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PLACING GLOBAL STREAM FLOW VARIABILITY IN GEOGRAPHIC AND GEOMORPHIC CONTEXTS

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ABSTRACT

The importance of hydrologic variability in sustaining natural riverine ecosystems is now well accepted. Over the last 15 years or so, many typologies and assessment tools have been developed to assist ecologists and managers in describing natural flow regimes in quantitative terms. In the course of this recent progress, however, some critical questions have arisen concerning the degree to which generalizations about flow regime characteristics are geographically dependent both within and among regions, and the degree to which flow variability alone captures critical environmental variability. In this paper we address these issues in a hierarchical framework that allows comparative statements about hydrologic variability to be made a multiple spatial scales, from local to global.

First, we examined hydrologic variability among 463 readily available daily streamflow gauges from five continents/countries around the world: Australia, New Zealand, South Africa, Europe, and the United States. Using ordination and clustering techniques, we identified similarities and differences among these gauges. We found that the US gauges exhibited the greatest overall flow variability among a suite of 66 hydrologic indicators, whereas Australian streams showed the greatest influence by interannual variability in flow. Similarities in overall flow regime were greatest between Australia and the US, whereas New Zealand streams were most regionally distinctive. These results support the idea of intercontinental distinction in streamflow variability at a global scale; however, they also point to important similarities in flow characteristics among continents/countries.

Second, within the continental United States, we examined how hydrologic variability changes along river profiles as catchment area increases for five river basins arrayed across a gradient of hydroclimatic variation. Using historical streamflow records that precede river impoundment, we found that small ‘headwater’ streams exhibit the greatest similarity in flow characteristics across the basins, as compared to mid-sized and larger river reaches, which often diverged among the rivers. These results reveal the importance of more carefully defining the spatial domain of allowable hydrologic extrapolation from individual stream gauges and emphasize the need to stratify within basins when considering hydrologic variability at regional scales.

Third, we used a modeling approach to illustrate how geomorphic setting provides a context for assessing the ecological consequences of flow variation at the local scale of stream reaches. For modeled channels having the same sediment size distribution but with either entrenched or floodplain morphology, we found that the effective regime of bed movement for three hydrologically distinct streams depended as much on geomorphic setting as on flow regime *per se*. These results emphasize the need to integrate hydrology with geomorphology to characterize ‘disturbance regimes’ at the channel reach scale to allow generation of spatially explicit mapping of flow-mediated habitat dynamics for entire drainage networks within specific regions.

In sum, if riverine scientists wish to develop a general framework for comparing hydrologic variability across basins, regions, and continents, a hierarchical approach is advised. At very broad scales, intercontinental differences in flow regimes could allow a stratification of basins to identify similar hydroecological settings. Within continents or hydroclimatically similar regions, finer-scale spatial analysis of flow regime types would further assist in hydrologic stratification, based only on the regionally-relevant components of flow variability. Finally, within hydrologically homogeneous sub-regions, geomorphic stratification could be applied to identify stream reaches or segments having similar hydrogeomorphic properties. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: hydrologic variability; flow regime; hydroecology; disturbance; hierarchy

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INTRODUCTION

A principal goal of applied river ecology is to develop rules for managing flow regimes to attain some desirable level of ecological function (Richter *et al*., 1997, 2003; Poff *et al*., 2003). Much progress has been made over the last 15 years in our fundamental understanding of how hydrologic variability promotes self-sustaining riverine ecosystems (e.g., Resh *et al*., 1988; Poff and Ward, 1989; Naiman *et al*., 1995; Stanford *et al*., 1996; Walker *et al*., 1995; Richter *et al*., 1997; Poff *et al*., 1997; Bunn and Arthington, 2002; Baron *et al*., 2003). Among river ecologists there is now a general consensus that 'natural' or 'normative' flows are a desirable goal to sustain riverine function and native biodiversity (Poff *et al*., 2003). This viewpoint is supported by numerous case studies that clearly indicate the importance of natural flow variability for both ecological processes (see reviews in Poff *et al*., 1997; Bunn and Arthington, 2002) and evolutionary adaptations (Lytle and Poff, 2004).

Current application of our general understanding of flow variability occurs in two major contexts. First, management decisions are often urgently needed at specific locations where detailed knowledge of hydrologic-ecological linkages is lacking. In these instances, techniques that develop flow prescriptions based on natural flow variability can be proposed (e.g., Stanford *et al*., 1996; Richter *et al*., 1997), which secondarily can be combined with adaptive management to learn more about the system being actively managed (e.g., Bunn and Arthington, 2002; Poff *et al*., 2003; Richter *et al*., 2003). Second, environmental regulation and management are often applied broadly at regional or national scales, which encompass substantial variation in climatic, physiographic, and ecological conditions. At these scales, comparison and classification of flow regimes can be used to stratify ecological potential; several such classifications have been published (see below). To date, many approaches and analytical techniques have emerged around the world (see Olden and Poff, 2003; Tharme, 2003), and there is no clear consensus as to which variables are most generally relevant in hydrologic classification or river management.

Despite the growing global consensus on the ecological importance of natural flow variability, some critical limitations remain that challenge our ability to robustly extrapolate knowledge from specific sites to broader scales, both within and across regions (see Poff *et al*., 2003). In this paper, we explore some of the generalities and constraints to flow characterization that should guide future hydroecological research. We focus on three areas that we believe represent current research needs to generate greater transferability between hydroecological studies within and among regions around the world. All three are based on the simple observation that characterization of a 'natural flow regime' is typically derived using historical gauging data taken from a single point in space, that is, an individual stream gauge. But the limited spatial coverage of gauges (and their variable temporal records) injects uncertainty into how well flow regime characterization can be extrapolated across space (or time) beyond the gauge location (and record). This, in turn, raises the issue of how spatially robust flow-regime characterizations are. We believe that by placing flow regime characterization into a hierarchical framework, progress can be made in identifying global hydrologic generalizations.

First, we consider the differences and similarities among flow regimes at the intercontinental scale, where a surprising amount of uncertainty remains as to how well we might generalize patterns of flow variation across political boundaries. The few global-scale analyses that have been conducted have examined flow data at relatively coarse time scales, such as months (Haines *et al*., 1988) or years (McMahon, 1982, 1992; Puckridge *et al*., 1998), from which it has been asserted that flow variability in temperate zone streams/rivers is globally maximal in Australia and South Africa. However, for ecological applications, Poff (1996) showed that daily hydrologic data provide important information not revealed by monthly, seasonal, or annual data. Similarly, Olden and Poff (2003) showed that daily hydrologic indices were not always correlated strongly with monthly or annual ones. Ecological inferences about flow variability on a global scale, therefore, should also include measures of daily hydrologic variation, which can reasonably capture high frequency fluctuations (e.g., flow pulses) of ecological significance. Here we compare streams around the world in terms of high frequency, daily flow data, which is becoming increasingly available through computer-based data storage and retrieval in many countries. Daily flow data have been used to evaluate flow regimes in individual countries or continents, including Australia (Hughes and James, 1989), New Zealand (Biggs *et al*., 1990; Jowett and Duncan, 1990; Clausen and Biggs, 2000), and the United States (Poff and Ward, 1989; Richards, 1990; Poff, 1996); however, ours is the first intercontinental comparison of hydrologic regimes using daily flow data.

Second, we evaluate how flow regimes vary within river basins. The spatial extent to which the hydrologic characteristics for an individual gauge can be extended upstream or downstream is largely unknown. Flow regime typologies often assume that a gauge represents the flow regime for the entire catchment or for some unspecified distance upstream or downstream. However, at this scale, extrapolation from individual gauges may be problematic, because of variation among sub-basins in climate and geology (e.g., Burn, 1997; Thoms and Parsons, 2003). It is well known that large rivers generally differ hydrologically from small streams due to scale averaging of spatially-distributed flow inputs (e.g., Dunne and Leopold, 1978); however, one might expect streams and rivers to maintain more of a homogeneous hydrologic signature as they increase in size if they remain in one hydroclimatic region. In many cases, rivers flow through different climatic, geologic, and biological zones as they increase in basin area. These differences may result in very different hydrologic signatures throughout a basin. Since most basins have only sporadic gauge coverage, it is useful to know how well hydrologic information from one gauge might be transferred throughout the basin. Characterizing this within-basin variability is difficult, both because many larger streams have highly modified 'natural' flow regimes (e.g., due to dams) and because smaller streams are generally sparsely gauged. In this paper, we compare hydrologic variability within and among basins for five river basins in the USA, where the occurrence of many long-term historical gauge records allows the opportunity to reconstruct the 'natural' flow regime for some period on streams prior to ubiquitous impoundment by dams.

Third, at the scale of stream reaches, we consider how geomorphic context influences the ecological relevant characteristics of a given flow regime, often a major uncertainty in hydroecology. Disturbance is widely recognized as a key process regulating riverine ecosystem structure and function (Resh *et al*., 1988; Townsend, 1989; Poff, 1997; Lake, 2000). Because characteristics of the hydrologic regime are easier to measure and more readily available than hydraulic and substrate stability data, streamflow metrics are frequently used as surrogates for disturbance (e.g., Hughes and James, 1989; Poff and Ward, 1989; Poff, 1996; Clausen and Biggs, 2000). However, frequency, magnitude, and duration of bed movement and overbank flow depend fundamentally on local geomorphic context (i.e., channel and floodplain geometry, slope, bed particle size distribution, roughness) that dictates thresholds of hydrologic disturbance (e.g., Andrews and Nankervis, 1995; Knighton, 1998). Ecologists have recognized this interaction in general models of both flood disturbance (Resh *et al*., 1988; Poff and Ward, 1990; Poff, 1992; Lake, 2000), and more recently in terms of low-flow extremes that shrink habitat (Boulton, 2003; Lake, 2003). Despite this recognition, there have been limited systematic efforts to integrate hydrologic and geomorphic drivers into a general model or classification of lotic disturbance (but see Montgomery, 1999). Such efforts are a major research need to completely characterize the ecological consequences of flow variability. In this paper, we model an important interaction between hydrologic regime and local geomorphic context. Specifically, we show how channel confinement ('entrenched' vs. 'floodplain') interacts with three distinctly different flow regimes to define the effective substrate disturbance regime within the stream channel.

Overall, our objective in this paper is simply to compare flow variation at different scales, not to construct a comprehensive global typology of flow regime types. We approach this analysis hierarchically to better capture the different scales of variation in important hydrologic and geomorphic processes that define the ecological relevance of flow variability. We believe this will help identify future research needs in hydroecology. However, we also believe a global typology would be a useful, future effort. Any eventual global typology will require a merging of historical runoff records with hydroclimatology, the science that examines the climatic mechanisms responsible for spatial variation in runoff at continental (e.g., Lins, 1997; Cunderlik and Burn, 2002) to intercontinental (e.g., Hayden, 1988—see Poff *et al*., 2001, Figure 14.1) scales.

METHODS

Global analysis of streamflow regimes

We used streamflow records from 463 gauging stations in five countries/continents for which high quality, daily flow data were readily available: Australia (AU), New Zealand (NZ), South Africa (SA), Europe (EU), and the United States (US). Gauge locations are shown in Figure 1, and their diagnostic attributes are provided in Table I. All stations met three criteria: (1) unregulated upstream reaches, (2) minimum 20 year period of record, and (3) no data gaps >10 consecutive days. We stratified our station selection within each region using the World Wildlife Fund's terrestrial

Figure 1. Global distribution of 463 stream gauges in five continental regions or countries

Table I. Summary statistics for the 463 streamflow gauges used in the global geographic analysis of flow regimes

	Australia	New Zealand	South Africa	Europe	United States
N (Total = 463)	83	88	40	115	137
Mean area	628.1	826.8	8503	343	988.5
Minimum area	15	11	1.7	201	22.1
Maximum area	6810	6643	63437	499	5801.6
Begin–End	1968–1994	1971–2000	1944–1972	1953–1991	1943–1997
Period of record	26	29	28	38	54

All areas are in km^2. ‘Begin–End’ refers to the mean beginning and ending year for each region. ‘Period of Record’ is the mean number of years of daily streamflow values used for each region.

ecoregions (Olson *et al.*, 2001) to cover the climatic range in each region. The stations we selected do not necessarily represent an exhaustive (or even optimal) set of gauges from these regions. For example, many more US gauges are available (see Poff, 1996) but we chose not to include them all to maintain similar sample sizes across the regions. Also, these gauges do not necessarily represent the range of runoff patterns on a global scale; rather, they represent available data for unregulated streams and small rivers in selected regions.

We acquired data from a variety of sources. In Australia, we identified unregulated gauging stations from eastern Australia as reported by Growns and Marsh (2002), and we accessed supplemental data through the Australia Bureau of Meteorology’s web-based Water Resources Station Catalogue (http://www.bom.gov.au/hydro/wrsc). From New Zealand, we acquired data from the National Institute of Water & Atmospheric Research (NIWA, http://www.niwa.co.nz/). In South Africa, data were provided by the Department of Water Affairs and Forestry, Hydrological Service (http://www.dwaf.gov.za/default.asp). Data for representative, unregulated stations across the United States were acquired through the U.S. Geological Survey’s National Water Information System database (http://waterdata.usgs.gov/nwis). In Europe, we selected gauge records from the Flow Regimes from International Experimental and Network Data (FRIEND, http://www.nwl.ac.uk/ih/www/research/bfriend.html) database. Unlike the other data sources, the FRIEND database did not include a field identifying the regulation status of gauging stations. Therefore, we restricted our station selection to those with upstream catchment areas less than 500 km^2, under the assumption that larger catchments would likely be regulated. As a second filter, we visually inspected the daily hydrographs from each of the potential stations in Europe and discarded those with obviously regulated hydrographs (e.g., abrupt stepped flow changes or aseasonal flows).

We used daily mean flow records to calculate the indicators of hydrologic alteration (IHAs: Smythe Scientific Software, Boulder, Colorado, USA)—a set of 'biologically relevant' hydrologic indices that quantify the major components of the flow regime (Richter *et al*., 1996). There are a total of 66 IHAs representing 33 measures of central tendency (mean) and 33 measures of dispersion (coefficient of variation) that collectively quantify the magnitude of monthly flows ($n = 24$), magnitude and duration of annual extreme events ($n = 24$), timing of annual extreme events ($n = 4$), frequency and duration of high and low pulses ($n = 8$), and rate and frequency of flow changes ($n = 6$). The 66 IHA variables adequately represent the majority of variation explained by a larger group of 171 hydrologic indices commonly used in the literature (see Olden and Poff, 2003). Flow regimes were 'normalized' across the 463 gauges by dividing all daily flow values by the corresponding long-term mean annual flow (i.e., mean flow for all records = 1.0). All time series were expressed in terms of Julian days, with southern hemisphere gauges 'adjusted' by 183 days to be seasonally synchronized with northern hemisphere gauges.

We used principal component analysis (PCA) to summarize patterns of variation in the hydrologic characteristics of the 463 stream sites. Data reduction by PCA aids in the interpretation of flow regimes in different regions by producing a low-dimensional ordination space in which similar sites are close together and dissimilar sites are far apart (Gauch, 1982). We assessed the flow regime 'uniqueness' of the five regions in terms of their flow regime characteristics (defined by all 66 variables) using classification tree analysis (Breiman *et al*., 1984) to test whether the 463 stream sites could be correctly assigned to the five regions from which they were sampled. This analysis is a nonparametric technique that uses a recursive-partitioning algorithm to repeatedly partition the dataset into a nested series of mutually exclusive groups, each of them as homogeneous as possible with respect to the response variable (here, regional affiliation of the 463 gauges). We used Gini's method to define splitting rules, employed a one-standard rule to determine optimal tree size and used 10-fold cross validation to determine model classification success (see De'ath and Fabricus, 2000).

Within-region analysis of hydrologic similarity

To evaluate within versus among river basin variation in flow-regime characteristics, we selected five river basins in the US to span a range of climatic and runoff conditions and for which historical (pre-dam era) flow data were available (Figure 2). Within each basin, we analyzed daily streamflow records from five gauging stations that span the available sizes and associated characteristics of gauged sub-basins (Table II). These river basins represent a broad range of climatic variation in the US, from very wet (Willamette basin) to intermediate runoff (White and Potomac basins) to arid (Colorado and Canadian basins).

We controlled for the hydrologic effects of regulation by analyzing pre-regulation records for all basins (Table II). We acquired daily streamflow data from these basins from the U.S. Geological Survey's online database (http://waterdata.usgs.gov/nwis). The flow records of each gauge were normalized and analyzed using the IHA parameters (as described earlier). We evaluated similarity among gauges within and among river basins with two techniques. First, we ordinated the 25 individual gauges for the five basins using PCA, and we plotted the relative locations of each gauge in a 2-dimensional PCA space (as above) to identify major hydrologic differences among the 25 gauges. Second, we used UPGMA agglomerative clustering (Euclidean distances) to group the 25 gauges according to their similarity in terms of all 66 IHA parameters to examine the relationship between gauges within versus among river basins.

Flow regime in geomorphic context

To examine the interaction between reach scale geomorphic context and flow regime, we used simulations for two-modeled channel forms ('entrenched' and 'floodplain') and three actual flow regimes with distinctly different patterns of hydrologic variability: 'snowmelt,' 'perennial flashy,' and 'harsh intermittent' (*sensu* Poff and Ward, 1989; Poff, 1996). By routing these different flow regimes through the modeled channel forms, we illustrate how

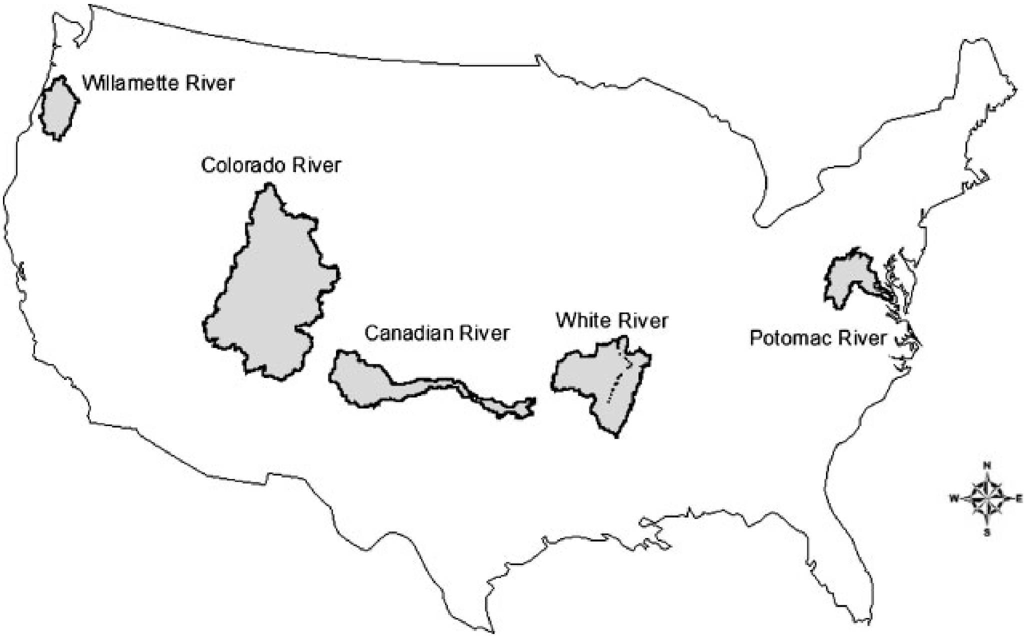


Figure 2. Locations of the five river basins in the United States used to evaluate changes in flow regime characteristics as a function of catchment area and geographic location

conspicuous differences in flow regime may not directly translate into similar differences in bed mobility (disturbance) regime due to the constraints imposed on mobility by channel form. In general, channels and floodplains can respond in complex ways to within-channel and overbank flows as substrate, roughness, bedforms, morphology, hydraulic patterns, and other variables adjust dynamically in space and time. Although we recognize the dynamic complexity of processes involved, our goal here is to produce a simple example illustrating how general differences in geomorphic context within hydrologic sub-regions can alter the instream effects of a particular flow regime.

Hydraulic geometry relationships and stable channel design criteria from Hey (1997) and Julien and Wargadalam (1995) were used to develop realistic cross-sectional forms of the modeled channels. All channels were designed to have a bankfull cross-sectional form determined from downstream hydraulic geometry and the 1.5-year return period flow event computed from annual maxima for each of the three gauge records ($Q_{1.5}$). Bed particle size was kept constant across scenarios, with a median grain size (d_{50}) of 50 mm and d_{84} grain size of 75 mm. The equilibrium channel slopes for all scenarios were designed to provide the same bedload transport capacity per unit width at bankfull discharge ($Q_{1.5}$), with a bankfull dimensionless shear stress of 0.035 referenced to d_{50} Dimensionless shear stress was defined as

$$\tau_* = \frac{hS}{1.65 d_s} \tag{1}$$

where h is main channel depth (equivalent to hydraulic radius for the wide channels modeled), S is slope, and d_s is reference grain size. The resulting channel configurations are realistic based on a variety of hydraulic geometry relationships and channel classifications (Andrews, 1984; Julien and Wargadalam, 1995; Wharton, 1995; Church, 2002).

Consistent at-a-station hydraulic geometry relationships (Knighton, 1998) were used for all channels to compute hydraulic conditions occurring at varying flows in the respective records. 'Entrenched' scenarios extend power trends for at-a-station hydraulic geometry to all flows regardless of whether discharge is greater than or equal to $Q_{1.5}$. Specifically, h increases with $Q^{0.4}$ for all flows. This at-a-station hydraulic geometry is also used in the 'floodplain' scenarios up to $Q_{1.5}$; however, flows exceeding bankfull spread over a wider floodplain zone as defined by $h \sim Q^{0.2}$. The values of hydraulic geometry exponents selected for the floodplain and entrenched scenarios are consistent with measured stage-discharge relationships of channels with and without overbank flows (Marion, 1964; Ackers, 1993; Atabay and Knight, 1999; Shiono *et al.*, 1999).

Table II. Summary statistics for 25 US streamflow gauging stations (in five basins) used for the within-region hydrologic similarity analysis

Sub-basin	Begin	Area (km^2)	MAF (m^3/s)	MAF/Area (ML/year km^2)
Wi1	1957	71	4.0	1773
Wi2	1939	526	19.3	1158
Wi3	1940	1300	47.3	1147
Wi4	1919	5258	132.7	797
Wi5	1948	21 756	769.8	1117
Co1	1939	96	0.5	179
Co2	1910	1564	14.5	292
Co3	1928	10 412	19.3	59
Co4	1910	116 161	204.2	55
Co5	1921	289 561	460.6	50
Ca1	1930	168	0.4	73
Ca2	1927	780	0.6	25
Ca3	1939	2859	1.7	19
Ca4	1928	28 855	11.7	13
Ca5	1938	98 098	168.3	54
Wh1	1939	99	2.7	846
Wh2	1939	782	13.8	557
Wh3	1937	2686	33.7	396
Wh4	1936	12 548	156.8	394
Wh5	1928	66 187	800.6	382
Po1	1950	131	1.2	286
Po2	1937	1476	13.3	285
Po3	1929	2271	32.1	445
Po4	1938	8104	85.1	331
Po5	1930	29 940	291.0	307

A 20-year record of daily streamflow values was analyzed for each gauging station. 'Begin' indicates the first year of this 20-year period. 'MAF' is mean annual flow. Alphanumeric codes are Wi = Willamette River, Co = Colorado River, Ca = Canadian River, Wh = White River, Po = Potomac River, and 1–5 refer to most upstream to most downstream gauge within each basin. See Figure 2 for basin locations.

Bed disturbance intensity was computed with the Einstein–Brown bedload transport equation for gravel (Einstein, 1950; Brown, 1950):

$$q_{bv*} = 2.15e^{-0.391/\tau_*} \quad \text{for} \quad \tau_* < 0.18 \tag{2}$$

where q_{bv*} is dimensionless bedload transport by volume per unit channel width (standardized by fall velocity and grain diameter). No modeled flood event exceeded a τ_* value of 0.08, which is consistent with the field observations of Andrews (1984). Bedload transport per unit width of channel is a reasonable representation of streambed disturbance as the areal proportion of unstable patches in gravel-cobble beds increases with bedload flux (Haschenburger and Wilcock, 2003).

Statistics describing the average duration and number of discrete events of bed disturbance were computed using an incipient motion criterion for mobilization of the coarser fractions of the channel substrates (d_{84}). Based on Andrews and Nankervis (1995), a critical τ_* value of 0.024 was required to initiate motion of d_{84}. Because all channels were modeled in accordance with natural channels (which tend to mobilize d_{50} at less than bankfull discharge), the mobilization of d_{84} provides a reasonable indicator of flow events that result in relatively acute bed disturbance.

RESULTS

Global comparison of streamflow regimes

The first two axes of the PCA explained 32.4% of the total variation (Figure 3) in the hydrologic characteristics of the 463 gauges. Given the large number of indices and the wide variation in their values (Appendix), the PCA performed reasonably well in representing the total variation; however, there were some clear differences among the countries/continents in hydrologic variables (seen in Figure 3B–F). The most heavily weighted variables from among the 66 IHA variables that contribute to the pattern in ordination space are shown in Figure 3A. The most important variables capture hydrologic variation explained by magnitude of daily minimum and maximum flows (inversely correlated), magnitude of seasonal flow patterns (expressed as monthly means of daily flow values), high daily flow variability, and variation in the rise and fall rate of daily flows (inversely correlated). The varying degrees of separation in this hydrologic space for the five countries/continents illustrate both similarities and differences in the hydrologic characteristics among regions.

AU streams (Figure 3B) are characterized by large magnitudes and variation in maximum flows and rise rates, indicating relatively flashy flows both intra- and inter-annually. NZ and EU streams (Figure 3C, E), by contrast, exhibited high-minimum flows, high-baseflow index, high coefficient of variation in fall rate, and relatively high-spring flows. SA streams (Figure 3D) are characterized by high-autumn flows and large coefficient of variation of maximum flow and rise rate. Finally, US streams (Figure 3F) show the broadest variation in flow regimes, essentially spanning the 2-dimensional hydrologic space defined by the other four regions. This broad variation is consistent with previous studies of US streams (Poff and Ward, 1989; Poff, 1996). We note, however, that the most ‘extreme’ streams might be those that load heavily on both PCA I and II, that is, those having the greatest intra- and inter-annual variation, and these are in Australia and South Africa. Although some arid-land US streams also show high variability, the general pattern for AU and SA provides support for the notion that temperate streams in these regions are globally extreme (cf. McMahon *et al.*, 1992; Puckridge *et al.*, 1998), at least for small, gauged basins considered here.

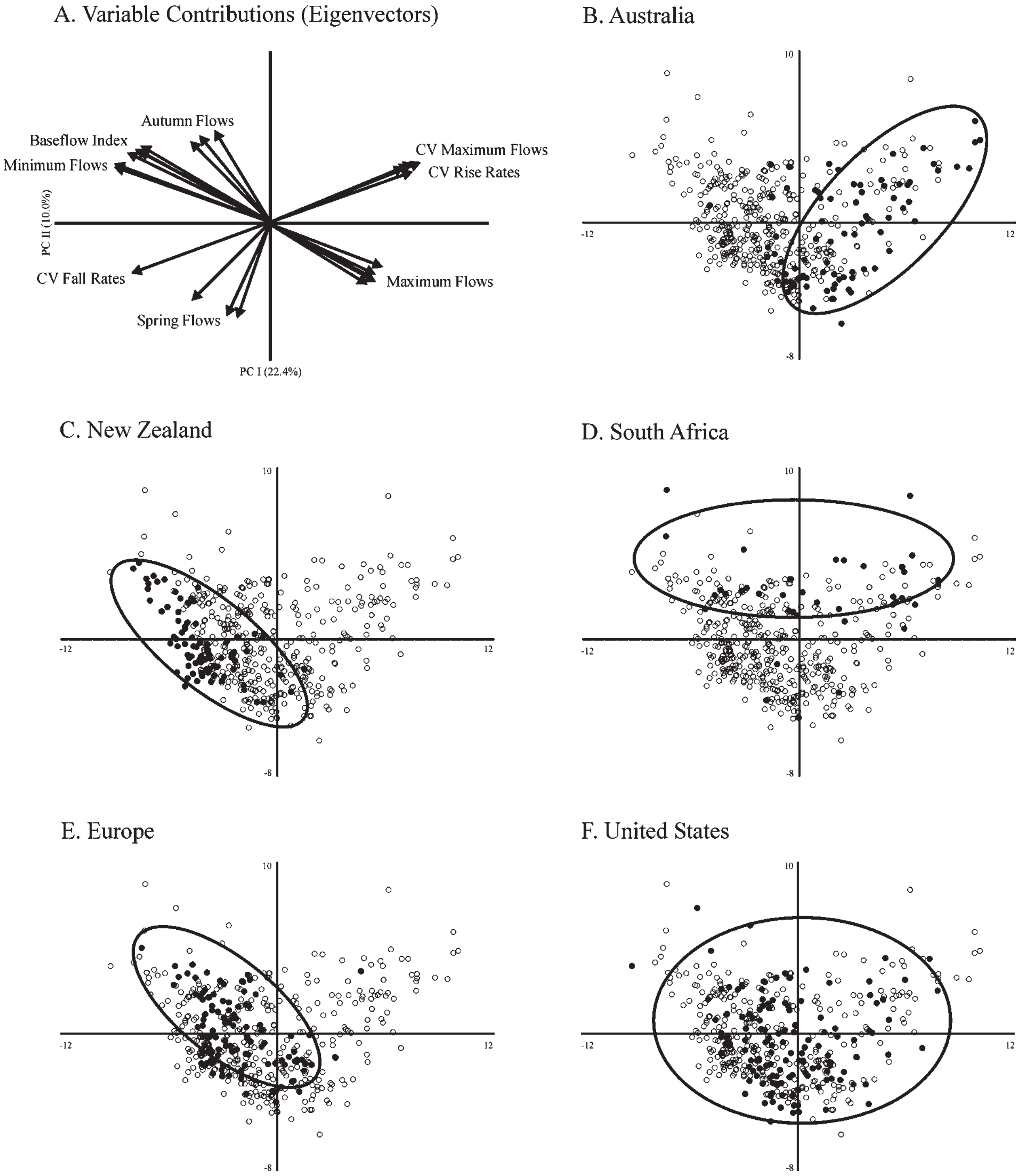
The classification tree analysis revealed the highest correct classification rates for streams in EU and NZ (ca. 86%), followed by US (78%), AU (63%), and SA (43%) (Table III). Thus, NZ and EU streams can be considered most globally distinct based on available gauging records. NZ streams were never misclassified as AU streams, and AU streams were misclassified as NZ streams in only 3 of 83 cases (4%). AU streams were never misclassified as EU streams, and neither SA nor US streams were ever misclassified as NZ streams. Other regions, however, were more similar. Nineteen of 83 (23%) AU streams were misclassified as US streams, and conversely, 23 of 137 (17%) of US streams were misclassified as AU streams. Eleven of 40 (28%) SA streams were misclassified as AU streams, and 9 of 83 (11%) AU streams as SA. Only EU streams were misclassified as all other regions.

These results are largely consistent with the PCA. Despite great overlap in the 2-dimensional space of Figure 3, however, EU and NZ gauges were rarely misclassified with each other, indicating significant separation of these two regions in higher dimensional space (not visible in Figure 3).

Within-region analysis of hydrologic similarity

PCA of the IHAs describing the 25 stream gauges grouped in the five river basins was successful in explaining the dominant flow patterns; the first two principle components explained a total of 46.2% of the variation. The locations of the five gauges within each basin in flow space are shown in Figure 4A, and their locations relative to dominant explanatory hydrologic variables can be seen by examining Figure 4B. The degree of hydrologic similarity varied within river basins as a function of sub-basin size, and sub-basins of roughly the same size varied among themselves across between the rivers.

Three river basins showed relatively high within-basin similarity as sub-basin size increased. For the Willamette basin, all five gauged sub-basins plotted close to one another in ordination space, which appears to reflect the influence of high mean winter (December–March) flows. The larger sub-basins show high variation in fall rates and low interannual variation in maximum flows and spring flows. Streams in this region are generally ‘rain-on-snow’ or ‘winter rain’ types (*sensu* Poff and Ward, 1989; Poff, 1996) and are characterized by a wet regional climate (see Table II) dominated by winter precipitation. In the Potomac basin the pattern of changes in flow variation as a function of increasing sub-basin size are similar to the Willamette; however, these patterns are weak in that the locations of the sub-basins plot near the center of the ordination space. For the Colorado basin all sites exhibit similar mean summer flow influence (May–July), essentially defining the snowmelt signature. Even though the mainstem Colorado River flows through the arid American Southwest, most of its runoff derives from headwater streams, which are characteristically defined by strongly seasonal snowmelt (Poff and Ward, 1989; Poff, 1996).


A. Variable Contributions (Eigenvectors)

B. Australia

C. New Zealand

D. South Africa

E. Europe

F. United States

Figure 3. Multivariate relationship between the 463 gauges defined in PCA space. The two PCA axes, respectively explain 22.4% and 11.0% of the overall variation in space defined by the 66 IHAs. The IHA variables with the highest eigenvector loadings are shown in (A), where single labels may be used to represent a group of similar indices (e.g., 'maximum flows' refers to 1, 3, 7, 30, and 90 day maximum flows (see Appendix)). Locations of five continental region or country stream gauges plotted in the same overall PCA space are shown for Australia (B), New Zealand (C), South Africa (D), Europe (E), and the United States (F)

Table III. Classification matrix for 463 stream gauges based on predictions from a classification tree using 66 IHA variables for each of five regions (AU = Australia, NZ = New Zealand, SA = South Africa, EU = Europe, US = United States)

	N	CC(%)	AU	NZ	SA	EU	US
AU	83	62.7	**52**	3	9	0	19
NZ	88	86.4	0	**76**	3	3	6
SA	40	42.5	11	0	**17**	9	3
EU	115	87.0	3	2	4	**100**	6
US	137	78.1	23	0	2	5	**107**

The number of gauges (*N*) is given for each region, as is the per cent correct classification (%CC). Numbers in boldface along diagonal show the absolute number of gauges correctly classified for each of five regions. Off-diagonals for each row show number of gauges in the corresponding region misclassified into other four regions.

The other two river basins show great variation in flow regimes as a function of increasing sub-basin size. In the Canadian basin the smallest sub-basin is located in the southern Rocky Mountains and it shows some affinity with the Colorado basin, having high August mean flows. As sub-basins increase in size (and increasing incorporate more territory on the southern Great Plains), they are characterized by increasing variability. Intermediate sized sub-basins exhibit high variation in high-flow days and high interannual variation in spring runoff and in maximum flows. The largest river gauge shows reduced interannaul variation in summer (and winter) flows, with both being consistently low. The White basin also varies greatly among its sub-basins. This basin, which drains the Ozark Plateau region of the south central US, is intermediate in precipitation and runoff between the wet Willamette basin and the dry Colorado and Canadian basins (Table II). The smallest, headwater gauge is characterized by high mean maximum flows and by large interannual variation in minimum and summer flows. The largest sub-basin gauges show affinity with Colorado River basin, that is, summer flows with low interannual variation.

A cluster analysis of the 25 gauges based on all 66 IHAs revealed patterns of similarities in the gauges within versus between basins (Figure 5). The smallest sub-basins cluster relatively close together, whereas larger sub-basins show an inconsistent pattern, depending on the particular river system. For example, mid-sized sub-basins in the Willamette, White, and Potomac basins were similar in their flow characteristics, as were the most downstream reaches of the Colorado, White, and Potomac basins. These findings were also supported by the PCA (Figure 4).

Flow regime in geomorphic context

Our simulations of bed mobility in two distinct geomorphic contexts revealed that flow regime alone does not necessarily adequately describe disturbance regime. This is shown in Figure 6, where flow regime type (top panel) does not obviously translate into bedload transport intensity. Further, for each of the three flow regime types, bed transport intensity was much greater for entrenched channels than for floodplain channels (Figure 6). Table IV shows that different flow regime types can have similar substrate disturbance regimes, depending on channel entrenchment. For example, the frequency of disturbance in the entrenched snowmelt scenario (39 events) is nearer the entrenched perennial flashy channel (33) than its floodplain counterpart (14). Similarly, the snowmelt with floodplain scenario has a disturbance duration (5.9 *d*) that is closer to the perennial flashy floodplain (4.4) than the entrenched snowmelt scenario (7.8). When evaluated purely in terms of hydrologic variability, a different picture of ‘flood disturbance’ emerges (Table IV). For these three particular streams, the perennial flashy stream has a higher ‘flood’ frequency than the harsh intermittent stream than the snowmelt stream. Similarly, the duration of ‘flood’ flows is greatest for the snowmelt stream and exceeds the perennial flashy which exceeds the harsh intermittent. Clearly, knowledge of local geomorphology and associated bed mobility adds additional, critical information needed to assess effective disturbance regime in stream and river channels.

DISCUSSION

Global analysis of streamflow regimes

Many previous papers have emphasized regional differences in natural flow regimes. For example, McMahon (1979) first suggested that arid zone stream and rivers have greater interannual variability than their temperate zone

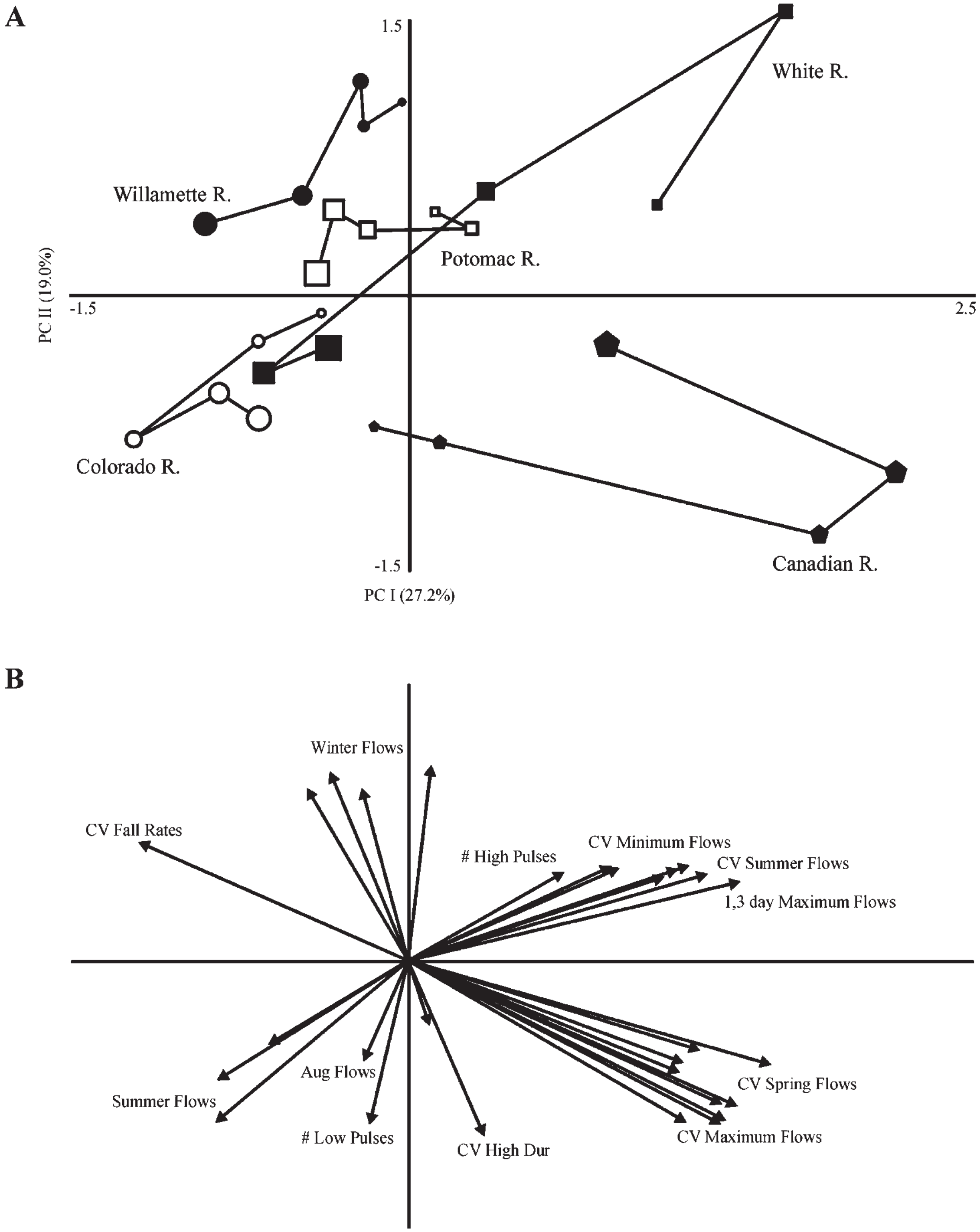


Figure 4. Multivariate relationship among 25 US gauges (grouped by river basin) in 2-dimensional PCA space (A) and the relative loadings of primary IHA variables that best explain the separation of sites in that space (B). Within basins, longitudinal position (i.e., gauge catchment area) is represented by symbol size

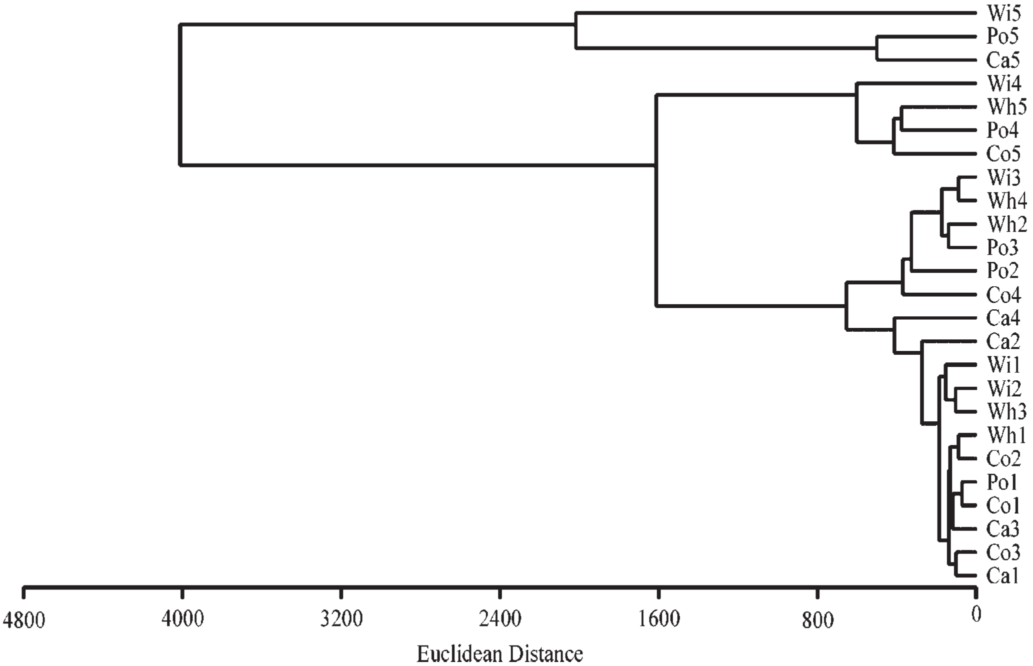


Figure 5. Dendogram for 25 US stream gauges in five river basins based on among-gauge similarity in the 66-dimensional IHA space. Codes are same as in Table II

counterparts. McMahon *et al.* (1992) and Puckridge *et al.* (1998) demonstrated that interannual flow variability in gauged streams/rivers of Australia and South Africa are more variable than the rest of the world. More recent work has suggested the ostensibly higher interannual flow variability in the arid land streams of temperate Australia (and South Africa) flow reflect the dominant control of evapotranspiration rates by evergreen vegetation in the southern hemisphere, versus deciduous in the northern (Peel *et al.*, 2001). Our global analysis of flow regimes provides some additional evidence for this; however, we also note that a number of streams in South Africa and the United States also exhibit high inter-annual variation, indicating that Australian streams are not 'unique' in this sense. The frequent misclassification of Australian streams as belonging to both South African and US regions further emphasizes this similarity.

The main implication of this analysis is that, while there are clearly some regional distinctions in flow regimes, there are also a number of overlaps among regions. This suggests some potential for similar flow management approaches across regions. In this paper, we have not attempted to construct a global classification, so our results are only suggestive of flow regime convergence across broad regional scales. We believe, however, it would ultimately be useful to construct a global classification (stratification) for streamflow, to further encourage international exchange of information and build more unified approaches to flow management across similar (and dissimilar) streams. Indeed, Haines *et al.* (1988) used monthly data to show regional convergence in runoff, providing an encouraging basis for a more detailed analysis using daily flow data. Such an effort would be worth pursuing given the growing availability of daily hydrologic data, although the quality control for synthesizing adequate daily data are not yet in place, at least for many regions of the world.

While it is currently unlikely that a global classification of streamflow regimes can be accomplished at the daily time step, we believe it would be possible to evaluate the convergence in classifications using for the same set of gauges using daily versus monthly versus annual time steps, as Poff (1996) did for several hundred US streams. Given the growing conflicts between human demand and ecosystem needs for water (Poff *et al.*, 2003), we believe such an effort is needed. This would be a very coarse filter, however, as such a classification would capture primarily the broad differences in runoff caused by regional climate, geology, and vegetation. Within any 'similar' stream types, additional issues of spatial extrapolation from the point gauge site and local channel geometry would need to be considered for finer scale application, as we discuss below.

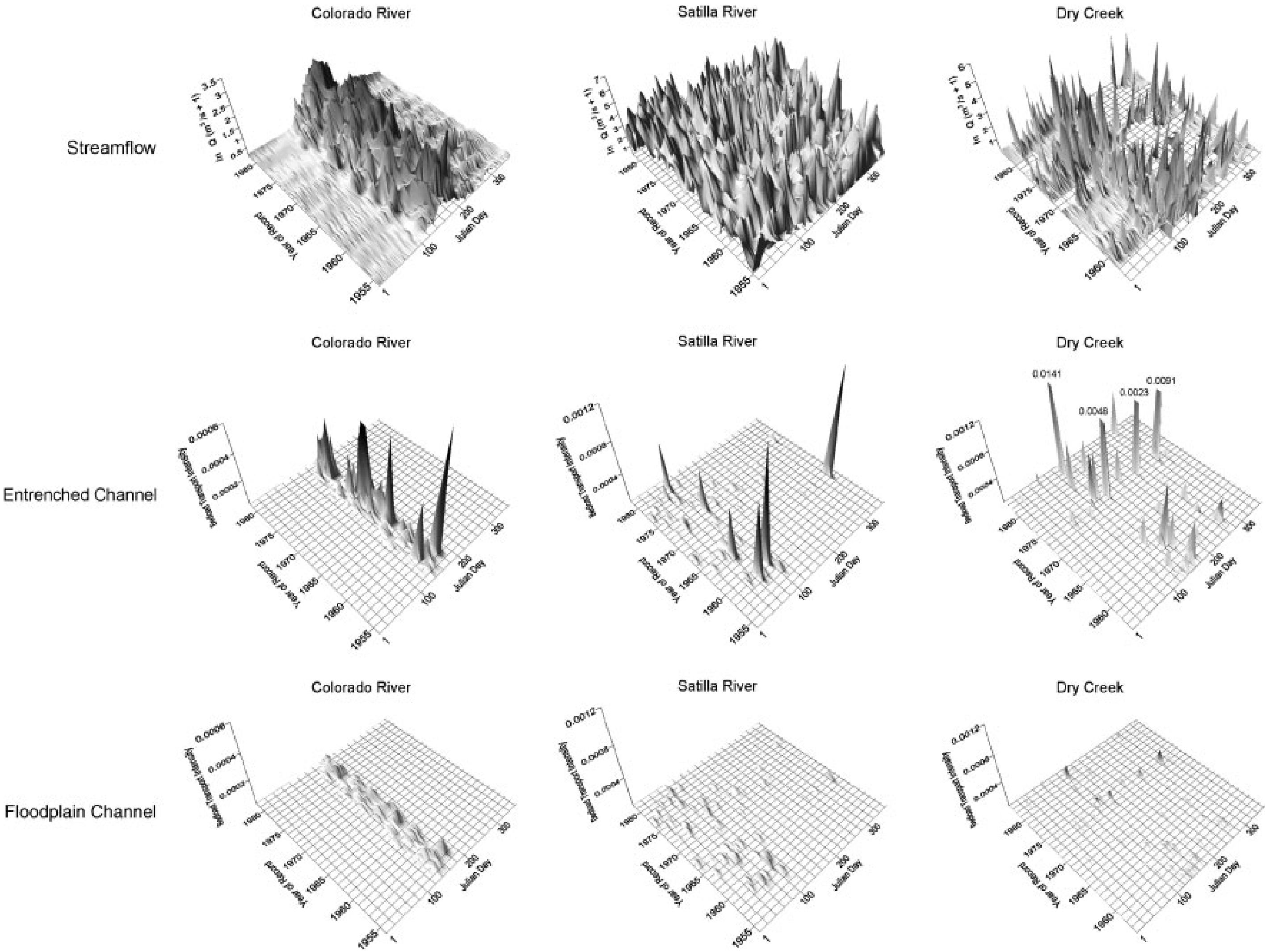


Figure 6. Long-term (30 year) record for daily discharge and bedload transport (movement of d_{84} gravel) for three United States streams under two modeled channel configurations—entrenched and floodplain. Note differences in scale of the response axis in each plot

Table IV. Summary of frequency and duration of d_{84} movement for simulated entrenched and floodplain channels and three distinct flow regimes (see text for details) over a common 30 year period of record

	Snowmelt		Perennial flashy		Harsh intermittent	
	Frequency (events/year)	Mean duration (*d*)	Frequency (events/year)	Mean duration (*d*)	Frequency (events/year)	Mean duration (*d*)
Floodplain	0.47	5.9	0.67	4.4	1.07	1.2
Entrenched	1.30	7.8	1.10	4.3	1.70	1.1
'Flood disturbance'	0.70	12.4	1.06	5.6	0.87	2.44

Specific streams are 'snowmelt' (Colorado River, USGS #09010500), 'perennial flashy' (Satilla River, GA, USGS #02226500) and 'harsh intermittent' (Dry Creek, OK, USGS #07243000) from Poff (1996). Values for 'flood disturbance' are from the dataset used in Poff (1996) and do not incorporate any geomorphic or substrate information.

Within-region analysis of hydrologic similarity

The analysis of the five river basins reveals no consistent pattern in flow regime variation with an increase in sub-basin size. In some basins, gauged sub-basins remain relatively similar in flow regime (Willamette, Potomac, Colorado) whereas others change markedly (Canadian, White). Accordingly, some small streams are more similar to larger rivers than larger rivers are to themselves.

Our findings are interesting, yet we are reluctant to forge many generalizations from them, as this analysis was not comprehensive. For example, we could not tightly control for hydrologic connectivity among the gauges (i.e., available gauges were not always hierarchically nested within sub-basins of increasing size), for differences in the years spanned by the available gauge records, or for sub-basin size across river basins. Further, we did not replicate sub-basin size within basins, nor did we extensively sample whole basins across the US. As with any statistical technique, adding more gauges to the analysis could alter the observed pattern and associated interpretation. Despite these limitations, we believe our findings allow some insights into geographic extrapolation from individual gauges.

Our results suggest that basins in a homogeneous hydroclimatic zone (e.g., the Willamette basin in the US Pacific Northwest or the relatively compact Potomac basin in the eastern US) may maintain some 'coherence' in downstream changes in flow regime. By contrast, the Colorado basin, which begins in strongly seasonal snowfall regions and passing through very arid lowlands, retains a strong snowmelt signal along its course. The Canadian River also flows from snowy mountain headwaters onto an arid plain, but in doing so it flows to the East along a gradient of first decreasing and then increasing mean annual precipitation which is highly variable inter-annually (http://www.ncdc.noaa.gov/oa/ncdc.html). The White River basin occupies a fairly mesic part of the US, and it shows perhaps the most variable response, with its headwaters being most similar to the Willamette and its mouth showing similarities with the Colorado and Potomac rivers.

The important point of the analysis is that it shows how there can be serious limitations in extrapolating flow regime characteristics from individual gauges across scales of even 100s of kilometers. This represents a serious constraint in terms of spatial 'mapping' of flow regimes across the landscape simply from available gauges. Clearly, some 'regionalization' process will be required to model flow regimes at ungauged points in river networks, an effort that is now underway in many parts of the world (e.g., the International Association of Hydrological Sciences 'Predictions in Ungauged Basins' initiative: http://cee.uiuc.edu/research/pub/default. asp).

Flow regime in geomorphic context

Our simulations clearly indicate that geomorphic context influences inferences about hydrologic disturbance regimes, despite the simplifying assumptions made in this analysis. The marked differences in bedload transport resulting from interactions between flows and channel context point to the need to more comprehensively link hydrology and geomorphology in the assessment of stream disturbance and ecological consequences (see Benda *et al*., 2002, 2004). Even in channels with similar morphology and bed material, floodplain connectivity plays an important role in determining the severity of conditions in the main channel and the extent to which the geomorphic template is reworked during flood disturbance events. For example, availability of refugia and retention of wood and other organic materials can be enhanced by floodplain connectivity. Moreover, channel and floodplain geometry, substrate material, slope, and energy dissipation characteristics may not only vary dramatically across stream and river types but also for individual rivers that traverse disparate rock types, valley morphologies, and riparian conditions (Lecce, 1997; Sambrook-Smith and Ferguson, 1995; Montgomery, 1999). Accordingly, understanding the full ecological implications of a particular flow regime necessitates understanding the behavior of substrates and the effects of energy dissipation features including floodplains, sinuous, and other complex plainforms, local morphologic variability, vegetation, and debris.

Concurrent improvements in the resolution of remotely sensed geospatial data and hydrologic predictions in ungauged catchments hold the potential to significantly improve spatially registered models of hydrogeomorphic variability and thus advance riverine ecology. By resolving flow-channel interactions at scales finer than those considered here, such models provide a more realistic characterization of disturbance regimes and a strong physical basis for understanding biological variation within and among catchments. Only by placing hydrology in a geomorphic context can we adequately characterize the hydraulic and habitat characteristics needed to effectively manage and restore river reaches.

PROSPECTUS

Effective management of stream and river flow regimes depends on adequately characterizing the ecologically relevant components of hydrologic variability. However, descriptions of flow variability can be developed at any number of scales (Thoms and Parsons, 2003; Biggs *et al*., 2005), suggesting that a hierarchical approach is needed for robustly classifying hydrologic variation. In this paper, we have shown how characterizations of flow variability or disturbance regimes could be hierarchically considered such that any particular flow regime can be placed in a global context. Hierarchical approaches used in lotic ecology (Frissell *et al*., 1986; Poff and Ward, 1989; Poff, 1997; Snelder and Biggs, 2002) provide some guidance in how such a global classification might be erected. Very broad-scale (regional) characterization of flow regimes could allow a stratification of basins to identify similar hydroecological settings. Within these regions, finer-scale spatial analysis of flow regime types would further assist in hydrologic stratification, based only on the regionally-relevant components of flow variability, as bounded both by regional climate and landscape setting and by a quantitative understanding of the linkages between hydrologic and ecological variability. Finally, within hydrologically homogeneous sub-regions, geomorphic stratification could be applied to identify stream reaches or segments having similar hydrogeomorphic properties.

At the global scale, we have shown regional similarities and differences in flow variability, which reflects broad climatic constraints (and perhaps geologic or vegetative setting). This analysis promotes recognition of similarities across political boundaries and suggests similar flow management techniques may be applicable in geographically distinct areas. Identifying hydrologically similar regions on a global scale can facilitate the development of transferable principles for ecological flow management that can be applied internationally. However, a more thorough accounting of global flow variability is needed because there is important within-region variability, much of which arguably cannot be captured given the existing networks of streamflow gauges. Hydrologic simulation of ungauged river reaches to support hydrologic mapping is a critical research need, one that is now receiving increasing attention. Finally, at the local scale of a river reach, geomorphic context is a key to understanding the actual or effective disturbance regime associated with a particular hydrologic regime. Our simple simulations make this point and indicate that fluvial ecologists need to forge new research in this area so that we may more accurately model the habitat template so critical to effective riverine management and restoration. We believe that multi-scaled characterizations are needed to properly identify ‘reference’ flow/disturbance regimes to guide successful riverine management and restoration.

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Appendix A. Summary of mean values of the hydrologic indices for each continent or country. Reported values are means and coefficient of variation (in brackets). Months in brackets refer to southern hemisphere. All values are unitless (scaled to continent or country mean) except rise and fall rates, which are in m^3/s.

Hydrologic index	Australia	New Zealand	South Africa	Europe	United States
Magnitude of monthly water conditions					
January [July]	0.84 (1341)	1.32 (89)	0.42 (208)	1.02 (94)	0.71 (168)
February [August]	1.25 (200)	1.26 (91)	0.50 (317)	0.99 (100)	0.89 (143)
March [September]	1.36 (176)	1.15 (114)	0.35 (267)	1.13 (92)	1.22 (116)
April [October]	0.84 (1125)	1.14 (93)	0.39 (1086)	1.25 (83)	1.46 (124)
May [November]	0.45 (434)	0.92 (76)	0.57 (277)	1.05 (107)	1.22 (140)
June [December]	0.28 (268)	0.82 (69)	0.65 (133)	0.91 (92)	0.89 (159)
July [January]	0.25 (326)	0.64 (63)	0.82 (3251)	0.68 (116)	0.49 (209)
August [February]	0.33 (545)	0.52 (63)	0.87 (345)	0.52 (147)	0.37 (243)
September [March]	0.34 (1064)	0.54 (73)	0.86 (867)	0.55 (164)	0.31 (263)
October [April]	0.25 (546)	0.65 (77)	0.49 (316)	0.66 (149)	0.33 (510)
November [May]	0.28 (1201)	0.88 (68)	0.35 (257)	0.81 (123)	0.46 (159)
December [June]	0.45 (955)	1.14 (82)	0.40 (995)	0.93 (99)	0.60 (135)
Magnitude and duration of annual extreme water conditions					
1-day Minimum	0.05 (377)	0.25 (44)	0.12 (64)	0.13 (27)	0.12 (195)
3-day Minimum	0.05 (199)	0.25 (58)	0.13 (319)	0.14 (39)	0.12 (133)
7-day Minimum	0.05 (477)	0.26 (52)	0.13 (80)	0.15 (47)	0.13 (125)
30-day Minimum	0.06 (690)	0.31 (59)	0.15 (785)	0.20 (88)	0.16 (165)
90-day Minimum	0.08 (208)	0.41 (56)	0.17 (415)	0.28 (205)	0.21 (149)
1-day Maximum	26.24 (155)	10.69 (57)	18.26 (126)	8.85 (66)	16.17 (99)
3-day Maximum	16.17 (152)	6.96 (53)	11.74 (128)	6.88 (61)	10.50 (98)
7-day Maximum	9.61 (146)	4.53 (48)	6.93 (135)	5.19 (58)	6.97 (94)
30-day Maximum	4.24 (133)	2.46 (42)	3.23 (132)	3.12 (51)	3.62 (80)
90-day Maximum	2.68 (120)	1.73 (37)	2.27 (131)	2.14 (46)	2.35 (67)
#Zero-flow days	22.63 (69)	0.30 (2)	71.98 (137)	32.29 (132)	6.55 (13)
Baseflow Index	0.05 (526)	0.26 (51)	0.16 (64)	0.15 (50)	0.14 (137)
Timing of annual extreme water conditions					
Min. Julian date	215 (15)	83 (18)	170 (16)	99 (24)	206 (17)
Max. Julian date	136 (26)	233 (34)	193 (21)	131 (23)	105 (22)
Frequency and duration of high and low pulses					
#Low pulses	4.2 (101)	9.8 (66)	3.5 (94)	3.4 (103)	5.8 (103)
Low pulse duration	12.9 (136)	8.8 (67)	6.2 (640)	6.5 (113)	11.5 (128)
#High pulses	7.0 (73)	17.3 (39)	8.6 (70)	10.4 (58)	9.3 (63)
High pulse duration	11.2 (120)	5.8 (58)	6.6 (174)	8.8 (68)	12.4 (97)
Frequency and rate of water condition changes					
Rise rate	116.4 (151)	498.8 (47)	3.0 (115)	4.8 (41)	178.2 (91)
Fall rate	45.0 (139)	195.0 (45)	1.6 (108)	2.9 (34)	78.4 (83)
#Reversals	83.2 (34)	111.1 (14)	71.0 (62)	58.5 (34)	90.8 (23)