of the IHA variables followed two steps. In the first step, we placed the most closely linked gauges into common flow variability units using cluster analysis (SAS, 1987). There are several methods of clustering available and there is no generally accepted optimal method (Manly, 1994). However, because we had no reason to assume equal sample sizes within each cluster, we used the centroid method to avoid undue bias (SAS, 1987). Euclidean distances for all gauges were established using the variables identified in the data exploration stage. We then determined meaningful cluster breaks using a minimum threshold criterion from the distance between two clusters (Sharma, 1996). Distances greater than the threshold were considered to indicate distinct units. The resulting flow variability units were then considered to be relatively homogenous.

The second step determined which variables accounted for the most variation among these units. We initially used stepwise discriminant analysis to identify which variables best discriminated among the groupings from the cluster analysis. Once these variables were ascertained, we then used discriminant analysis to determine the mis-classification rate using only the most descriptive variables. Determination of mis-classification provides insight into the validity of groups based upon the empirical data used in defining the groups (Sharma, 1996). Because the number of gauges was relatively small in our data set, we were not able to split the data into a training data set, used to establish classification criteria, and then apply those criteria to a test data set or use cross-validation techniques to estimate our mis-classification rate. Therefore, we used a randomized resubstitution of gauges into different groups (gauges were randomly assigned to groups) to ensure that the final variables did not provide significant discrimination by chance alone (Manly, 1994).

RESULTS

Our initial attempts to reduce the number of descriptive variables through data exploration techniques quickly identified several variables that were not well suited for grouping the 15 gauges (Appendix A). Nearly all of the variables that specifically dealt with central tendencies of the flow values (e.g. mean annual flow, mean monthly flow, etc.) were strongly correlated with watershed size. Furthermore, the location of gauges in longitudinal sequence along the Missouri River resulted in pronounced serial autocorrelation among these variables. Hence, we removed those variables that were directly influenced by watershed size (increasing trend moving downstream). Further graphical exploration of this data subset indicated that six variables could be used to identify hydrologically different reaches of the Missouri and lower Yellowstone Rivers: flow per unit area, coefficient of variation of annual flow, flow predictability, flow contingency, flow constancy, and the ratio of flow constancy to flow predictability. Flow predictability is the sum of flow contingency and flow constancy and not truly an independent measure so we omitted this variable from further analyses.

From these five flow variables, we identified six hydrologically distinct flow variability units from the cluster analysis: (1) inter-reservoir I; (2) upper channelized; (3) lower channelized; (4) upper unchannelized; (5) inter-reservoir II; and (6) unchannelized Yellowstone (Figure 2). Units often clustered more closely with distant rather than adjacent units (Figures 2 and 3). Interestingly, although they include the most spatially distant gauges, the upper unchannelized and lower channelized units clustered closer to each other than to units consisting of nearby gauges.

Stepwise discriminant analysis indicated that three of the original five variables significantly contributed to clustering the gauges into similar hydrological units (Figure 3). Univariate F-tests identified the contributing variables as coefficient of variation for mean annual flow ($F = 41.2$; $p = 0.0001$), flow per unit area ($F = 15.25$; $p = 0.0007$); and flow constancy ($F = 4.2$; $p = 0.05$) and pairwise correlations among these three variables were generally low and not statistically significant ($p > 0.10$). Our discriminant analysis

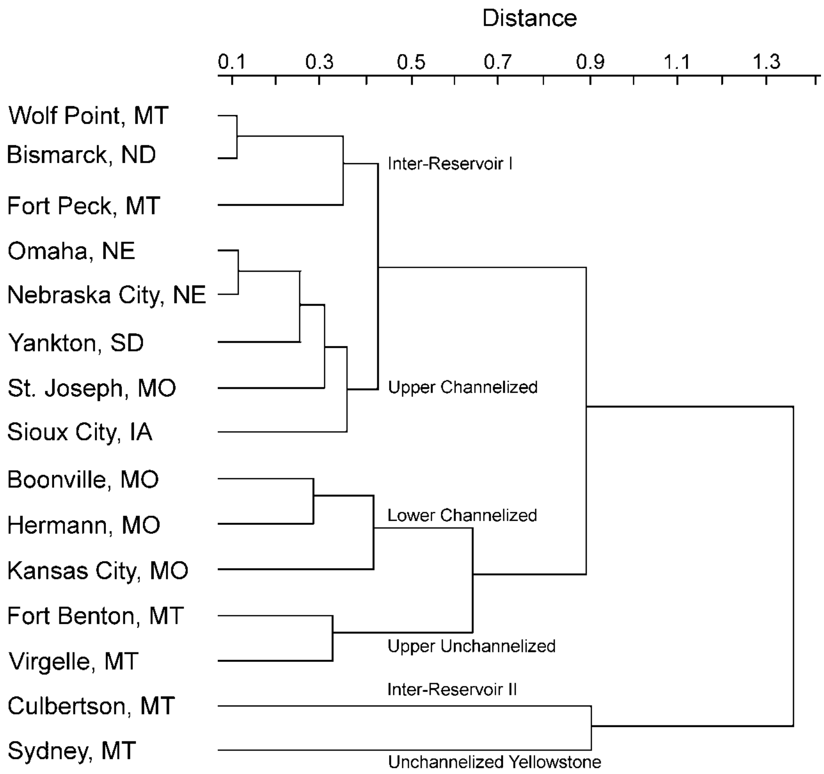

Figure 2. Flow variability unit groupings of the 15 gauges used in cluster analysis along the Missouri and lower Yellowstone Rivers

correctly classified all 15 gauges into their appropriate unit based on these three variables. We observed mis-classification rates that exceeded 20% through our resubstitution procedure indicating that these variables do not discriminate by chance alone.

Generally, the upper unchannelized, inter-reservoir II, and unchannelized Yellowstone units were characterized as having higher values for the three influential variables identified in the discriminant analysis (Figure 3). The upper channelized unit had the overall lowest values; whereas, the inter-reservoir I and lower channelized unit values were somewhat intermediate.

In contrast to the steady increase in annual mean discharge downstream (Figure 3), there was no evidence of continuous longitudinal trends throughout the entire length of the Missouri River in any of the flow variables we analyzed. However, there were continuous trends evident over considerable lengths of the uppermost and lowermost river reaches for several variables. Flow per unit area declined steadily in the upper reaches and increased steadily in the lower reaches. Flow constancy declined steadily in the lower reaches. Coefficient of variation for mean annual flow in the lower reaches of the river exhibited a sigmoid pattern, with low values for the first four gauges below the lowest reservoir, followed by a sharp increase over the next three gauges, finally stabilizing at the lowest two gauges (Figure 3).

In addition to separating flow variability units of the river where breaks in continuous flow occurred, the mainstem reservoirs also corresponded with other flow discontinuities. Coefficient of variation for mean annual flow on the Missouri River decreased dramatically between gauges directly above and below Fort Peck Reservoir, increased dramatically between Wolf Point and Culbertson, and decreased dramatically again between Culbertson and Bismarck (Figure 3). The decline in coefficient of variation for mean annual flow between Sydney on the lower Yellowstone River and Bismarck was very similar to the decline between Culbertson and Bismarck. The Yellowstone River gauge at Sydney had distinctly lower values for flow constancy and proportion of constancy within predictability than Missouri River gauges below Fort Peck Reservoir (Figures 1 and 3). Additionally, the Fort Benton and Virgelle gauges are affected by flow regulation

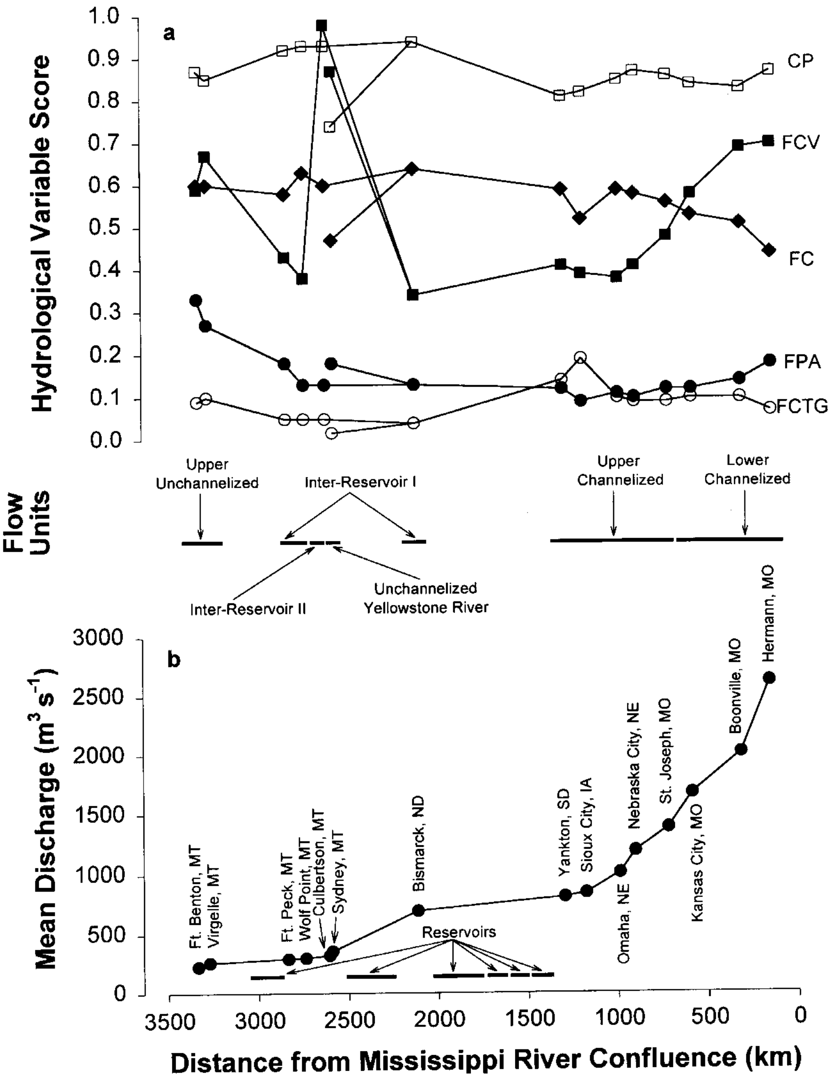

Figure 3. Hydrological variable scores (a) and resulting flow variability unit classification of gauges in relation to mean discharge and location along the Missouri and lower Yellowstone rivers (b). Scores for all five variables used in the cluster analysis are shown; the three variables best discriminating among hydrological units are identified by solid symbols (FPA = flow per unit area; FCV = annual flow coefficient of variation; FC = flow constancy; FCTG = flow contingency; CP = proportion of constancy within predictability)

more than the Sydney gauge because there are several reservoirs further upstream, but these gauges still grouped outside the inter-reservoir units.

DISCUSSION

The grouping of gauges into six flow variability units by our analyses generally followed a longitudinal continuum along the river system. This makes intuitive sense due to the cumulative nature of flow along the river's course. However, the division of the river into discrete units begs the questions of where and why these unit breaks occur. There are two likely reasons for the majority of the unit differences. The first is that the Missouri River has essentially been divided into three zones due to the massive alterations to the river during the early to mid-1900s. Impoundments and channelization in the middle and lower river have effectively divided the river into an upper least-altered zone, a middle inter-reservoir zone, and a lower channelized zone. These management practices have had a strong influence on the channel morphology and hydrology of the middle and lower Missouri River (Hesse and Mestl, 1993; Galat and Lipkin, 2000). Large-scale human alteration to the Missouri River system explains a coarse step in the delineation of major reaches. However, our detailed analysis of flow variability suggests further subdivision within these broad zones as flow patterns not intuitively linked with river alteration were evident from our analyses.

The upper unchannelized unit is characterized as having the highest flow per unit area values in all the gauges we studied (Figure 3). The coefficient of variation for mean annual flow tended to be relatively high in this unit as well. The high coefficient of variation for mean annual flow score indicates a substantial amount of annual flow variability within this unit, but the high flow predictability indicates that this variability occurs with some periodicity.

The inter-reservoir I unit had the lowest coefficient of variation for mean annual flow values when compared to the other units (Figure 3). Flow constancy was also high which played a large role in classifying this unit. Flow variability immediately downstream of dams tends to be reduced (Ligon *et al*., 1995). Thus, constancy is a consequence of the close downstream proximity of gauges to dams in the inter-reservoir I unit. The result is stable flow throughout the recent, post-regulation period of record.

The inter-reservoir II unit was similar to inter-reservoir I except that coefficient of variation for mean annual flow was markedly higher. The higher annual variation is most likely due to flow input from tributaries. There are tributaries that contribute to total flow in both units. However, between the Wolf Point and Culbertson gauges (Figure 1), two tributaries (Poplar River and Big Muddy Creek) enter the Missouri River. Streams in this region tend to be quite variable and dependent upon snowmelt in the spring and unpredictable precipitation throughout the remainder of the year (Poff and Ward, 1989). These tributaries typically contribute 1–2% of the mean annual flow to the Missouri River at the Culbertson gauge. However, during high precipitation periods, the tributaries contribute as much as 5–15% to the total Missouri River outflow (USGS, 2000). This added variability has created a point of separation between the two inter-reservoir units.

Similar to the inter-reservoir II unit, the unchannelized Yellowstone unit also had a high coefficient of variation for mean annual flow value in addition to the lowest flow constancy of all units. This would indicate that, while predictability is fairly similar to the other units, there is a large amount of annual variation. Consequently, the lower constancy suggests that there is a fair amount of daily and monthly variability, albeit occurring with some regularity, which can be attributed to its relatively free-flowing nature (Benke, 1990). This conclusion is also supported by Galat and Lipkin (2000) who reported the lower Yellowstone River to be the least hydrologically altered reach of the Missouri and lower Yellowstone Rivers. Thus, flows in the unchannelized Yellowstone unit tend to be more variable than the units of the Missouri River due to this natural heterogeneity.

Located directly below the six mainstem reservoirs and in the upstream reach of the channelized navigation corridor, the upper channelized unit is in a unique position on the Missouri River (Figure 3). The regulated flows coming out of the inter-reservoir units and reservoirs resulted in the lowest coefficient of variation for mean annual flow values of any in the system. Additionally, there are few major tributaries that contribute additional flow. The one exception to this is the Platte River which provides about 8% of mean annual flow at Hermann, Missouri (the lowermost gauge on the Missouri River; Hedman and Jorgensen, 1990). The low flow per unit area scores throughout this unit may reflect this lack of tributary contribution (Figure 3). The combination of upstream influence from impoundments and the scarcity of major tributaries results in one of the more stable flow units.

Finally, the lower channelized unit exhibits more variability than the upper channelized unit as the Missouri River approaches the confluence with the Mississippi River. Geographically, this unit's watershed area drains about 38% of the entire Missouri River basin, but supplies 61% of the average annual flow to the system (Galat and Lipkin, 2000). Additionally, major tributaries within the lower channelized unit (e.g. Kansas River, Grand River, Osage River) contributed nearly half (44%) of the total annual flows at Hermann, Missouri between 1951 and 1980 (Hedman and Jorgensen, 1990). Input from these tributaries ameliorates some of the influence that the impoundments have on the middle river reaches, resulting in much higher flow per unit area values compared to the upper channelized unit. The result is a relatively variable unit, giving the flows in this area a less regulated characteristic.

A consequence of this renewed variability, revealed by the cluster analysis, is the linkage between the extreme upstream and downstream flow variability units. The cluster analysis dendrogram (Figure 2) shows that the upper unchannelized and lower channelized units are more closely related with each other than with any of the other units. Galat and Lipkin (2000) and Pegg (2000) reported similar results from their analyses suggesting lower levels of flow alteration in the extreme upstream and downstream reaches of the Missouri River.

Hydrological effects of reservoirs are most notably observed on flow variations within a year (Allan, 1995; Hesse and Mestl, 1993). Specifically, mainstem Missouri River impoundments have typically been thought to change the timing rather than total discharge by depressing maximum flows and raising minimum flows throughout the year (Hesse and Mestl, 1993). Each reservoir has specific operating requirements that mandate particular water levels at certain times of year (USACOE, 1998). There are exceptions to this as evaporation removes some water and filling takes place in wet years that were preceded by dry years, but generally the same amount of water flowing into a reservoir flows out. If the total amount of discharge does not greatly change over the length of the reservoirs, then our coefficient of variation for mean annual flow estimates should reflect similar values at each gauge along the river because they are calculated at the inter-annual scale. Figure 3 illustrates that this is not the case, as variability in the inter-reservoir units is markedly lower than the other units. This suggests that the inter-annual effects from reservoirs may be greater than previously thought and warrants further investigation.

Our approach has identified six hydrologically distinct units along the Missouri and lower Yellowstone river system based on inter-annual patterns in flow variability. An important utility of this classification in the future will be testing for responses of lotic organisms to the differing flow conditions occurring in these units. Studies investigating among-stream differences at the intra-annual scale have shown that flow characteristics can influence the composition and structure of biological communities (DiMaio and Corkum, 1995; Poff and Allan, 1995). For fish, one premise is that assemblages in hydrologically stable environments generally consist of species with specialized life histories. Conversely, highly variable conditions are more conducive to generalist life-history traits. Application of this theory at the inter-annual temporal scale and to larger rivers has been limited due to the lack of multiple systems with similar characteristics for hypothesis testing. Comparing community attributes within one large system is especially difficult because of the inherent longitudinal gradient of species richness and diversity (Statzner and Higler, 1986), and perhaps further complicated by the disruptive nature of impoundments upon this gradient (Ward and Stanford, 1995). Many factors like habitat availability, flow regulation, and biotic interactions influence fish community structure in these large, complex systems. However, in a general context, we would expect the lower channelized unit to have the highest aquatic species diversity due, in part, to its position in the drainage network, lack of barriers to upstream migration from downstream source populations in the Mississippi River, and the somewhat less regulated nature of the flows. Conversely, the inter-reservoir units would be expected to have lower diversity due to influence of the reservoirs, position between physical barriers, and longitudinal position. The next step will be to test these predictions using biological data from the Missouri and lower Yellowstone Rivers and we are currently addressing some of these questions, along with a collaborating group of researchers (Young *et al*., 1997).

In large systems such as the Missouri River, there are reasons to group river reaches in various ways to meet specific needs (e.g. political, climatical, topographical, biological). The division of the river into three zones defined by human alteration, discussed earlier, is a useful first step in identifying regions sharing basic flow characteristics. However, we believe that objectively creating units based on a suite of driving variables with demonstrated biological significance, as we have done here, can set the stage for further exploration into how these factors influence biological communities in large river systems.

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APPENDIX A

Index of Hydrological Alteration Variables

Index of Hydrological Alteration (IHA) data used to identify flow units along the Missouri and lower Yellowstone Rivers.

	Fort Benton (3336)	Virgelle (3272)	Fort Peck (2835)	Wolf Point (2738)	Culbertson (2606)	Sydney (2592)	Bismarck (2115)	Yankton (1297)	Sioux City (1178)	Omaha (991)	Nebraska City (905)	St. Joseph (721)	Kansas City (589)	Boonville (317)	Hermann (158)
Zone Designation	Upper	Upper	Middle	Middle	Middle	Upper	Middle	Lower	Lower	Lower	Lower	Lower	Lower	Lower	Lower
Summary Statistics															
Mean Annual Flow (m^3 s^{-1})	228.00	263.00	294.00	300.00	325.00	358.00	698.00	812.00	846.00	1012.00	1193.00	1386.00	1673.00	2020.00	2629.00
Mean Flow/Area	0.33	0.27	0.18	0.13	0.13	0.18	0.13	0.12	0.09	0.11	0.10	0.12	0.12	0.14	0.18
Annual Flow CV	0.59	0.67	0.43	0.38	0.98	0.87	0.34	0.41	0.39	0.38	0.41	0.48	0.58	0.69	0.70
Flow Predictability	0.69	0.70	0.63	0.68	0.65	0.64	0.68	0.73	0.71	0.69	0.67	0.65	0.63	0.61	0.55
Flow Constancy	0.60	0.60	0.58	0.63	0.60	0.47	0.64	0.59	0.52	0.59	0.58	0.56	0.53	0.51	0.48
Constancy/ Predictability	0.87	0.85	0.92	0.93	0.93	0.74	0.94	0.81	0.82	0.85	0.87	0.86	0.84	0.83	0.87
Flow Contingency	0.09	0.10	0.05	0.05	0.05	0.17	0.04	0.14	0.19	0.10	0.09	0.09	0.10	0.10	0.07
Maximum and minimum flows (m^3 s^{-1}) for 1–9-day averages															
1-day Min	96.00	112.00	118.00	153.00	158.00	91.00	374.00	336.00	279.00	374.00	444.00	458.00	560.00	647.00	832.00
3-day Min	109.00	126.00	129.00	158.00	164.00	95.00	393.00	351.00	313.00	409.00	471.00	523.00	593.00	671.00	891.00
7-day Min	122.00	135.00	139.00	163.00	169.00	105.00	407.00	373.00	342.00	461.00	531.00	576.00	645.00	723.00	944.00
30-day Min	133.00	143.00	156.00	175.00	180.00	144.00	439.00	427.00	403.00	529.00	627.00	701.00	794.00	889.00	1151.00
90-day Min	145.00	158.00	195.00	212.00	213.00	177.00	509.00	476.00	489.00	597.00	736.00	841.00	960.00	1121.00	1455.00
1-day Max	642.00	914.00	503.00	513.00	1411.00	1524.00	1060.00	1269.00	1518.00	1955.00	2771.00	3787.00	5091.00	7123.00	9062.00
3-day Max	618.00	871.00	498.00	499.00	1197.00	1453.00	1044.00	1264.00	1514.00	1845.00	2595.00	3524.00	4736.00	6814.00	8719.00
7-day Max	581.00	788.00	492.00	485.00	865.00	1331.00	1020.00	1255.00	1486.00	1711.00	2317.00	3101.00	4144.00	6105.00	7867.00
30-day Max	490.00	627.00	466.00	443.00	566.00	1068.00	973.00	1226.00	1395.00	1501.00	1859.00	2359.00	3257.00	4353.00	5810.00
90-day Max	372.00	447.00	412.00	391.00	454.00	731.00	890.00	1142.00	1240.00	1344.00	1585.00	1917.00	2505.00	3206.00	4336.00
Calendar Date of the 1-day maximum and minimum flow values															
Minimum	300.00	215.00	156.00	245.00	253.00	50.00	223.00	62.00	28.00	14.00	8.00	22.00	12.00	11.00	41.00
Maximum	178.00	151.00	124.00	122.00	97.00	161.00	101.00	272.00	213.00	193.00	165.00	170.00	172.00	178.00	176.00
Counts of extreme conditions															
Low Pulse Count	0.80	9.00	3.60		3.30	1.80	0	0.40	0	0.30	0.30	0.30	0.30	0.20	0.70
Low Pulse Duration	0.60	0.70	6.80		7.50	3.80	0	0.90	0	0.30	15.80	0.70	0.60	0.40	1.00
High Pulse Count	1.30	0.20	0	7.00	0	1.40	0	0	2.00	0.70	1.90	3.50	2.50	3.70	3.80
High Pulse Duration	10.10	2.10	0	7.9	0.10	5.70	1.50	0.96	0.50	1.20	3.30	3.50	3.40	4.80	5.40

(*continued overleaf*)

APPENDIX A (*Continued*)

	Fort Benton (3336)	Virgelle (3272)	Fort Peck (2835)	Wolf Point (2738)	Culbertson (2606)	Sydney (2592)	Bismarck (2115)	Yankton (1297)	Sioux City (1178)	Omaha (991)	Nebraska City (905)	St. Joseph (721)	Kansas City (589)	Boonville (317)	Hermann (158)
Rise Rate	473.10	555.70	451.40	431.00	450.90	1052.50	829.50	676.40	1027.70	1391.40	2015.90	3665.10	4844.70	518.90	9545.10
Fall Rate	−442.50	−549.50	−486.60	−425.20	−586.50	−753.00	−864.90	−752.60	−1048.90	−1198.60	−1566.70	−2529.70	−3237.30	−4828.60	−6136.20
Number of Reversals	162.50	157.40	154.70	153.70	109.10	86.10	161.10	119.90	127.10	124.90	119.20	115.90	108.80	95.40	106.20
Monthly average flows (m^3s^{-1}) and Coefficients of Variation (CV)															
October	167.00	188.00	268.00	251.00	267.00	250.00	615.00	1044.00	1079.00	1161.00	1286.00	1429.00	1671.00	1939.00	2362.00
October CV	0.26	0.25	0.34	0.4	0.36	0.28	0.39	0.28	0.27	0.25	0.24	0.25	0.4	0.55	0.69
November	177.00	194.00	277.00	260.00	267.00	232.00	642.00	941.00	982.00	1076.00	1211.00	1343.00	1537.00	1793.00	2386.00
November CV	0.25	0.24	0.31	0.37	0.34	0.25	0.34	0.42	0.41	0.38	0.34	0.32	0.34	0.34	0.41
December	179.00	200.00	295.00	289.00	296.00	197.00	655.00	565.00	607.00	679.00	813.00	937.00	1118.00	1391.00	2015.00
December CV	0.19	0.2	0.12	0.15	0.14	0.18	0.16	0.31	0.32	0.34	0.33	0.34	0.37	0.44	0.53
January	113.00	213.00	335.00	332.00	342.00	193.00	731.00	489.00	508.00	564.00	670.00	767.00	882.00	1070.00	1561.00
January CV	0.16	0.17	0.13	0.16	0.12	0.2	0.15	0.21	0.22	0.26	0.28	0.31	0.37	0.44	0.5
February	196.00	223.00	361.00	357.00	386.00	229.00	800.00	492.00	543.00	627.00	823.00	964.00	1144.00	1434.00	2023.00
February CV	0.18	0.16	0.14	0.2	0.12	0.32	0.19	0.23	0.23	0.26	0.29	0.33	0.38	0.45	0.45
March	206.00	227.00	264.00	309.00	424.00	329.00	696.00	571.00	605.00	872.00	1167.00	1387.00	1684.00	2083.00	2863.00
March CV	0.26	0.3	0.29	0.27	0.75	0.46	0.27	0.25	0.36	0.29	0.32	0.39	0.48	0.55	0.54
April	231.00	252.00	234.00	289.00	348.00	275.00	643.00	761.00	898.00	1141.00	1394.00	1622.00	2029.00	2589.00	3560.00
April CV	0.3	0.32	0.41	0.48	0.5	0.29	0.33	0.26	0.21	0.23	0.29	0.32	0.43	0.5	0.52
May	358.00	407.00	257.00	298.00	318.00	522.00	674.00	855.00	912.00	1153.00	1420.00	1723.00	2167.00	2785.00	3668.00
May CV	0.40	0.38	0.43	0.40	0.45	0.30	0.38	0.19	0.19	0.19	0.25	0.31	0.39	0.45	0.46
June	423.00	563.00	278.00	316.00	329.00	986.00	727.00	893.00	972.00	1249.00	1554.00	1834.00	2312.00	2786.00	3605.00
June CV	0.52	0.49	0.51	0.42	0.44	0.36	0.34	0.23	0.27	0.24	0.33	0.36	0.41	0.46	0.46
July	270.00	313.00	321.00	322.00	334.00	629.00	770.00	985.00	996.00	1234.00	1406.00	1699.00	2090.00	2496.00	2989.00
July CV	0.55	0.48	0.54	0.47	0.49	0.53	0.37	0.41	0.21	0.25	0.33	0.49	0.62	0.7	0.62
August	178.00	197.00	329.00	304.00	303.00	237.00	773.00	1065.00	1031.00	1189.00	1283.00	1448.00	1710.00	1922.00	2265.00
August CV	0.26	0.27	0.48	0.30	0.34	0.42	0.32	0.29	0.25	0.24	0.22	0.23	0.34	0.46	0.59
September	166.00	180.00	320.00	276.00	291.00	218.00	662.00	1078.00	1018.00	589.00	1288.00	1468.00	1714.00	1942.00	2248.00
September CV	0.29	0.28	0.53	0.35	0.32	0.35	0.34	0.27	0.25	0.23	0.22	0.22	0.32	0.4	0.49

Numbers in parentheses below each gauge indicate distance (km) upstream from Missouri River mouth. Zone designation places each gauge into the three zones that resulted from major human alteration on the Missouri River (Upper = upstream from major mainstem impoundments; Middle = river reaches between impoundments; Lower = river downstream of impoundments). Variables highlighted in bold were used for initial flow variability unit identification in cluster analysis.

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