

A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors

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SUMMARY

1. Relatively undisturbed streams in continental U.S.A. were classified according to variation in ten ecologically relevant hydrological characteristics. Measures of flow variability and predictability for average conditions, as well as for low- and high-flow extremes, were extracted from long-term (15–58-year) daily streamflow data for 806 streams.

2. Two groups of sites were analysed: all 806 sites and a subset of 420 'best' sites. For each group, cluster analysis identified ten distinctive stream types, seven permanent and three intermittent. The geographical clustering exhibited by the stream types indicated regional differences in climatic and geological features. A bootstrapping technique applied to the permanent stream classes showed the majority of them were statistically robust.

3. The derived classification of U.S. streams based on ecologically relevant hydrological characteristics provides a comprehensive catalogue of small to mid-size streams that, according to ecological theory, may differ in major aspects of their ecological organization. The classification provides a basis for hypothesis generation and affords an objective framework for matching streams for purposes of comparative ecological investigations.

4. A subset of 118 streams from the ten classification groups was selected to determine whether certain hydrological variables often used by ecologists to make cross-system comparisons are sensitive to the temporal coarseness of the hydrological time series used to derive the variables. The three hydrological variables considered were streamflow predictability, streamflow variability and flood timing.

5. Streamflow predictability (using Colwell's Index) was calculated at daily, weekly, monthly and seasonal time scales. Estimates of predictability showed either no change across time scales, a gradual and consistent increase across time scales, or a maximum value at the monthly time scale. Coefficient of variation of streamflow was calculated at daily, weekly, monthly, seasonal, and annual time steps. Daily values were always greatest for all streams. Some groups showed minimum variability at the monthly scale, others at the seasonal. Timing of daily peak flows could be detected with 50–90% accuracy across stream groups using coarser grain monthly and annual hydrographic data.

6. Inferences about hydrological similarity among streams across broad geographical scales can be sensitive to choice of time scale used in the hydrological characterization.

Introduction

There is growing interest in characterizing streamflow regimes across geographical scales to make inferences about lotic ecosystem structure and function (e.g. Resh *et al.*, 1988). Because streamflow mediates many physiological and ecological processes in streams (e.g. gas exchange, timing and success of reproduction, habitat selection, etc.), hydrological *variation* has come to be viewed as an important element of the habitat template (*sensu* Southwood, 1977) that influences population and community dynamics in streams (Minshall, 1988; Schlosser, 1990; Poff & Ward, 1990; Hildrew & Giller, 1994; Townsend & Hildrew, 1994). Accordingly, geographical patterns of hydrological variation among streams can suggest regional-scale differences in ecosystem structure and function (Poff & Ward, 1989; Naiman *et al.*, 1992). However, hydrological analysis can provide information useful to ecologists and managers only if *ecologically relevant* aspects of the hydrological regime are identified and analysed and then put into a geographical context. Different combinations of streamflow variation (e.g. range and predictability), patterns of flooding (e.g. frequency and predictability) and extent of intermittence are critical variables that *presumably* result in different degrees of physical control over biotic organization in streams (Minshall, 1988; Resh *et al.*, 1988; Poff & Ward, 1989, 1990; Richter *et al.*, 1996). Most comparative geographical studies have considered only a few measures of flow variability, e.g. mean flow conditions (Hawkes, Miller & Layher, 1986; Moss *et al.*, 1987; Townsend, Hildrew & Schofield, 1987), variation about the mean flow (Horwitz, 1978), short-term estimates of flood frequency (Cushing *et al.*, 1980, 1983; Minckley & Meffe, 1987; Fisher & Grimm, 1988), and predictability of monthly flow patterns (Bunn, Edward & Loneragan, 1986; Resh *et al.*, 1988). Fewer comparative studies have considered several hydrological factors simultaneously (but see Poff & Ward, 1989; Hughes & James, 1989; Jowett & Duncan, 1990). A useful method of describing geographical variation in streamflow patterns is classification, where similar 'types' of hydrological regimes are identified and associated. The scale at which streamflow classifications have been previously constructed range from regional (Gentilli, 1952; Alexander, 1985; Hughes & James, 1989; Jowett & Duncan, 1990; Richards, 1990) to continental (Grimm, 1968; Poff & Ward, 1989) to

global (Beckinsale, 1969; McMahon, 1979, 1982; Haines, Findlayson & McMahon, 1988).

The first objective of this research was to develop an ecologically relevant classification of naturally flowing streams and rivers based on their geographical distribution. An earlier analysis (Poff & Ward, 1989) used seventy-eight streams to show that hydrological variation of ecological interest exists for U.S. streams and rivers. The present paper reports on a comprehensive extension of that earlier effort by examining 806 streams and rivers from the continental U.S., and it serves two purposes. First, it establishes patterns in hydrological regimes for virtually all unregulated, gauged streams with largely unregulated flow in the continental U.S. Establishment of such broad geographical patterns can provide useful baseline information for assessing regional hydrological changes, such as those induced by climate change (Wallis, Lettenmaier & Wood, 1991; Dolph & Marks, 1992). Second, the geographical distribution of hydrological regimes can help identify similar streams for the purpose of broad-scale, comparative ecological research, an area of growing interest in stream ecology (e.g. Resh *et al.*, 1988).

Interest in comparing hydrological similarity among stream ecosystems is relatively new, and 'standard' methods for establishing similarity do not exist. Indeed, stream ecologists have paid little attention to the sensitivity of important hydrological variables to the method by which such variables are characterized. For example, hydrological extremes are recognized for the constraints they impose on stream communities, and a host of important ecological questions arise from considering the temporal distribution (regime) of such extremes (see Resh *et al.*, 1988; Poff, 1992). Yet the temporal resolution in hydrological data required to characterize a stream's disturbance regime adequately is not clear. If monthly (or seasonal) data are as useful as daily data in describing accurately the frequency and predictability of extreme events, then the task of matching sites is made much easier, because monthly (or seasonal) data are generally more accessible than are daily data. However, the usefulness of coarse grain data to describe extreme events may depend on regional climate or local catchment geology and thus may vary geographically among streams.

Similarly, it is not clear how sensitive are estimates

of streamflow variability (irrespective of spates) to the temporal grain of the hydrological time series used to derive the estimates. For example, a formal index for calculating streamflow predictability (Colwell, 1974) has seen increasing use in the literature (see Gordon, McMahon & Findlayson, 1992) and has been calculated at both the monthly (Bunn *et al.*, 1986; Resh *et al.*, 1988) and daily (Poff & Ward, 1989) time scales. Although this index is known to be sensitive to the length of the hydrological time series used in its calculation (Gan, McMahon & Findlayson, 1991), there has been no assessment of whether the index is sensitive to the time step used to calculate it, or whether relative differences in predictability among streams depend on the time step.

The second objective of this research therefore was to evaluate how the characterization of hydrological regime varies with the degree of aggregation of hydrological data (from daily to annual). General flow variability is first examined using the coefficient of variation of flow and Colwell's (1974) predictability index. Variation in the characterization of extreme events (spates) as a function of data aggregation is also examined. A specific goal of this analysis was to determine whether sensitivity to temporal aggregation varies among the stream types identified in the hydrological classification.

Materials and methods

Streamflow classification

Sample selection. Data were acquired from a commercially available database (EarthInfo, 1990) that consists of a digital compilation of the U.S. Geological Survey (USGS) daily and peak values files on CD-ROM. Each of the *c.* 7000 stations in the dataset was scanned to determine if the stream met certain specific criteria: (i) little or no flow regulation (e.g. diversion, damming, groundwater pumping); (ii) little or no catchment urbanization; (iii) a period of record ≥ 20 -year of continuous daily streamflow data, preferably extending throughout water year 1985; (iv) an accuracy rating of 'good' or 'better' for almost the entire record of flow values; and (v) catchment area ≤ 5000 km² (to keep all streams relatively small). The *c.* 1200 sites resulting from this search were matched against two independently derived datasets containing compilations of undis-

turbed streams (Wallis *et al.*, 1991; Slack & Landwehr, 1992) to produce a final dataset of 806 sites, which were divided into two subsets. One contained 420 sites with records that included water year 1985 and that were 36–56-year long. Stable estimates of streamflow predictability result when *c.* 40 years of data are used (Gan *et al.*, 1991). Period of record was not held constant across sites to use all available data in producing long-term estimates of flood and lowflow regimes. The second subset contained all 806 sites, which had at least 15 years of continuous daily flow data ending after 1978. These two subsets were analysed separately to provide: (i) a core classification of the 'best' gauged sites available ($n = 420$) in the U.S., and (ii) a classification of all 'acceptable' sites ($n = 806$), which, while satisfying less rigorous criteria, none the less represents the exhaustive classification based on available data. The names and locations of these sites (and statistical summaries) are contained in Poff & Allan (1993) and are available from the Global Climate Change Information Management Systems in EPA's Environmental Research Laboratory in Duluth, MN.

Definition of flow variables. Four general categories of hydrological variables were defined for extraction from the long-term hydrological records. A computer program written in True-Basic language (Kemeny & Kurtz, 1988) was used to extract hydrological variables. Documentation for this program and the values of the extracted variables for each site are housed at the EPA, Duluth.

Static basin descriptors. These variables contain no information about hydrological variability. *Elevation* (m) is the datum above sea level of the stream gauge. *Basin drainage area* (AREA, km²) is the surface area of the catchment topographically above the gauge elevation. *Daily mean discharge* (QMEAN, m³ s⁻¹) is the average daily flow at the site over all years in the record. *Mean annual run-off* (MAR, m yr⁻¹) is the ratio of QMEAN/AREA expressed as a depth. MAR, which represents the difference between annual evaporation and precipitation (Gordon *et al.*, 1992), was suggested by Hughes & Omernik (1983) as an alternative for stream order in classifying stream and catchment size across different hydroclimatological regions.

Measures of flow variability and predictability. These variables assess the degree of variation in daily discharge. *Coefficient of variation* (DAYCV, %) is the average (across all years) of the standard deviation of the daily flows divided by the annual mean daily flow, multiplied by 100. DAYCV describes overall flow variability without considering the temporal sequence of flow variation. *Predictability of flow* (DAYPRED, %) was determined using an index developed by Colwell (1974), which is based on information theory. When expressed as a percentage, this index ranges in value from 0 to 100 and is composed of two independent, additive components: constancy (C), a measure of temporal invariance, and contingency (M), a measure of periodicity. The index can be used to express the degree to which flow 'states' (i.e. quantity of discharge) are predictably distributed across specified time intervals (here, days). For example, a stream with a discharge that never varies would be perfectly predictable, with all the predictability deriving from the constancy component. Theoretically, a stream with fluctuating discharge could also be completely predictable due to perfect contingency, i.e. streamflow changes state with certainty on a daily basis. Predictability values are sensitive to definition of the flow states, which are ultimately arbitrary (Gordon *et al.*, 1992), and to some extent period of record (Gan *et al.*, 1991). In this analysis, flow was divided into eleven categories partitioned at 0.1, 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, and 2.25 times the logarithm of the overall mean flow (i.e. standardized mean for a stream = 1.00). Thus, the eleven flow states ranged from < 0.125 to > 64 times mean flow.

High flow disturbance. This is defined as flows of magnitude exceeding a return interval of 1.67 years based on a log-normal distribution. The 'annual peak flow series' for each station was used to determine these flood values, because the peak series provides the maximum *instantaneous* (rather than 24-h) flow values that are needed to determine flood frequencies properly. The peak values were assumed to represent a sample from a log-normal distribution (see Dunne & Leopold, 1978; p. 306); hence, by knowing the mean and variance of the sample, floods of specified probability of occurrence can be calculated (e.g. a 2-year flood has a 50%

probability of occurring in any given year and is represented by the mean value of the annual series on a logarithmic scale). A flow with a 1.67-year return interval is often recognized as 'bankfull,' but this may vary regionally and with climate. The bankfull stage, according to Dunne & Leopold (1978; p. 608) corresponds to the 'discharge at which channel maintenance is most effective. in doing work that results in the average morphological characteristics of the channels'. Thus, this level of flow can be considered an index of physical habitat disturbance in streams (see Poff & Ward, 1989). The flood history for a site was determined by regressing the log of the peak flow values against the log of the corresponding 24-h mean flows (i.e. those occurring on the same dates as the peak flows) so that 'daily flood' values could be determined. The long-term daily flow record was then analysed with respect to these 'daily flood' values.

Several measures were derived for the entire period of record. *Flood frequency* (FLDFREQ, yr⁻¹) is the average number of discrete flood events per year having a magnitude \geq that of the 1.67-year flood. A 10-day period separating individual bankfull events was used as a criterion to identify separate bankfull events. *Flood duration* (FLDDUR, days) is the average number of days that flow remains above the flood threshold for a site. *Seasonal predictability of flooding* (FLDPRED, dimensionless) is the maximum proportion of all floods over the period of record that fall in any one of six 60-day 'seasonal' windows. This index ranges from 0.167 (uniform seasonality) to 1.0 (perfectly seasonally predictable) For this metric, the 'partial duration series' from the Earth-Info CD-ROM was used. All instantaneous flows \geq 1.67-year return-interval flow in the period of record were ordered according to day of the year, and the temporal distribution of this collapsed data set was analysed for seasonal patterns. High flows occurring within 30 days of the beginning or end of the water year were considered to fall within the same 'season'. *Timing of flooding* (FLDTIME, day) is the day of the water year marking the beginning of the 60-day period when FLDPRED was highest. This variable was not used as a primary classification variable, but was used to evaluate the range of timing of flood onset within groups of hydrologically similar streams as identified by the cluster analysis. *Seasonal predictability of non-flooding* (FLDFREE, dimensionless) is the maximum proportion

of the year (number of days/365) during which no floods have ever occurred over the period of record. Again, the partial series was used and no-flood periods were allowed to pass through the end of one water year into the beginning of the next.

Low flow disturbance. Low flows were characterized both by identifying periods of zero discharge and by calculating lowflows of specified return intervals. The latter was accomplished by taking the annual 1-day minimum 24-h low-flow values for a station and assuming that they represent a sample from a population with a Gumbel (extreme value) distribution (Linsley, Kohler & Paulhus, 1982; p. 375). The parameters from this distribution were used to calculate 1-day low flows with various return intervals. The long-term daily record was scanned to locate periods when low flows with ≥ 5 -year recurrence intervals occurred. Several low flow variables were derived. *Baseflow Index* (BFI, %) is the average annual ratio of the lowest daily flow to the mean daily flow times 100. It indexes flow stability and susceptibility to drying. *Extent of intermittence* (ZERODAY, days) is the average annual number of days having zero discharge. *Seasonal predictability of low flow* (LOWPRED, dimensionless) is the proportion of low-flow events ≥ 5 year magnitude falling in a 60-day 'seasonal' window (as described above for flood predictability). *Timing of low flow* (LOWTIME, day) is the day of the water year marking the beginning of the 60-day period when LOWPRED was highest. This variable was not used as a primary classification variable, but was used to evaluate the range of timing of low-flow onset within groups of hydrologically similar streams as identified by the cluster analysis. *Seasonal predictability of non-low flow* (LOWFREE, dimensionless) is the maximum proportion of the year (number of days/365) during which no 5-year + low flows have ever occurred over the entire period of record.

Statistics. Basic relationships among hydrological variables were evaluated with Pearson correlation coefficients among the ten hydrological classification variables and the four static basin descriptors. To identify meaningful classifications of the stream sites, ecologically relevant criteria were used. First, streams were categorized a priori as either 'permanent' or 'intermittent' streams. The permanent groups of streams generally had continuous discharge, although

sites with ≤ 10 d yr⁻¹ of no discharge recorded at the stream gauge were included in this group. Within the intermittent group, streams having > 90 d yr⁻¹ of zero flow were classified as 'harsh' streams. These divisions, while arbitrary, represent a preferential variable weighting guided by the established ecological importance of flow permanence in regulating lotic process and pattern (e.g. Delucchi, 1988, 1989; Grimm, 1992; Stanley & Valett, 1992; Ward, 1992).

Sites having similar hydrological features within the permanent and intermittent groups (excluding the harsh streams) were clustered using the two-stage density linkage method provided in SAS's PROC CLUSTER (SAS, 1988). This non-parametric clustering uses a k -th nearest neighbour criterion, which seeks regions surrounding local maxima in the estimated probability density function associated with a set of variables. The method is robust even when true clusters are known to be of unequal size and variability, or when the clusters are irregularly (e.g. non-convex) shaped (SAS, 1988). In the absence of a priori expectations regarding the shape, size or dispersion of stream clusters, a non-parametric approach is reasonable.

Determining the number of clusters in an arbitrary data set is a problem which lacks a clear statistical solution. Wong & Schaack (1982) suggest applying the clustering algorithm with different values for the nearest neighbour parameter. Therefore, clustering solutions were identified that gave consistent estimates of the number of modes of the distribution across a range of parameter values, while at the same time yielding clusters with clear interpretations. Precedence was given to scientific interpretability rather than to arbitrary criteria based on unsupported statistical assumptions. A distinct advantage of this method *v* other k -th nearest neighbour methods (e.g. k -means clustering used by Poff & Ward, 1989) is that individual sites are always assigned to the same cluster for a fixed sample size. k -means clustering produces slightly different cluster memberships depending on the initial input order of the sites.

Stream cluster stability. Given that the number of clusters was arbitrarily set, it is critical that the stability of the putative clusters be examined. To avoid reliance on parametric assumptions, a method based on bootstrapping, a computer-intensive method of drawing repeated resamples from the original data (Efron, 1979), was developed and applied to the 383 per-

manent streams from the 420 sample set. First, 383 resamples were drawn with replacement (i.e. the same stream could be drawn more than once to keep sample size constant) from the original set of 383 points in the permanent stream dataset. Second, the two-stage density linkage clustering algorithm was applied to identify seven clusters from the 'new' collection of 383 points. Third, the set of resampled points was assessed in terms of the number of points sharing membership both in a resample-derived cluster as well as in an original cluster. Two indices were computed for the resample. $M_{o|r}$ is the proportion of points in resample clusters, which also were together in original clusters, and it represents the extent to which resample clusters represent the membership structure of the original clusters. $M_{r|o}$ is the proportion of points in original clusters, which also were together in resample clusters, and it represents the tendency for points originally clustered together to stay together, regardless of which resample cluster they are assigned to. Fourth, the process was repeated 200 times, at which time there was no further change in the average values of $M_{r|o}$ and $M_{o|r}$.

Sensitivity of hydrological descriptors to data aggregation

Site selection. Sites for analysis were selected from each of the classification groups derived from the 420 site data set of gauged streams (see above). For each of the classification groups, the streams closest to the multivariate centroid of the group were selected by inspection to insure that the sample would represent the sites most characteristic of each group. Of the original ten groups identified by the cluster analysis (see Results), two had members that occurred both in the eastern and the western U.S., regions that differ in climatic seasonality. These two groups were partitioned geographically (for a total of twelve groups) to evaluate the extent to which the classification results were robust against geographical location. No more than twelve sites per classification group were selected for a total sample size of 118 gauged streams. Each site was evaluated for a 36-year period (1950–85), a length of time sufficient to allow a stable estimate for Colwell's Index of predictability (see Gan *et al.*, 1991).

Temporal scale and flow variability. Flow variability was measured using the coefficient of variation and

Colwell's Index (see above for definitions). For coefficient of variation, five increasingly coarse time steps were used: daily, weekly, monthly, seasonal and annual. For the predictability index, only daily, weekly, monthly and seasonal time steps were used (because Colwell's Index cannot calculate predictability at the coarsest time step available). These time intervals span the range of temporal frames with which stream ecologists generally work. For each site, a daily matrix consisted of 365 days \times 36 years of data. Day 366 of leap years was omitted. The weekly matrix was derived by taking the average weekly flow for fifty-two separate 7-day periods for each of the 36 year (with day 365 omitted). The monthly matrix was derived by determining the average flow for each calendar month of the year. The seasonal matrix consisted of four, 3-month 'seasons', starting with 1 October. The null hypotheses were that neither the coefficient of variation nor Colwell's predictability values would vary within the twelve streamflow types as a function of temporal scale used to calculate the values. Differences among the twelve groups were tested for each time step after arcsine transformation (predictability index) or logarithmic transformation (coefficient of variation) with one-way ANOVA and Student–Newman–Keuls multiple comparison tests (SAS, 1988).

Temporal scale and extreme events. To determine how effectively hydrological data of coarse temporal resolution can assess transient events (spates) in streams, monthly and annual flow statistics were compared with daily flow statistics. If coarse grain data (e.g. monthly to annual) are capable of allowing detection of transient events then, at a minimum, the signatures of the maximum daily (instantaneous) flow ought to be present in the time series of the coarse grain data. For the *monthly* time scale, the month in each of the 36 years having the highest average flow was determined. Using the 36-year daily flow matrix, the frequency with which the annual maximum daily flow occurred in the same month having the highest average flow was determined. For example, a stream with the highest daily flow each year in the same month having the highest average monthly flow would score a maximum proportion of 1.0. Differences among the twelve groups were tested with respect to proportion of matched flow events after arcsine transformation

Table 1 Range (minimum and maximum) and selected percentiles (10, 25, 50, 75 and 90) for five static descriptors used in the 420 and 806 sample analysis

	Period of record (yr)	Elevation	Area (km ²)	Mean daily flow (m ³ s ⁻¹)	Mean annual runoff (m yr ⁻¹)
420 streams					
Minimum	35	0	22	0.06	0.006
10%	38	27	169	1.58	0.091
25%	44	117	339	3.86	0.240
50%	48	229	787	8.76	0.402
75%	57	385	1577	18.29	0.607
90%	58	884	2777	32.73	0.828
Maximum	58	2996	4947	111.78	4.144
806 streams					
Minimum	15	0	4	0.03	0.003
10%	22	27	80	1.53	0.061
25%	31	117	211	2.11	0.232
50%	42	235	518	5.51	0.397
75%	50	412	1228	13.14	0.598
90%	58	884	2183	26.61	0.851
Maximum	58	2996	4947	111.78	4.144

with one-way ANOVA and Student–Newman–Keuls multiple comparison tests (SAS, 1988).

The feasibility of using average *annual* flow data in assessing peak daily flows was assessed using rank correlation. For each year, the annual maximum daily flows and annual average flows were determined, and the thirty-six values in each series were ranked (allowing for ties). Spearman's rank correlation coefficient (r_s) was determined for the ranks of these two series. The null hypothesis of no positive correlation between the daily and annual series for each individual stream site was tested using a one-tailed Spearman's r (Conover, 1971; p. 248). Differences among the twelve groups with respect to average rank correlation were examined after arcsine transformation with one-way ANOVA and Student–Newman–Keuls multiple comparison tests (SAS, 1988).

Results

Streamflow classification

Statistical characteristics across sites. Gauged stream sites were available from all states and for most ecoregions and USGS hydrological units. The gauged sites exhibited a wide range of values for several important static descriptors, including catchment area, mean daily flow, mean annual run-off, gauge elevation, and period of record (Table 1). Correlations among hydrological variables across all sites were generally low. Of the

ninety possible pairwise correlations, only twelve exceeded an absolute value of 0.40 (i.e. $r^2 \geq 0.16$) for both the 420-site and 806-site data sets (Table 2). The similar correlation structure for both data sets suggests that linear relationships among hydrological variables were relatively robust, irrespective of record length or specific years in the period of record.

Statistical relationships among clusters. For the 420 and 806 site samples, ten clusters were formed into groups of permanent and intermittent streams and given abbreviations (Table 3). Among the intermittent streams, sites having > 90 days of zero flow per year were characterized as harsh intermittent (HI). Two clusters were identified for the remaining intermittent streams: intermittent flashy (IF) and intermittent run-off (IR) streams. For the permanent group of streams, a seven cluster solution was accepted as most interpretable. For the 420- and 806-site samples, six clusters were shared: perennial run-off (PR), stable groundwater (GW), superstable groundwater (SS), snow + rain (SR), snowmelt (SN) and perennial flashy (PF) streams. For the 420 site sample, the seventh cluster was a variant of snow + rain (SR2), while for the 806-site sample, the seventh cluster was a variant of snowmelt (SN2).

The statistical properties of these ten clusters (seven permanent + three intermittent) are given for the 420-site sample in Table 4, which indicates sources of

Table 2 Matrix of Pearson correlation coefficients for 13 variables on 420 streams (upper panel) and 806 streams (lower panel). Variables in parentheses were not used in derivation of clusters. Variable definitions are given in Methods. Correlations (>0.12) are significant at $\alpha = 0.05$ level (Bonferroni test). Correlations >|0.40| are bold-faced. See text for descriptions of variables

	(AREA)	(QMEAN)	(MAR)	DAYCV	DAYPRED	BFI	ZERODAY	FLDFREQ	FLDPRED	FLDFREE	FLDDUR	LOWPRED	LOWFREE
<i>n</i> = 420	1.00												
(AREA)	1.00												
(QMEAN)	0.57	1.00											
(MAR)	-0.23	0.41	1.00										
DAYCV	-0.03	-0.27	-0.34	1.00									
DAYPRED	0.10	0.44	0.42	0.73	1.00								
BFI	-0.01	0.07	0.09	0.56	0.60	1.00							
ZERODAY	-0.07	-0.16	-0.18	0.60	-0.23	-0.19	1.00						
FLDFREQ	0.15	-0.08	-0.23	0.39	-0.32	-0.12	0.34	1.00					
FLDPRED	0.09	0.16	0.09	-0.12	0.28	0.06	0.03	-0.14	1.00				
FLDFREE	0.07	0.15	0.15	-0.02	0.20	0.03	0.09	-0.04	0.81	1.00			
FLDDUR	0.25	0.02	-0.24	0.12	0.07	0.07	0.10	0.13	0.59	0.55	1.00		
LOWPRED	0.19	0.16	0.38	-0.23	0.25	-0.26	-0.20	-0.31	-0.03	-0.01	-0.19	1.00	
LOWFREE	-0.18	0.20	0.39	-0.32	0.28	-0.28	-0.28	-0.31	-0.04	-0.04	-0.19	0.85	1.00
<i>n</i> = 806													
(AREA)	1.00												
(QMEAN)	0.57	1.00											
(MAR)	-0.23	0.36	1.00										
DAYCV	-0.01	-0.27	-0.36	1.00									
DAYPRED	0.09	0.41	0.40	0.57	1.00								
BFI	0.02	0.09	0.09	0.52	0.58	1.00							
ZERODAY	-0.02	-0.18	-0.24	0.67	-0.13	-0.24	1.00						
FLDFREQ	0.09	-0.08	-0.22	0.25	-0.29	-0.12	0.21	1.00					
FLDPRED	0.07	0.12	0.08	-0.11	0.31	0.04	0.04	-0.15	1.00				
FLDFREE	0.05	0.09	0.14	-0.04	0.26	0.02	0.09	-0.09	0.82	1.00			
FLDDUR	0.26	0.02	-0.24	-0.07	0.13	0.04	0.17	0.08	0.61	0.56	1.00		
LOWPRED	-0.20	0.14	0.38	-0.31	0.22	-0.16	-0.30	-0.24	0.02	0.03	-0.17	1.00	
LOWFREE	-0.23	0.15	0.42	-0.39	0.28	-0.13	-0.38	-0.23	0.01	0.02	-0.18	0.84	1.00

Table 3 Listing of abbreviations for 10 clusters formed in the 420- and 806-site analyses

Category	420 sites	806 sites	Description
Perennial	PR	PR	perennial runoff
	GW	GW	stable groundwater*
	SS	SS	superstable groundwater
		SR	snow + rain
	SR1		snow + rain, type 1 [†]
	SR2		snow + rain, type 2
	SN		snowmelt
		SN1	snowmelt, type 1
	SN2	snowmelt, type 2	
	PF	PF	perennial flashy
Intermittent	IR	IR	intermittent runoff
	IF	IF	intermittent flashy
	HI	HI	harsh intermittent

*Equivalent to Poff & Ward's (1989) 'mesic groundwater' stream type.

[†]Equivalent to Poff & Ward's (1989) 'winter rain' stream type.

significant variation among clusters in terms of the ecologically important hydrological variables. For the intermittent streams, the HI group averaged 190 days yr^{-1} without flow. The IF and IR groups showed many fewer days of no discharge while differing from one another both in terms of average intermittence and average flood frequency. Among the permanent streams, the SN group sites had very high seasonality of flooding, the snow + rain streams had intermediate seasonality of flooding coupled with very high seasonality of low flow and either a stable or variable daily flow. The PR streams were characterized by low-flood seasonality coupled with high seasonality of low flow and variable daily flow. The GW group had low variability in daily flow coupled with aseasonal flooding, while the SS streams showed extremely stable daily flow and very high baseflow stability. The PF group exhibited high flow variability and high flood frequency with low seasonality for both floods and low flow events. Figure 1 provides a graphical summary of a dichotomous key for classifying streams according to the hydrological variables derived in this analysis.

The distinction between SR1 and SR2 clusters in the 420-site sample cannot be easily discerned from the hydrological variables or basin descriptors used in the study. However, SR1 streams tended to be at lower elevation and to have an earlier onset of flooding

(mid-December, Table 4) due to heavy precipitation (rainfall) generated by seasonal Pacific storms. High elevation and inland SR streams had flooding more heavily influenced by snowmelt (median day = 21 February). This contrast suggests that the SR1 group is very similar to Poff & Ward's (1989) 'winter rain' stream group, while the SR2 cluster more closely represents their 'snow + rain' stream group.

The clusters for the 806-site sample were segregated in very similar fashion (Table 5) except that two SN groups (rather than two snow + rain groups) were formed. The distinction between SN1 and SN2 clusters in the 806-site sample can be appreciated by examining the differences among clusters in terms of average timing of flood onset and elevation (Table 5). SN1 sites tended to be at higher elevations, which would contribute to a more enduring snowpack and a later seasonal onset of snowmelt. In practical terms, SN1 and SN2 could be lumped together to form a unitary SN group for the 806-site sample, as the ecological distinction among the two groups is subtle at best.

Geographical distribution of clusters. The spatial distribution of the identified clusters showed reasonably good geographical affiliation. Results for the 420-site and 806-site analyses are presented in Figs 2 and 3, respectively. Inspection of these figures shows there is good agreement between the two analyses in terms of geographical distribution of stream types and in stability of cluster membership, although some differences are seen for individual streams. PR sites were mostly in the east, as were GW streams. SS sites were predominantly upper mid-western in distribution. Snowmelt streams were mostly restricted to the Rocky Mountain region, but for the 806 site analysis, a noticeable proportion (five of twelve) of SN1 streams occurred in the upper Midwest (Fig. 3). Snow + rain streams occurred in the Pacific north-west and along the northern tier of states, with SR1 showing a more coastal and SR2 a more interior distribution in the 420 site analysis (Fig. 2). PF streams were located mostly in the Midwest along the forest-prairie transition zone. Among the intermittent stream types, HI streams were most strongly associated with the northern prairie, the southern prairie and the far south-west. IF streams appeared to occur in the forest-prairie transition zone of the southern plains, while IR streams were more widespread, showing a more eastern, northern and far western distribution.

Table 4 Numerical means and standard deviations (in parentheses) of sixteen variables and ten clusters for 420 gauged stream sites. Variables in parentheses were not included in the two-stage cluster routine at any time, but are included for comparative purposes. For intermittent streams, excluded variables are indicated by '-'. For each of the ten hydrological variables, the minimum and the maximum average values for each stream group are indicated by boldfacing and italics, respectively. For the variables FLDTIME and LOWTIME, only the median values for each cluster are given

	Perennial runoff (PF)	Stable water (GW)	Super ground-stable (SS)	Snow rain (SR1)	Snow + rain (SR2)	Snowmelt (SN)	Perennial flashy (PF)	Intermittent runoff (IR)	Intermittent flashy (IF)	Harsh intermittent (HI)
N	209	55	17	27	29	22	24	20	10	7
DAYCV	173.5 (46.9)	114.3 (36.9)	86.4 (49.1)	167.4 (40.5)	111.6 (28.8)	134.1 (27.3)	270.4 (42.1)	289.2 (91.0)	474.5 (85.3)	481.0 (123.0)
DAYPRED	56.0 (11.6)	72.7 (3.9)	73.2 (5.5)	64.9 (9.3)	76.0 (7.0)	78.8 (10.5)	34.0 (9.8)	29.8 (7.2)	20.4 (4.7)	47.1 (13.6)
BFI	7.3 (5.6)	27.8 (8.1)	47.5 (16.8)	5.4 (3.9)	18.2 (8.3)	15.8 (8.5)	<i>4.4</i>	-	-	-
ZERODAY	0.4 (1.3)	0.0 (0.0)	0.0 (0.0)	0.4 (1.7)	0.02 (0.12)	0.05 (0.02)	2.4 (2.9)	21.7 (8.5)	43.7 (17.4)	189.7 (58.7)
FLDFREQ	0.69 (0.13)	0.80 (0.16)	0.66 (0.09)	0.75 (0.16)	0.68 (0.08)	0.65 (0.10)	0.97 (0.13)	0.79 (0.16)	0.94 (0.19)	1.04 (0.30)
FLDPRED	0.47 (0.12)	0.43 (0.09)	0.62 (0.14)	0.68 (0.11)	0.68 (0.14)	0.97 (0.06)	0.48 (0.11)	0.55 (0.15)	0.46 (0.13)	0.58 (0.14)
FLDFREE	0.23 (0.12)	0.19 (0.11)	0.37 (0.14)	0.57 (0.09)	0.46 (0.10)	0.79 (0.11)	0.31 (0.13)	0.39 (0.20)	0.19 (0.12)	0.46 (0.16)
FLDDUR	3.0 (2.5)	2.6 (1.6)	4.3 (2.4)	2.9 (1.6)	3.7 (2.5)	9.6 (2.7)	2.8 (0.9)	-	-	-
(FLDTIME)	143	149	126	100	170	218	205	167	229	148
LOWPRED	0.74 (0.16)	0.61 (0.14)	0.43 (0.07)	0.87 (0.10)	0.78 (0.16)	0.70 (0.17)	0.48 (0.11)	0.61 (0.13)	0.46 (0.05)	0.49 (0.16)
LOWFREE	0.64 (0.17)	0.51 (0.17)	0.26 (0.09)	0.76 (0.10)	0.66 (0.18)	0.62 (0.16)	0.31 (0.13)	0.53 (0.20)	0.76 (0.05)	0.25 (0.17)
(LOWTIME)	310	307	304	312	280	98	318	293	285	245
(AREA)	1128	1324	1144	546	1099	1417	1310	1133	845	644
(QMEAN)	13.0 (12.8)	17.5 (14.7)	11.5 (8.8)	20.2 (24.3)	27.6 (27.8)	23.7 (30.5)	8.4 (5.9)	5.2 (5.0)	3.0 (2.4)	0.4 (0.2)
(MAR)	0.44 (0.26)	0.49 (0.21)	0.44 (0.40)	1.28 (0.94)	1.11 (0.96)	0.43 (0.20)	0.22 (0.12)	0.22 (0.18)	0.12 (0.02)	0.03 (0.03)
(POR)	49.7 (7.0)	50.4 (6.5)	50.4 (5.8)	46.1 (7.8)	49.2 (7.2)	49.1 (7.0)	47.0 (7.3)	43.9 (7.1)	43.8 (5.7)	43.0 (6.9)

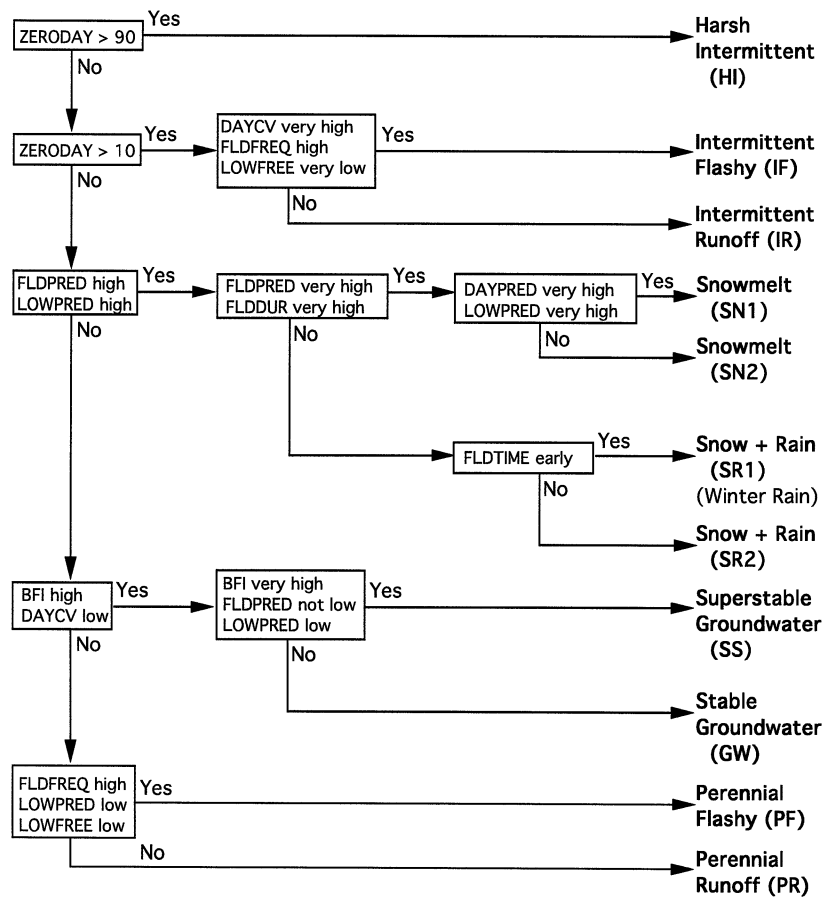


Fig. 1 Flowchart for assigning individual streams to stream groups for both the 420- and 806-stream classifications. Magnitudes of variables used to partition streams into groups are qualitative and relative to the range of variable values in Tables 4 and 5. Individual streams classified with this key are likely to fall into the identified group; however, misclassifications would result because not all variables included in the original clustering are used in the figure (see text).

Stream cluster stability. To assess the 'robustness' of the clusters identified in this analysis, the 383 permanent streams from the 420 'best' sites were selected and a bootstrapping technique used (see Methods). Based on 200 replicates, the median value of M_{r10} was 0.80 (5th and 95th percentile values = 0.69 and 0.87, respectively), indicating that streams originally clustering together tended to stay together. The median value for M_{o1r} was 0.54 (5th and 95th percentile values = 0.42 and 0.68, respectively), indicating that points which are together in the resample-based clusters do not necessarily share common original clusters. In other words, the resample clusters tended to join together several of the original clusters. Inspection of the resample clusters showed that original clusters PR, SS, SN and PF were highly reproducible, but that clusters GW, SR1 and SR2 often merged together into the PR group.

Analysis of sensitivity to data aggregation

A total of 118 streams were selected from the ten groups identified by the above-described streamflow

classification. Two of the ten groups were further subdivided based on geographical criteria. PR and GW streams occurred both in the eastern and western U.S., regions that have differential seasonality of precipitation. These two groups were divided into eastern and western subgroups (PR-E and PR-W, and GW-E and GW-W) to determine whether estimates of hydrological variables were sensitive not only to data aggregation but to geographical location as well. The number of streams included in the analysis varied among the twelve operational groups, because only those sites that were closest to the multivariate centroid of each classification group were selected (by inspection). Final sample sizes were as follows: PR-E (11), PR-W (11), GW-E (11), GW-W (4), SS (12), SR1 (9), SR2 (12), SN (11), PF (12), IR (10), IF (9) and HI (6).

Colwell's Index: differences among groups for fixed time steps. Clear differences among the twelve identified groups were found in terms of flow predictability at all temporal scales. For all four time steps, significant ($P < 0.0001$) among-group differences existed (Fig. 4).

Table 5 Numerical means and standard deviations (in parentheses) of sixteen variables for ten clusters for 806 gauged stream sites. Variables in parentheses were not included in the two-stage cluster routine at any time, but are included for comparative purposes. For intermittent streams, excluded variables are indicated by '-'. For each of the ten hydrological variables, the minimum and the maximum average values for each stream group are indicated by boldfacing and italics, respectively. For the variables FLDTIME and LOWTIME, only the median values for each cluster are given

	Perennial runoff (PR)	Stable water (GW)	Super ground-stable (SS)	Snow + rain (SR)	Snowmelt (SN1)	Snowmelt (SN2)	Perennial flashy (PF)	Intermittent runoff (IR)	Intermittent flashy (IF)	Harsh intermittent (HI)
N	384	84	23	101	48	12	54	49	21	40
DAYCV	175.1 (53.8)	108.5 (37.9)	73.4 (49.3)	142.1 (41.9)	139.5 (29.1)	175.8 (27.8)	312.1 (89.9)	272.4 (82.9)	430.1 (100.1)	496.9 (192.3)
DAYPRED	55.4 (11.9)	72.0 (5.4)	74.4 (5.2)	68.4 (10.9)	77.6 (9.3)	58.7 (4.9)	33.8 (9.4)	31.7 (6.7)	20.6 (4.1)	48.9 (17.2)
BFI	8.3 (7.1)	29.5 (10.0)	51.3 (17.7)	10.4 (7.6)	15.2 (7.1)	9.7 (4.9)	3.5 (4.8)	-	-	-
ZERODAY	0.43 (1.3)	0.0 (0.0)	0.0 (0.0)	0.11 (0.90)	0.01 (0.06)	0.06 (0.16)	2.5 (2.9)	24.5 (12.4)	39.1 (18.6)	183.5 (68.4)
FLDFREQ	0.71 (0.20)	0.74 (0.15)	0.67 (0.09)	0.75 (0.18)	0.62 (0.11)	0.66 (0.10)	0.87 (0.14)	0.81 (0.17)	0.88 (0.17)	0.91 (0.25)
FLDPRED	0.47 (0.12)	0.44 (0.10)	0.63 (0.12)	0.69 (0.10)	0.96 (0.08)	0.91 (0.11)	0.44 (0.09)	0.53 (0.14)	0.46 (0.10)	0.58 (0.13)
FLDFREE	0.24 (0.13)	0.19 (0.09)	0.39 (0.14)	0.53 (0.12)	0.77 (0.15)	0.74 (0.17)	0.21 (0.12)	0.36 (0.19)	0.19 (0.11)	0.42 (0.18)
FLDDUR	2.8 (2.2)	2.3 (1.5)	4.4 (2.8)	3.6 (2.4)	9.9 (2.7)	7.0 (1.7)	2.7 (1.3)	-	-	-
(FLDTIME)	147	142	106	200	220	170	166	210	214	170
LOWPRED	0.74 (0.16)	0.65 (0.14)	0.45 (0.10)	0.81 (0.15)	0.76 (0.16)	0.57 (0.19)	0.54 (0.40)	0.65 (0.13)	0.49 (0.06)	0.47 (0.14)
LOWFREE	0.66 (0.17)	0.57 (0.16)	0.28 (0.09)	0.72 (0.15)	0.68 (0.16)	0.50 (0.16)	0.39 (0.19)	0.54 (0.19)	0.23 (0.10)	0.25 (0.15)
(LOWTIME)	310	313	305	265	275	285	293	268	285	251
(AREA)	916	757	1233	804	969	1082	1041	754	997	870
(QMEAN)	(980)	(901)	(1154)	(891)	(1112)	(1549)	(795)	(965)	(1027)	(1074)
(MAR)	10.2 (11.1)	12.1 (13.2)	12.0 (10.5)	18.9 (9.0)	16.3 (22.0)	5.9 (24.6)	6.3 (6.1)	4.0 (3.9)	2.8 (0.7)	0.6 (0.3)
(POR)	0.46 (0.28)	0.58 (0.28)	0.40 (0.35)	1.06 (0.89)	0.48 (0.20)	0.27 (0.16)	0.20 (0.14)	0.27 (0.18)	0.14 (0.08)	0.05 (0.06)
	42.4 (11.7)	42.5 (12.9)	47.6 (9.0)	39.3 (12.7)	39.2 (12.8)	37.3 (11.8)	40.3 (11.6)	35.7 (11.0)	40.6 (7.1)	29.8 (9.8)

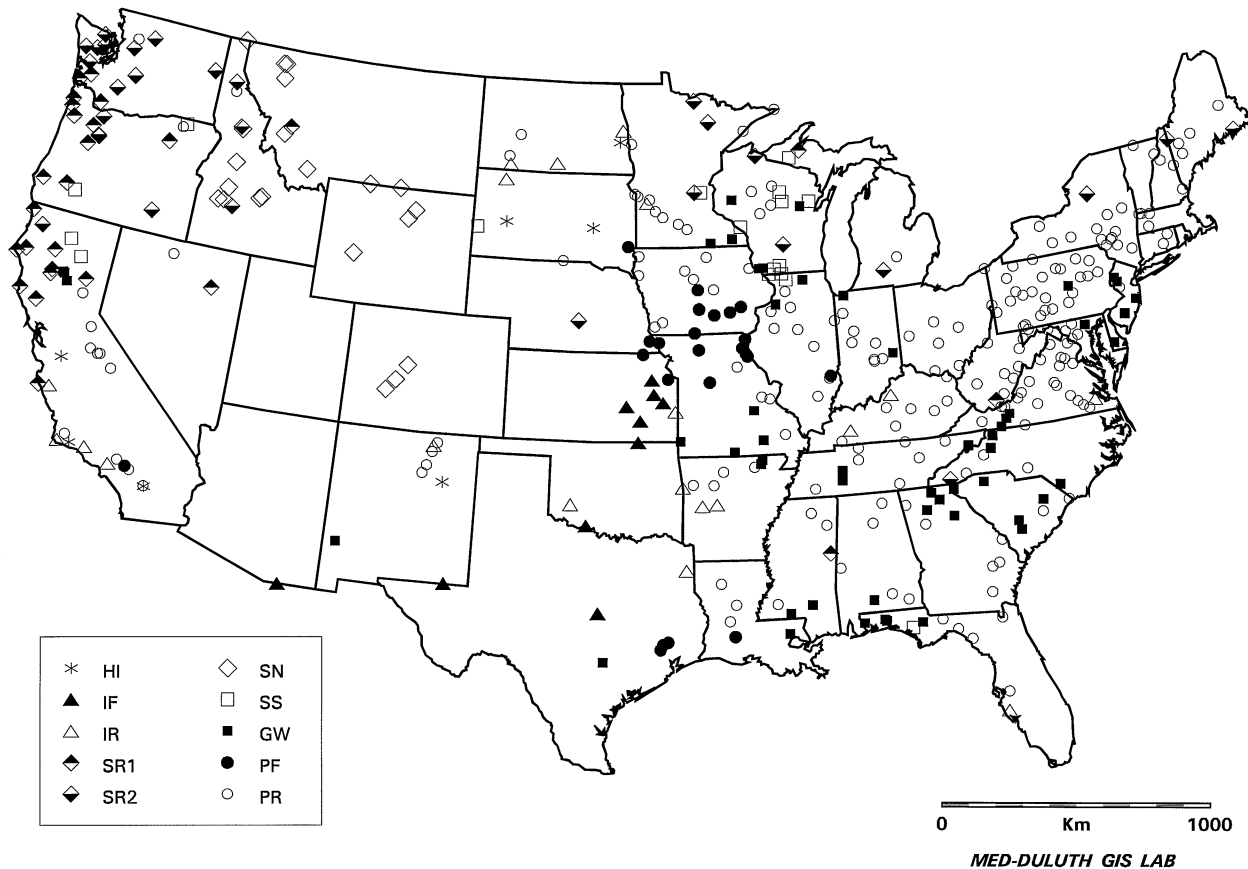


Fig. 2 Geographical locations of 'best' 420 gauged streams grouped into ten clusters based on ten hydrological descriptors. HI = harsh intermittent, IF = intermittent flashy, IR = intermittent run-off, SR = snow + rain (types 1 and 2), SN = snowmelt, SS = superstable groundwater, GW = stable groundwater, PF = perennial flashy, PR = perennial run-off.

Significant pairwise differences among groups were examined for each predictability measure using the SNK multiple comparisons test (SAS, 1988). The following groups were always statistically similar for all four predictability time steps: SN and SR2; SS and SR2; GW-E, GW-W, and SS; PF and IR; IR and IF. SR1 and SR2 streams were always different, except for the monthly time step. Geographical location did not obscure the hydrological patterns characterizing eastern and western PR and GW groups: GW-E and GW-W were always the same, and PR-E and PR-W differed for only the monthly time step.

Colwell's Index: differences within groups for variable time steps. The twelve groups fell into three categories. First, a set of four stream types (SN, SR1, SR2 and GW-W) showed no discernible change in predictability with increasing time scale (Fig. 4a-d). Second, two groups (PR-E and GW-E) showed slight increases in predictability with increasing time step. Third, the

remaining perennial groups (SS, PR-W and PF) and the intermittent groups (IR, IF and HI) showed large increases in predictability at the monthly time scale relative to other time scales. Differences between PR-W and PR-E at the monthly time scale (Fig. 4) indicated some geographical sensitivity in calculation of Colwell's predictability within the PR cluster.

Coefficient of variation: differences among groups for fixed time steps. For all five time steps, there were significant ($P < 0.0001$) among-group differences (Fig. 5). Differences among groups in terms of relative variability were greatest at the daily time step and least at the seasonal time step. Across all five time steps, the most variable streams were always in the HI, IF and IR groups. SS streams always showed the lowest variation. Significant pairwise differences among groups were examined for each time step using the SNK multiple comparisons test (SAS, 1988). The following groups were always statistically similar for all five

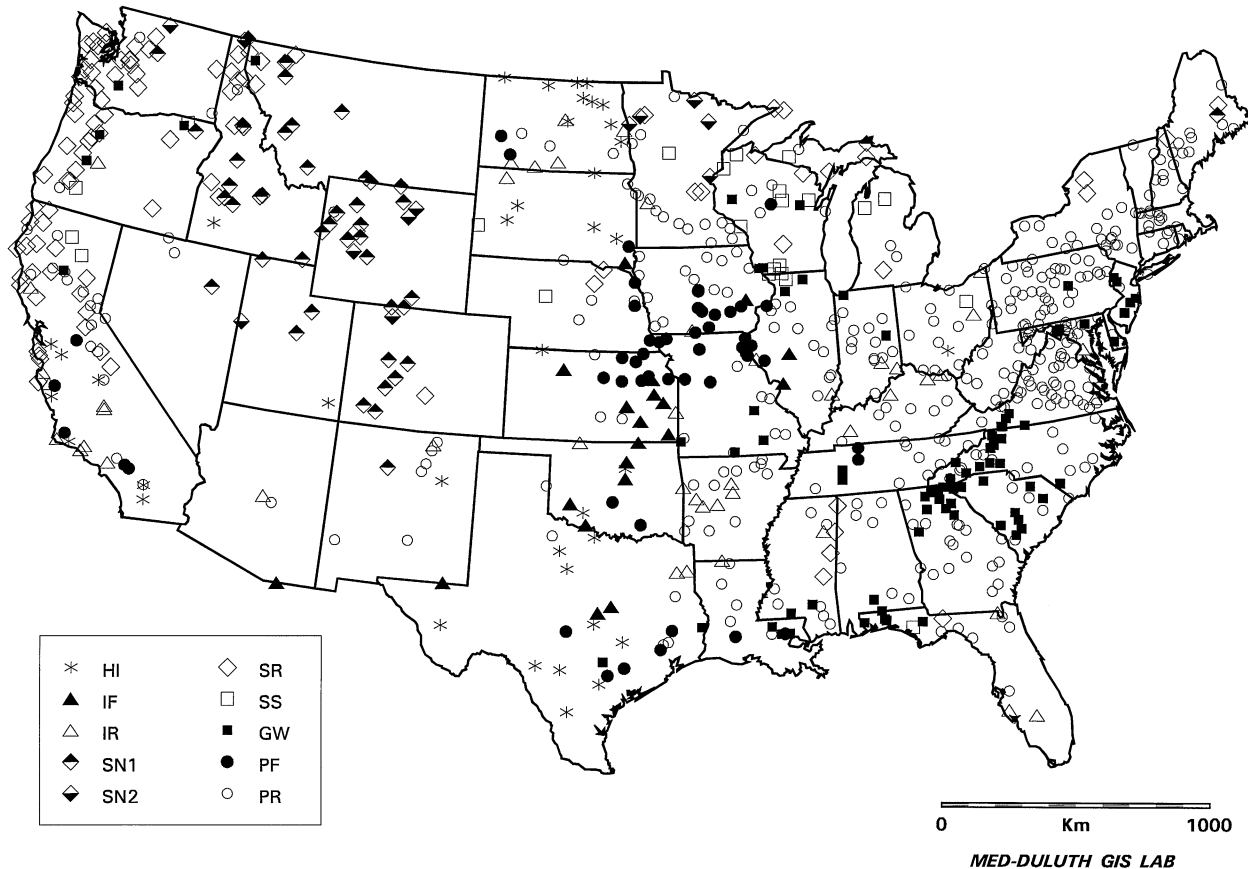


Fig. 3 Geographical locations of all 806 gauged streams grouped into ten clusters based on ten hydrological descriptors. HI = harsh intermittent, IF = intermittent flashy, IR = intermittent run-off, SR = snow + rain (types 1 and 2), SN = snowmelt, SS = superstable groundwater, GW = stable groundwater, PF = perennial flashy, PR = perennial run-off.

time steps: IR and PF; PR-E and PR-W; and, GW-E and GW-W. SR1 and SR2 were different at daily, seasonal and annual time scales. The similarity of PR-E and PR-W and of GW-E and GW-W suggests that geographical location does not obscure the hydrological patterns characterizing these groups using coefficient of variation.

Coefficient of variation: differences within groups for variable time steps. All twelve groups showed maximum variability at the daily time step (Fig. 5). Declines in variability at longer time steps followed three patterns. A set of five stream types (HI, IF, IR, PF and PR-E) showed minimum variability at the seasonal scale, followed by an increase in variability at the annual scale. Interestingly, these five stream types showed the greatest variability among all stream types for daily coefficient of variation used in the earlier cluster analysis. The three most seasonal stream groups (SN, SR1 and SR2) showed minimum variability at the

monthly time scale, followed by an increase at the seasonal and annual time steps. The remaining stream groups (SS, GW-E, GW-W and PR-W) attained minimum variability at the monthly time and did not change at longer time steps. These groups were the least variable in terms of daily variability. Slight differences between PR-W and PR-E streams indicated some geographical sensitivity in calculation of the coefficient of variation for within the PR cluster.

Daily v monthly data in characterizing spates. The correspondence between months with the highest average flow and months having the maximum daily flow for the year ranged from 30 to 90% across the twelve groups (Fig. 6a). The groups with the greatest percentage of concurrence were SN and HI streams, both of which had median scores > 80%. All other groups had medians > 60%, with the exception of PR-W streams, which had a median score < 50%. An SNK multiple comparisons test distinguished a more pre-

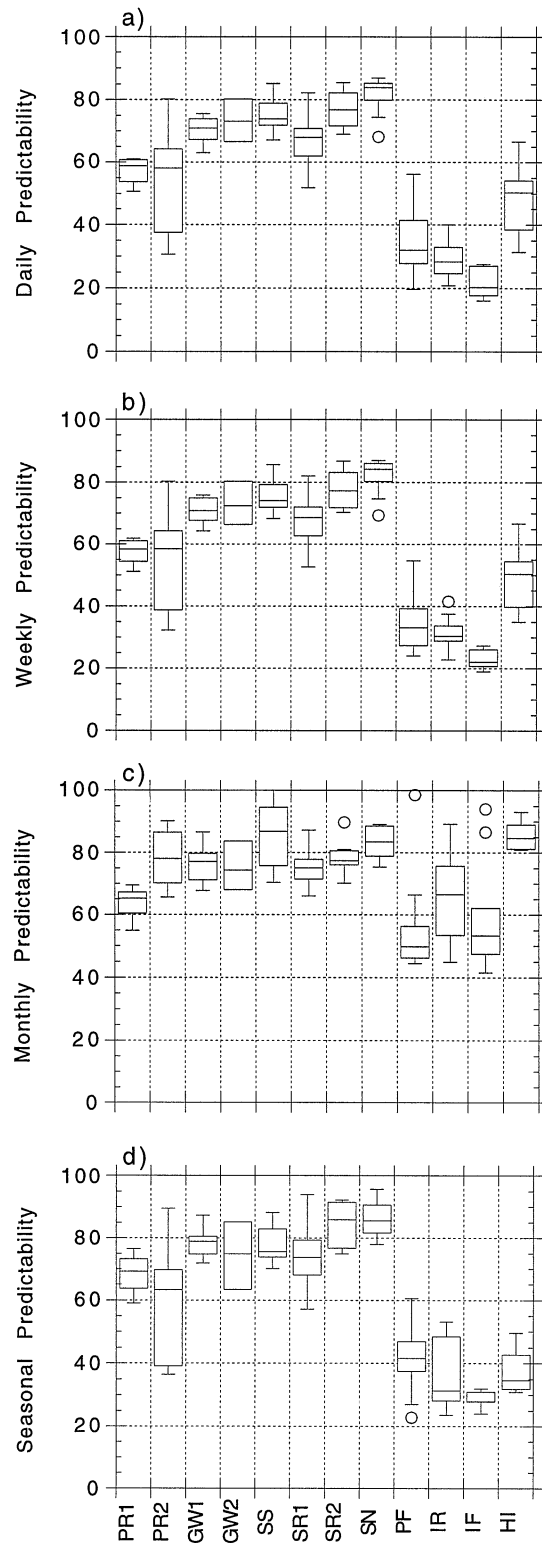


Fig. 4 Range of values for Colwell's (1984) Index of predictability calculated for 118 sites in twelve groups for each of four different time steps over a common 36-year period. Each box encloses 50% of the observed values (median = horizontal line). Observed range is contained within upper and lower bars except for extreme outliers (circles). Stream-type abbreviations as in Fig. 2 (except PR and GW clusters are divided into eastern and western subgroups—see text).

dictable group of stream types (HI and SN) from a less predictable group (PR-E, PR-W, GW-E, GW-W, SS and SR1).

Daily v annual data in characterizing spates. When the rank correlations between the 36-year series of annual maximum daily flows and annual mean flows were

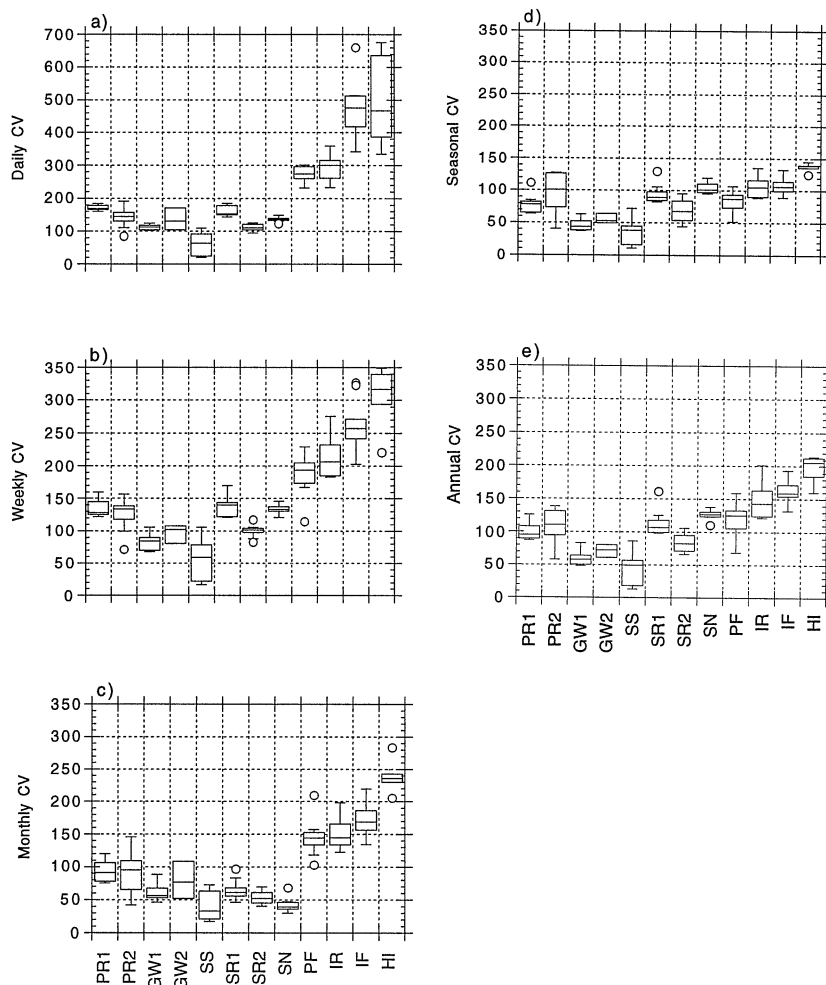


Fig. 5 Range of values for coefficient of variation calculated for 118 sites in twelve groups for each of five different time steps over a common 36-year period. Legend as in Fig. 4.

determined, values ranging from 0.32 to 0.95 were observed (Fig. 6b). For a sample size of thirty-six, a r_s value > 0.30 was significant at $\alpha = 0.05$; therefore, all 118 individual streams used in the analysis had significant correlations between ranked annual maximum and annual average flows. For all twelve stream groups, medians exceeded 0.60, with the exception of PR-E streams. HI streams were the only group with a median exceeding 0.90. The HI and IR streams had significantly higher correlation coefficients than did the PR-E, SR2, GW-E and SS streams.

Discussion

Streamflow classification

The stream classification presented here provides a hydrogeographic description of free-flowing streams in the continental U.S. Because the classification is based on hydrological variables of ecological interest,

streams that cluster together presumably share certain ecological features. The results of this paper are similar to those of Poff & Ward's (1989) analysis of only seventy-eight streams. A discussion of the ecological implications of among-stream hydrological variation was presented in that paper, and it will not be repeated here. It is increasingly recognized that hydrological variability may be an important component of the habitat template in stream ecosystems (e.g. Minshall, 1988; Poff & Ward, 1990; Schlosser, 1990; Hildrew & Giller, 1994); however, while flow regime can describe temporal environmental variability in streams, it does not provide information on the contribution to the habitat template of equally important spatial heterogeneity (Poff & Ward, 1990; Townsend & Hildrew, 1994). None the less, streams having similar hydrological regimes are expected to express greater than random similarity in ecological organization (e.g. Resh *et al.*, 1988; Naiman *et al.*, 1992). Limited research sup-

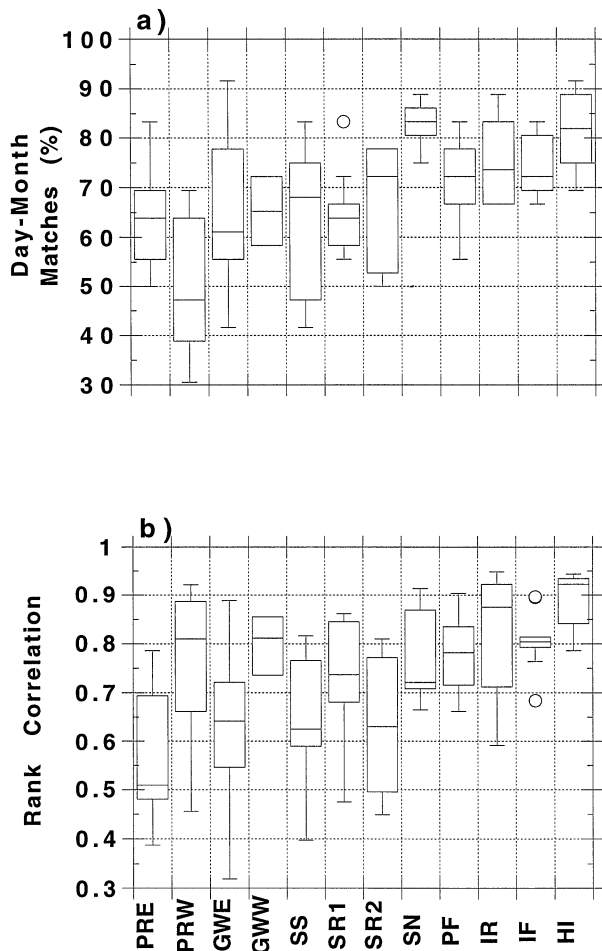


Fig. 6 Range of values for twelve groups of streams for (a) proportion of matches for months having maximum average flows and months also containing the annual maximum daily flow, and (b) rank correlation coefficient between maximum daily flows and annual maximum flows. Legend as in Fig. 4.

ports this assertion, particularly for fish (e.g. Horwitz, 1978; Bain, Finn & Booke, 1988; Scarnecchia, 1988; Poff & Allan, 1995).

Additional research is needed to determine how much variation in stream community structure or organization can be explained by coarse hydrological descriptors at geographical scales. The approach presented here provides a basis for selecting hydrologically similar sites to test such specific ecological hypotheses, a necessary step for geographical comparative ecology (Fisher & Grimm, 1991). Similarly, this approach can also be used to 'control' for hydrological variation to examine the role of other major environmental factors in structuring stream communities. For example, one might select hydrologically similar streams along a latitudinal gradient in the Central

Plains to 'isolate' the effects of temperature on stream community organization or on ecosystem dynamics. It is important to point out that, because the hydrological descriptors used in the analysis are based on long-term averages, residual variance in observed ecological patterns might be reduced by taking site-specific hydrological history into account. This should be more pronounced for ecological variables that fluctuate directly in response to hydrological disturbance (e.g. relative abundance, Flecker & Feifarek, 1994) than for ecological variables that represent long-term adjustments to a regime of disturbance (e.g. species traits, Poff, 1992; Townsend & Hildrew, 1994).

Evaluation of cluster stability with the bootstrapping technique identified which clusters were statistically distinct. Weak separation among some clusters potentially argues for merging several clusters into one group. For example, GW and SR streams tended to merge with the PR cluster during the re-sampling simulation, indicating some statistical similarity among these three stream types. However, the high baseflow stability and low overall variability of GW streams, and the high seasonal predictability of flooding in SR streams, provide an arguable *ecological* rationale for retaining these as groups separate from the less stable and predictable PR streams (e.g. see Poff & Allan, 1995). GW streams represent a transitional group between PR and SS streams, while SR streams are transitional between PR and SN streams.

The statistical similarity among the PR, GW and SR streams also helps explain apparent inconsistencies in the results. First, the classification of some individual streams changed between the 420 and 806 site analysis (cf. Figs 2 and 3). As sample size changes, so does the total multivariate space within which relative differences among clusters are defined. Streams that changed cluster affiliation between the 420 and 806 site analysis were mostly PR, GW and SR streams. Second, occasional geographical 'outlier' streams were observed in the classification. For example, some sites in the extreme south-east were classified as SR streams (see Figs 2 and 3), when they are probably more properly considered as GW or PR streams.

Analysis of sensitivity to data aggregation

Colwell's Index and coefficient of variation. The results from the repeated calculation of Colwell's Index of predictability and daily coefficient of variation applied

to streamflow records for the twelve groups of streams identified here show three things. First, there are generally large among-group differences regardless of what temporal scale is used. Thus 'types' of streams can be identified that retain their identities regardless of the temporal scale chosen. Therefore, as long as temporal grain is consistent, it is possible to discern major differences in predictability for a wide range of hydrologically diverse streams. However, there are some important exceptions to this generalization. For example, SN streams have very high predictability relative to most other stream types when predictability is calculated with daily, weekly, or seasonal data. But at a monthly scale SN streams are very similar to SS and HI streams in terms of predictability (Fig. 4c). Similarly, SS streams always have a characteristic, very low, coefficient of flow variation but, at a monthly time step, SN streams are equally invariant. Second, within certain groups, significant changes in the estimates of hydrological variability occur, *depending* on the time scale chosen. These changes were more pronounced for Colwell's Index than for the coefficient of variation. For example, the predictability of some stream types increased, for others it stayed the same, and for others, it declined as time scale was changed. By contrast, the coefficient of variation was always highest at the shortest (daily) time step, regardless of stream type. Third, the streamflow classification types were generally robust against geographical location. Specifically, geographically distant PR-E and PR-W streams were usually similar in terms of mean predictability at different time scales, both for Colwell's Index and for daily coefficient of variation. The same held for GW-E and GW-W streams. By contrast, geographically proximate (e.g. PR and GW) or distant (e.g. SN and IF) streams not in the same cluster showed very different degrees of hydrological variation.

These results suggest that, when comparing measures of predictability among hydrologically and/or geographically diverse streams, one should give due consideration to the rationale for choosing a particular temporal window for analysis. Others have shown that Colwell's predictability index is sensitive to length of record used to calculate the index (Gan *et al.*, 1991). This paper shows that the index is also sensitive to temporal resolution in the hydrological time series and that relative differences among streams may change depending on the time scale of analysis. Further, relative differences among streams for Colwell's Index

can vary depending on the way one defines flow states (e.g. the number of flow categories, mathematical transformation of values, etc.) in the initial matrix design (N.L. Poff, unpublished). Flow states not based on physically meaningful thresholds (e.g. extremely low or high flow levels) are basically arbitrary. For among-stream comparisons of predictability to be valid using this index, investigators will have to 'standardize' the method by which this index is calculated. Coefficient of variation is a more straightforward, less arbitrary measure of flow variability that shows more stability with respect to length of the time series than does Colwell's predictability index. For example, the mean deviation between the values calculated across the 118 sites for 36-year *v* 20-year periods of record were 3.4% and 8.0% for coefficient of variation and predictability index, respectively (N.L. Poff, unpublished). Given the relatively high inverse correlation between coefficient of variation and Colwell's predictability (for the daily time step—see Table 2), coefficient of variation may be an adequate single descriptor of flow variability in streams.

Daily v monthly/annual data in characterizing spates. These results indicate that coarse-grained hydrological data are best suited to capturing short-duration extreme flows in highly seasonal stream types (SN and HI). More uncertainty exists for less seasonal streams. Given the high seasonality of high flows in SN streams, it is not surprising that these streams would be relatively insensitive to the temporal scales used in this study. The high correspondence across temporal scales for HI streams can probably be explained by considering that these streams have, on average, zero flow for at least half of each year. Thus, any large flow occurring in these streams, however, transient, will make a significant contribution to flow values averaged over longer time scales.

For estimation of the flood regime for most streams, these results show that coarse-grain data can be used only if one is willing to accept a high error rate. Further, many streams experience high flows of ecological interest more than once per year, and, as the number of these flows increases, it is increasingly unlikely that monthly data can capture adequately the temporal distribution of those transient but important events. By contrast, monthly data may be adequate for analysis of low-flow events (not analysed here),

because low-flow events are generally of greater duration than high-flow events (N.L. Poff, unpublished).

The significant rank correlations between the ranked series of annual average flows and annual maximum daily flows suggest that annual flow data might be useful in reconstructing hydrological extremes for some types of streams, for which only annual flow data exist or for which only precipitation data exist. However, the low *absolute* value of the rank correlations for most streams indicates the low explanatory value in this approach. Further, the correlations provided do not take into account the possibility that, in particular years, several high flows may occur that exceed the magnitude of even the highest annual flow of some other years. Thus, the information contained in the rank correlation structure cannot be used reliably to describe the *frequency* of flooding of a particular intensity for many stream types. For highly seasonal streams (e.g. SN), however, where maximum annual flows almost always occur at a particular time of year average annual flow statistics may provide very useful information in determining magnitudes of major flows on a yearly basis (e.g. Dahm & Molles, 1990).

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