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CHARACTERIZING SUB-DAILY FLOW REGIMES: IMPLICATIONS OF HYDROLOGIC RESOLUTION ON ECOHYDROLOGY STUDIES

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ABSTRACT

Natural variability in flow is a primary factor controlling geomorphic and ecological processes in riverine ecosystems. Within the hydropower industry, there is growing pressure from environmental groups and natural resource managers to change reservoir releases from daily peaking to run-of-river operations on the basis of the assumption that downstream biological communities will improve under a more natural flow regime. In this paper, we discuss the importance of assessing sub-daily flows for understanding the physical and ecological dynamics within river systems. We present a variety of metrics for characterizing sub-daily flow variation and use these metrics to evaluate general trends among streams affected by peaking hydroelectric projects, run-of-river projects and streams that are largely unaffected by flow altering activities. Univariate and multivariate techniques were used to assess similarity among different stream types on the basis of these sub-daily metrics. For comparison, similar analyses were performed using analogous metrics calculated with mean daily flow values. Our results confirm that sub-daily flow metrics reveal variation among and within streams that are not captured by daily flow statistics. Using sub-daily flow statistics, we were able to quantify the degree of difference between unaltered and peaking streams and the amount of similarity between unaltered and run-of-river streams. The sub-daily statistics were largely uncorrelated with daily statistics of similar scope. On short temporal scales, sub-daily statistics reveal the relatively constant nature of unaltered stream reaches and the highly variable nature of hydropower-affected streams, whereas daily statistics show just the opposite over longer temporal scales. Published 2014. This article is a U.S. Government work and is in the public domain in the USA.

KEY WORDS: instream flow; hydropower; peaking; sub-daily

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INTRODUCTION

Natural variability in flow is a primary factor controlling geomorphic and ecological processes in riverine ecosystems. Human uses such as flood control, agricultural withdrawals and power generation have the potential to alter natural flow conditions in ways that are detrimental to the ecological health of rivers. Management strategies for addressing issues of flow alterations focus on getting stakeholders to examine metrics of flow variability between unaltered and altered conditions in order to determine environmental flow recommendations to support concurrent human and natural uses of rivers (e.g. Poff *et al.*, 2010). The first step in such a process involves the quantification of flow variability of both altered and unaltered conditions. Currently, the most commonly used approaches for quantifying flow variability are based on statistical analyses of daily-averaged flow records like the metrics computed by the Indicators of Hydrologic Alteration software package (Richter *et al.*, 1996).

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Within the hydropower industry, there is growing pressure from environmental groups and natural resource managers to change reservoir releases from daily peaking to run-of-river (ROR) operations on the basis of the assumption that downstream biological communities will improve under a more natural flow regime (Jager and Bevelhimer, 2007). Hydropower peaking operations have the potential to alter downstream flows beyond the natural variations that occur over the course of a day, and these fluctuations are not captured by flow metrics on the basis of daily-averaged statistics (Zimmerman *et al.*, 2010). To more closely evaluate the influence of hydropower operations on naturally occurring flow variability, it is necessary to quantify flow metrics at the sub-daily scale. It is also important to evaluate the potential correlation between sub-daily flow metrics and changes in downstream geomorphic processes and biologic responses that occur over a wide range of temporal and spatial scales.

For many peaking projects, the hydrograph for hourly data contains a significant amount of variation compared with a hydrograph of daily data over the same period (Figure 1). Daily data reveal periods of reduced flows that occur on weekends when the general demand for energy is reduced but little variation otherwise except for an occasional high flow event (Figure 1—top panel). A hydrograph based

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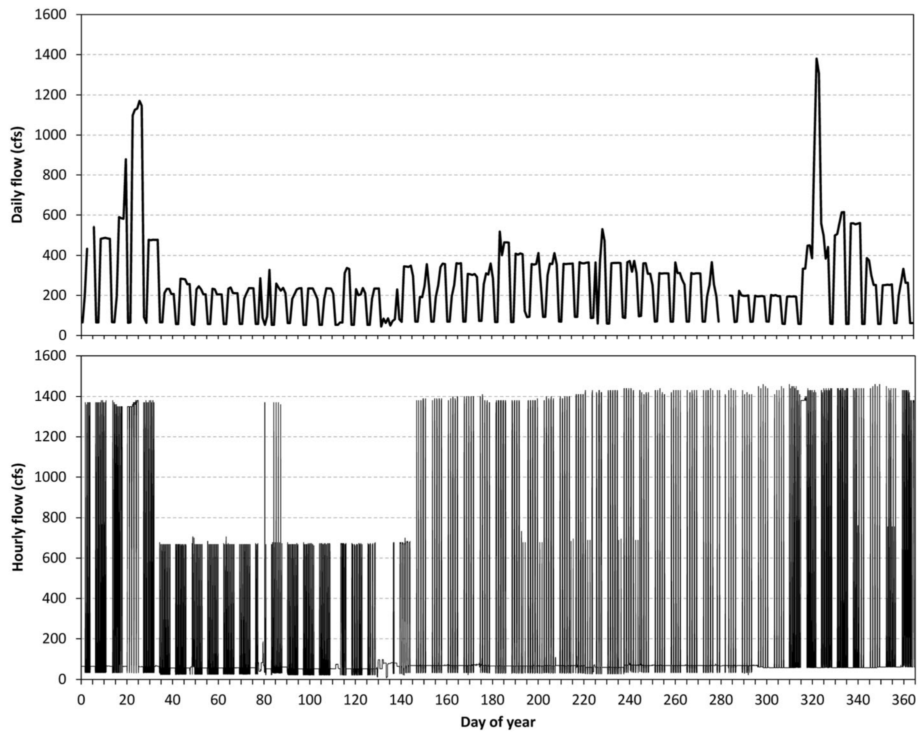

Figure 1. Daily (top panel) and hourly (bottom panel) hydrographs from 2006 for the Smith River, Virginia, measured at US Geological Survey gauge #020720002 located about 5 km downstream of Philpott Dam hydropower project

on hourly flow typically reveals extreme differences between high and low flows within the day and sometimes even fluctuations that occur twice daily (see the black areas in Figure 1—bottom panel where lines are too close to differentiate).

In addition, patterns of within-day variation often change seasonally because of changes in load-following operational schemes. The hydrograph of hourly data for a stream with unaltered flow typically shows seasonally varying base flow but little variation within a day; days of periodic high flows are also common as a result of precipitation events (Figure 2). Conversely, hourly hydrographs of a stream altered by peaking hydropower operation exhibit alternating periods of high and low flows occurring almost daily (Figure 3). Seasonal differences are more likely to be the result of changes in facility hours of operation and varying energy demands than the result of natural causes. High flows are typically bounded by the maximum powerhouse capacity and often do not reflect natural high flow events that are moderated by a facility's ability to store water and manage releases. Because daily statistics do not fully characterize the hydrologic conditions experienced by biota, it is important to evaluate how much hydrologic variation is explained by daily versus sub-daily statistics and to analyse relationships between statistics calculated from different temporal resolutions.

In this paper, we discuss the importance of sub-daily flows to physical and ecological dynamics within river systems that may not be accounted for in daily flow metrics. We then present a variety of metrics for characterizing sub-daily flow variation and use these metrics to evaluate general trends among streams affected by peaking hydroelectric projects, ROR projects and streams that are largely unaffected by flow altering activities. Univariate and multivariate techniques were used to assess the degree of similarity among the different stream types on the basis of the sub-daily metrics. For comparison, similar analyses were performed using analogous metrics calculated with mean daily flow values. Lastly, we provide discussion regarding the need for future research in characterizing sub-daily flows and evaluating associated ecological responses.

Importance of sub-daily flow variation

Flow variability in rivers is important for maintaining hydraulic complexity, sediment transport, surface water–groundwater exchange and floodplain connections, all of which interact to influence water temperatures, nutrient and organic matter concentrations, and the establishment of biotic habitats in the channel and riparian areas. The natural flow regime consists of five components that describe the magnitude, frequency, duration, timing and rate of change of hydraulic conditions that are known to control ecological health in riverine ecosystems (Poff *et al.,* 1997). Each of these five components describes flow variability over a range of spatial and temporal scales.

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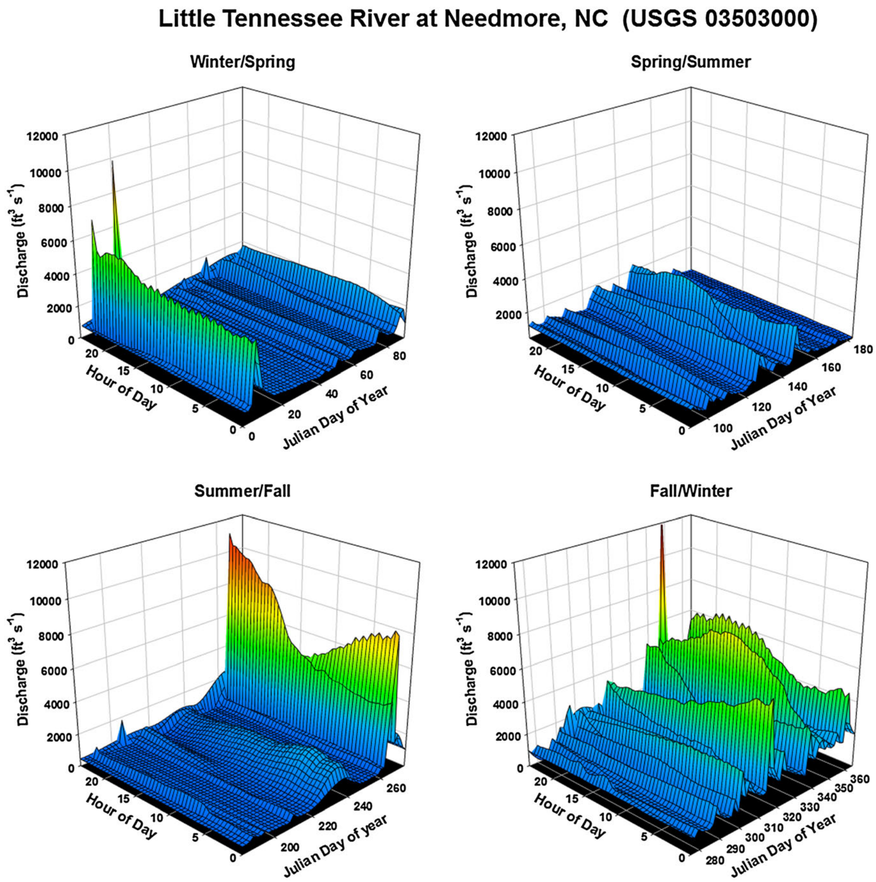

Figure 2. Surface plots of hourly flows at US Geological Survey gauge #03503000 on the Little Tennessee River near Needmore, North Carolina, showing the typical daily and seasonal variations in flow recorded at streams below run-of-river projects. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

Naturally occurring sub-daily flow variation results from the interaction of climatic processes such as precipitation, snowmelt and evapotranspiration with watershed characteristics such as drainage area, slope and land use. Diel variations in flow by natural processes can often be on the order of 10% of the mean daily flow (Lundquist and Cayan, 2002; Schuster *et al*., 2008). Seasonal patterns of natural daily variability are often common among rivers of similar geographic and hydro-climatic conditions (Lundquist and Cayan, 2002). On the other hand, sub-daily flow variations resulting from hydropeaking operations are generated by reservoir releases timed to meet peak energy and pricing demands that vary on daily, weekly and seasonal time scales. The resulting range of flows (i.e. minimum and maximum) below a peaking project is often within the annual range of natural flows for the river, but the temporal dynamics are entirely different. High and low flows usually occur at a greater sub-daily frequency and during seasons when natural sub-daily variation is minimal (Zimmerman *et al.*, 2010).

Sub-daily flow variations from hydropeaking operations can result in numerous pulses of water that propagate downstream and can cause rapid changes in water depths, velocities, bed shear stress and bank inundation or dewatering (Shen and Diplas, 2010). A significant research challenge in defining hydropower-related impacts is understanding how flow variability is manifested in ecological responses over time. The majority of research on environmental flows has focused on flow variability at the daily, seasonal and longer time scales (e.g. Poff *et al.*, 2007; Gao *et al.*, 2009; Fitzhugh and Vogel, 2011). Several studies have shown that daily-averaged flow records do not capture key components of sub-daily flow variation, and thus, it is critical to evaluate potential impacts of sub-daily flow variation on ecological processes (Zimmerman *et al.*, 2010).

Ecological consequences of hydropeaking operations and sub-daily flow variation

Ecological concerns of sub-daily flow variations from hydropeaking operations are related to the rapidly fluctuating pulses of water releases that occur. These fluctuating flow pulses can result in destabilized river beds and habitats,

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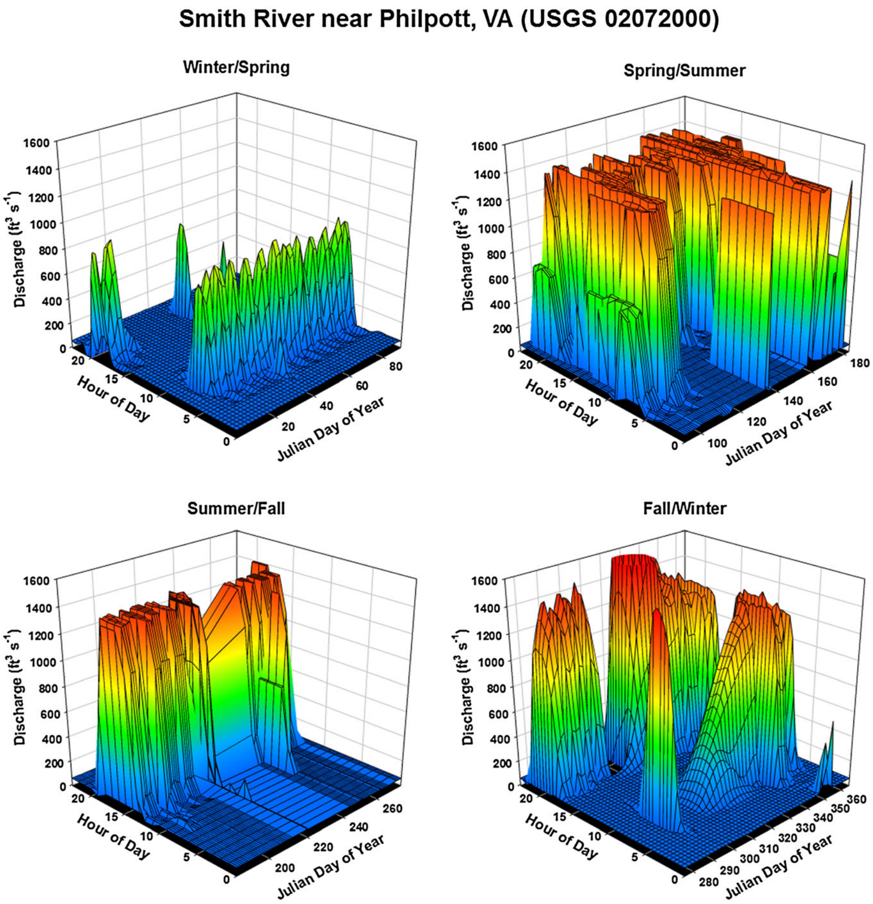

Figure 3. Surface plots of hourly flows at US Geological Survey gauge #02072000 on the Smith River below Philpott Dam showing the typical daily and seasonal variations in flow often observed below hydropower peaking projects. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

increases in fish stranding, scouring of fine sediments and macroinvertebrates, and a reduction of nearshore-riparian habitats (Fette *et al.*, 2007; Richter and Thomas, 2007; Korman and Campana, 2009). Coupled hydraulic and habitat modelling of unsteady flows has shown that hydropeaking operations reduce persistent shoreline habitats, which is particularly harmful to juvenile fish (Valentin *et al.*, 1996; Freeman *et al.*, 2001; Korman *et al.*, 2004). Fish assemblage surveys downstream of hydropeaking operations have shown that more mobile fish species are able to adapt to hydropeaking pulses more easily than slower moving and/or territorial fish species (Richter and Thomas, 2007; Scruton *et al.*, 2008). Research has shown that the rate of flow reduction from hydropeaking has a strong influence on fish stranding, with slower flow declines improving fish conditions depending on the time of day and season (Saltveit *et al.*, 2001; Halleraker *et al.*, 2003).

A variety of studies exist that used daily to seasonal flow metrics to evaluate temporal and spatial differences among flow regimes and potential effects on ecological resources (Poff and Allan, 1995, Herbert and Gelwick, 2003, Pyron and Lauer, 2004, Knight *et al.*, 2008, Carlisle et al., 2011). Few studies, however, have used sub-daily metrics for the same purpose (Roy *et al.*, 2005; Helms *et al.*, 2009; Sauterleute and Charmasson 2012). The few studies that have assessed sub-daily flow variation have focused on metrics that describe the daily range in flows and the number of reversals (Zimmerman *et al.*, 2010; Meile *et al.*, 2011).

METHODS

Flow data selection and preparation

In the past, the majority of readily available discharge data at stream gauging stations from the US Geological Survey (USGS) National Water Information System were in the form of daily averages. Recently, for a sub-set of stream gauges, the USGS started disseminating instantaneous discharge data (i.e. sub-daily data), collected on a 15-min, 30-min or hourly basis. Discharge sampled at these frequencies

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makes it more practical to evaluate fine-scale temporal characteristics of a stream. Data sets downloaded for our analysis included all three sampling frequencies; however, for consistency of data analysis, we converted all data sets to hourly by only using one flow value per hour, usually the top of the hour. We selected 30 gauges from across the US that represented three different flow regime types: unaltered flow (upstream is unimpounded), ROR hydropower operations and peaking hydropower operations (Table I).

Four years of sub-daily flow records were downloaded from the USGS National Water Information System website (waterdata.usgs.gov/nwis) for the 30 gauge stations. The 4-year period selected was not the same for all sites and depended on data availability and completeness. By using 4-year blocks of data, we minimized the chance that a single dry or wet year might misrepresent the normal effect of hydropower project operations on sub-daily flows, and we also avoided issues with leap days since every 4-year block, no matter when it starts, includes one leap day. Each leap day was left in the data set for a total number of 1461 days in each analysis. A Miscrosoft Office Excel spreadsheet programme was created that accepts 4 years of hourly flow data (~35,000 observations per site) and calculates sub-daily flow metrics as described earlier for each day.

For analyses with daily flow metrics, we used at least 30 years of mean daily data from the same 30 gauge stations (~11,000 observations per site). At least 15 years of data are typically required for analyses assessing spatial patterns in

Table I. Summary statistics for USGS streamflow data for 30 gauges across the US

USGS gauge #	Location	Drainage area (km^2)	Sub-daily years	Daily years	Mean flow (cfs)
Natural unaltered (upstream is unimpounded)					
06036905	Firehole River near West Yellowstone, MT	676.9	2003–2006	1980–2012	292
14308000	South Umpqua River at Tiller, OR	1167.2	2003–2006	1980–2012	1064
09505200	Wet Beaver Creek near Rimrock, AZ	285.7	2003–2006	1980–2012	31
03550000	Valley River at Tomotla, NC	268.1	2003–2006	1980–2012	241
01667500	Rapidan River near Culpeper, VA	1209.7	2003–2006	1980–2012	721
07066000	Jacks Fork at Eminence, MO	1053.5	2003–2006	1980–2012	477
11264500	Merced River at Happy Isles Bridge near Yosemite, CA	468	2003–2006	1980–2012	459
06430850	Little Spearfish Creek near Lead, SD	71.8	2003–2006	1980–2012	12
05212700	Prairie River near Taconite, MN	962.8	2003–2006	1975–2012	204
09352900	Vallecito Creek near Bayfield, CO	188.2	2003–2006	1980–2012	165
Run-of-river (downstream of ROR project)					
03503000	Little Tennessee River at Needmore, NC	1129.9	2006–2009	1980–2012	746
04118000	Thornapple River near Caledonia, MI	2077.9	1990–1993	1970–2012	908
02163500	Saluda River near Ware Shoals, SC	1505.4	2006–09	1980–2012	591
04064500	Pine River below Pine R powerplant near Florence, WI	1387	2006–2009	1970–2012	305
04078500	Embarrass River near Embarrass, WI	986.1	2006–2009	1975–2012	254
01072800	Cocheco River near Rochester, NH	244	2005–2008	1971–2012	220
03080000	Laurel Hill Creek at Ursina, PA	313.3	2004–2007	1980–2012	284
03165500	New River at Ivanhoe, VA	3496.5	2006–2009	1980–2012	1,748
03498500	Little River near Maryville, TN	696.8	2006–2009	1980–2012	425
04271815	Little Chazy River near Chazy, NY	130.5	2006–2009	1979–2012	68
Peaking (downstream of peaking project)					
02072000	Smith River near Philpott, VA	557.7	2006–2009	1980–2012	251
02080500	Roanoke River at Roanoke Rapids, NC	21947.9	2006–2009	1979–2012	6,009
13341050	Clearwater River near Peck, ID	20665.1	2006–2009	1980–2012	14,151
04062500	Michigamme River near Crystal Falls, MI	1673.4	2005–2008	1980–2012	547
02011800	Jackson River below Gathright Dam near Hot Springs, VA	895.1	2006–2009	1980–2012	400
14233500	Cowlitz River near Kosmos, WA	2652.8	2005–2008	1980–2012	4,268
02335450	Chattahoochee River above Roswell, GA	3155.9	2006–2009	1980–2012	1,371
11510700	Klamath River below John Boyle powerplant near Keno, OR	18499.9	2006–2009	1980–2012	1,625
02414500	Tallapoosa River at Wadley, AL	4336.8	2006–2009	1980–2012	1,895
01325000	Sacandaga River at Stewarts Bridge near Hadley, NY	2776.7	2006–2009	1980–2012	2,795

USGS, US Geological Survey; cfs, cubic foot per second.

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daily flows (Kennard *et al.*, 2010a). Because of missing data, slightly different record lengths were used to ensure that at least 30 years were presented.

Sub-daily metrics

We conducted a literature review to identify existing sub-daily flow metrics and ideas for new metrics. We settled on 13 metrics that use hourly data to quantify the magnitude, variation, frequency and rate of change of flow changes during the day (Table II). For better use in comparisons among streams of different sizes, five of the metrics (daily standardized delta, annually standardized delta, coefficient of variation, standardized maximum hourly ramping rate, Richards–Baker flashiness index) were standardized versions of simpler metrics (daily delta, standard deviation, maximum ramp rate and daily path length). Standardization included dividing the original metric either by the mean flow for each 24-h period or by the mean annual daily flow (4-year mean) as described in Table II. Each of these metrics provides a value for each day, 1461 values for a 4-year period. In this paper, we provide an analysis of seven of these sub-daily metrics: daily coefficient of variation, daily standardized delta, annually standardized delta, standardized maximum hourly ramp, reversals exceeding 10% of mean flow, the Richards–Baker flashiness index, and rise and fall counts.

Daily metrics

In order to compare the amount of hydrologic variation captured at different temporal scales, we identified seven daily metrics (Table II) that are analogous to the sub-daily metrics presented earlier (Olden and Poff, 2003). We analysed daily discharge data with USGS Hydrologic Index Tool software (Henriksen *et al.*, 2006). Daily metrics are calculated on annual time steps using daily average discharge values. Each metric is presented along with the analogous sub-daily metrics (identified in brackets in Table II).

Statistical analysis

To compare the variation for each metric among the three classes of stream types, cumulative frequency plots were generated for each sub-daily metric for each gauge. To better describe the range of values for each of the metrics, we calculated the 25th, 50th, 75th and 95th percentiles for all sub-daily and daily flow values for each stream gauge. We conducted Spearman's rank correlations among the sub-daily-based metrics and daily-based metrics using the 50th and 95th percentile values (instead of the mean) to determine (i) whether each sub-daily metric is uniquely informative or redundant, and (ii) relationships among sub-daily and daily metrics.

Examining the correlative structure of stream gauges in multivariate space on the basis of sub-daily and daily metrics provides an assessment of hydrologic variation among the three stream types (i.e. natural, ROR and peaking). In addition, multivariate analyses can be used to compare the level of hydrologic variation attributed to sub-daily versus daily metrics. For example, sub-daily and daily metrics may differ in their ability to assess the degree of hydrologic variation among streams or degree of hydrologic variation within a single stream. We conducted separate principle components analyses (PCAs) for each of the three stream types using the 25th, 50th, 75th and 95th percentile values for each stream for sub-daily metrics and daily metrics separately. All variables were $\log(x+1)$ transformed and scaled from 0 to 1 prior to analysis.

RESULTS

Correlations among sub-daily metrics (both 50th and 95th percentile values) were examined to identify redundant metrics (Table III). For both percentile groups, the coefficient of variation was highly correlated ($R^2 = 0.99$) with the daily delta (standardized by the daily mean), and as expected, the correlation between these two and any of the other metrics is nearly equal. Consequently, it is probably not useful to use both of these metrics in future analyses. Despite daily metrics being analogous to their sub-daily counterparts, correlation analysis among sub-daily and daily metrics suggested that metrics quantified at different temporal scales were capturing different variation in hydrology (Table III). Among the daily metrics, only the number of reversals (RA8) was consistently correlated ($R^2 > 0.60$) with sub-daily metrics when comparing the 50th percentile values. When comparing the 95th percentile values, several pairs of daily and sub-daily metrics had significant correlation, including fall rate (RA3) with five of the sub-daily metrics.

Cumulative frequency plots for seven of the sub-daily flow metrics show a large difference in the range of values for peaking compared with unaltered flow regimes (Figure 4). Only two of the peaking projects appear to be within the range defined by the 10 unaltered streams. ROR sites are intermediate but are generally more like unaltered flows than peaking flows.

The multivariate analysis revealed different patterns in hydrologic variation among streams and within streams depending on the use of sub-daily or daily metrics. When considering only sub-daily flow metrics, peaking projects showed the most variation in PCA space compared with ROR and natural streams (Figure 5). Conversely, when considering only daily flow metrics, natural streams displayed the most variation in PCA

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Table II. Descriptions of 13 sub-daily flow metrics calculated with hourly flow values and six daily flow metrics calculated with daily mean values

Metric[a]	Description[b]
	Sub-daily
Daily minimum	Lowest measured flow during a 24-h period (Qmin). Qmin is important to organisms that cannot withstand even a short period of dewatering or being stranded away from the main stream channel (Weisberg and Burton, 1993; Travnichek *et al*., 1995)
Daily maximum	Highest measured flow during a 24-h period (Qmax). On a sub-daily basis during normal non-flood conditions, the daily maximum flow is not usually considered an environmental stressor; however, daily high flows could affect habitat use and feeding
Daily delta (or range)	Difference between daily minimum and daily maximum (Qmax − Qmin) represents the amount of daily flow change. A large daily range suggests a wide range in habitat quality and quantity within a 24-h period, which likely results in significant behavioural changes over the course of the day
Daily standard deviation	The common statistical calculation of the 24 hourly flow values. Like daily range, daily standard deviation is an indicator of degree of habitat change
Maximum hourly ramp rate	The greatest hourly incremental change in flow during a 24-h period (Meile *et al*., 2011). Rapid flow decreases are known to strand fish in dewatered areas (Halleraker *et al*., 2003)
Daily path length	The path length of flow oscillations calculated as the geometric distance of the daily hydrograph of flow versus time (adapted from Baker *et al*., 2004). Daily path length is the sum of the absolute values of hour-to-hour changes in flow with time and is calculated as $\sum\sqrt{\left((Q_i + Q_{i+1})^2 + (t_i + t_{i+1})^2\right)}$ where Q is discharge at the ith hour and t is time. Higher values indicate greater stream flashiness or more rapid variation in flow
Reversals	Number of changes between rising and falling periods of the hydrograph; adapted from a similar metric derived with daily data (Richter *et al*., 1996; TNC, 2007). Counting reversals with hourly data can be misleading because even the slightest positive or negative change could produce a reversal count that has insignificant ecological relevance. Therefore, a more meaningful calculation of reversals includes quantifying positive or negative changes of a certain magnitude. For this study, we used 10% of the 4-year mean flow as a threshold
Rise and fall counts difference	Difference between the number of hours of rising and falling flow as determined with each pair of consecutive flow values. Over a 24-h period, the difference between rise and fall counts can range from +24 to −24. Continuous rising flows throughout a day would produce a score of +24, while all falling flows would produce a score of −24; an equal number of rising and falling counts would produce a score of 0. Over a longer period, the difference between the rise and fall counts reveals whether flows take longer to rise towards a maximum or fall towards a minimum. For example, flood flows often take longer to subside than to rise
Daily standardized delta	A variation of the percent of total flow metric, this metric is calculated as the daily delta divided by the daily mean over each 24-h period (adapted from Meile *et al*., 2011). This value is twice the standardized daily range as defined by Lundquist and Cayan (2002) as the ratio of the amplitude (half of daily range) of the diurnal cycle to total daily discharge over the analysis period (e.g. 24 h). An alternative to dividing by each day's mean flow is to use the mean annual daily flow as the denominator
Annually standardized delta	An alternative to the daily standardized delta that is standardized by dividing by the mean annual daily flow instead of by each day's mean flow
Coefficient of variation	Daily standard deviation divided by the daily mean
Standardized maximum hourly ramping rate	Maximum daily ramp rate divided by the mean annual daily flow
Richards–Baker flashiness index	The daily path length of flow oscillations divided by the daily mean over each 24-h period (Baker *et al*., 2004). Higher values indicate greater stream flashiness or more rapid variation in flow

(*Continues*)

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Table II. (Continued)

Metric[a]	Description[b]
	Daily
Daily coefficient of variation (MA3)	Calculated from daily flow averages for each year and then averaged across years. [Corresponding sub-daily metric is coefficient of variation]
Spread in daily flows 1 (MA9)	Difference between the 90th and 10th percentile of the flow data divided by the median flow for the entire record [standardized daily delta]
Spread in daily flows 2 (MA11)	Computed similarly to MA9 except using the 25th and 75th percentiles. [standardized daily delta]
High flood pulse count (FH1)	Average number of flow events per year exceeding a threshold equal to the 75th percentile value for the entire flow record. [flashiness index]
Rise rate (RA1)	Average rate of positive changes in flow from one day to the next divided by median daily flow. [flashiness index]
Fall rate (RA3)	Average rate of negative changes in flow from one day to the next divided by median daily flow. [flashiness index]
Number of reversals (RA8)	Annual number of positive or negative changes in flow direction from one day to the next (e.g. changes from positive to negative). [reversals]

[a]For the daily metrics, the Indicators of Hydrologic Alteration indicator code is included.
[b]For the daily metrics, the analogous sub-daily metric is listed.

space compared with the other stream types. Within-stream variation was more noticeable in the sub-daily PCA compared with the daily PCA. Peaking projects showed considerable amounts of variation in sub-daily hydrology compared with the other stream types; however, within-stream variation was not different among stream types in the daily PCA.

Table III. Spearman's rank correlations among sub-daily and daily flow metrics

	CoefVar	DeltaAnn	DeltaDaily	HrlyRamp	Reversals	Flash	RiseFall
50th percentile values							
DeltaAnn	0.91						
DeltaDaily	0.99	0.93					
HrlyRamp	0.74	0.91	0.78				
Reversals	0.70	0.70	0.70	0.70			
RB-Flash	0.82	0.91	0.86	0.93	0.70		
RiseFall	0.09	0.17	0.10	0.42	0.22	0.36	
MA3	−0.10	−0.37	−0.15	−0.62	−0.34	−0.46	−0.51
MA9	−0.04	−0.35	−0.09	−0.52	−0.15	−0.40	−0.40
MA11	0.11	−0.07	0.12	−0.21	−0.12	−0.10	−0.47
FH1	0.53	0.56	0.54	0.33	0.40	0.49	−0.25
RA1	0.21	0.26	0.24	0.17	0.28	0.27	−0.11
RA3	0.26	0.31	0.30	0.26	0.42	0.35	0.03
RA8	0.58	0.75	0.63	0.81	0.68	0.82	0.36
95th percentile values							
DeltaAnn	0.64						
DeltaDaily	0.99	0.68					
HrlyRamp	0.92	0.73	0.91				
Reversals	0.75	0.41	0.76	0.74			
RB-Flash	0.81	0.85	0.85	0.81	0.72		
RiseFall	−0.33	−0.23	−0.38	−0.22	−0.39	−0.36	
MA3	0.02	0.42	0.02	0.08	−0.17	0.14	0.26
MA9	−0.05	0.45	−0.05	0.08	−0.09	0.23	0.25
MA11	−0.05	0.32	−0.05	−0.06	−0.01	0.17	−0.03
FH1	0.60	0.53	0.66	0.50	0.38	0.56	−0.40
RA1	0.33	0.64	0.36	0.38	−0.04	0.35	0.11
RA3	0.64	0.82	0.66	0.72	0.33	0.66	−0.06
RA8	0.56	0.11	0.58	0.40	0.62	0.44	−0.53

Daily metrics include the following: MA3, mean of the coefficients of variation; MA9, spread in daily flows 1; MA11, spread in daily flows 2; FH1, high flood pulse count; RA1, rise rate; RA3, fall rate; and RA8, reversals.

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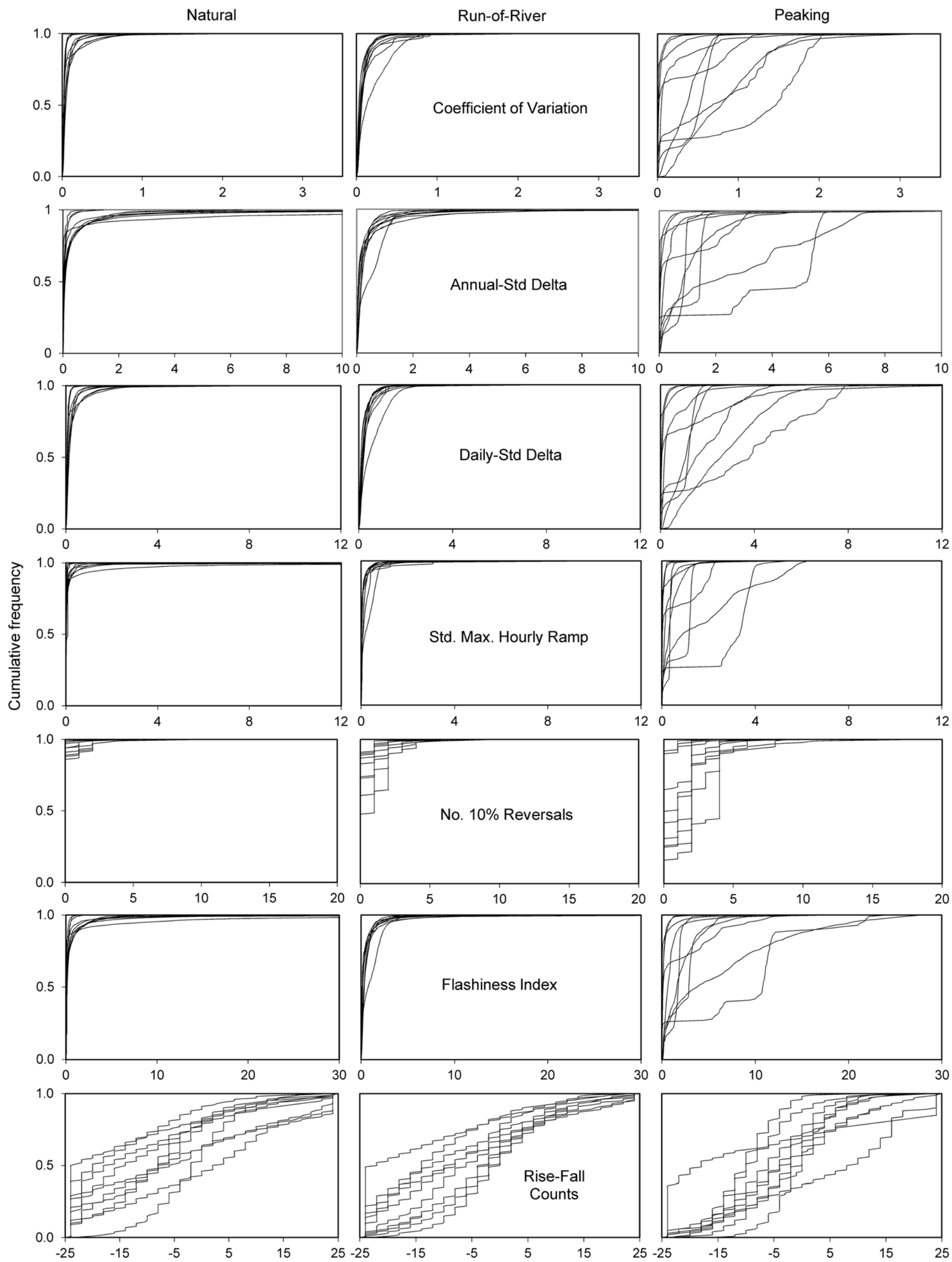

Figure 4. Cumulative frequency distributions for seven sub-daily flow metrics from 4 years of hourly flow data for 30 stream sites, 10 each representing natural unaltered flows, run-of-river hydropower operation and peaking hydropower operation

DISCUSSION

Our results confirm that sub-daily flow metrics reveal variation among and within streams that is not captured by daily flow statistics. Multiple sub-daily statistics were not correlated with daily statistics despite being similar in purpose and scope (Table III). Sub-daily statistics seem to show a greater tendency towards generalization and clustering when considering responses to hydropower regulation (Figure 5). Daily flow statistics of natural streams showed considerably more variation than those influenced by ROR and peaking facilities. However, peaking projects exhibited the most variation in sub-daily flows with far less variation in ROR and natural streams. These findings show that temporal resolution is extremely important in assessing spatial patterns in hydrology. Furthermore, our results suggest that statistics from multiple time scales are required to fully capture patterns in both natural and hydrologically altered systems.

Many studies have evaluated spatial patterns in ecology because of variation in daily and seasonal hydrologic statistics

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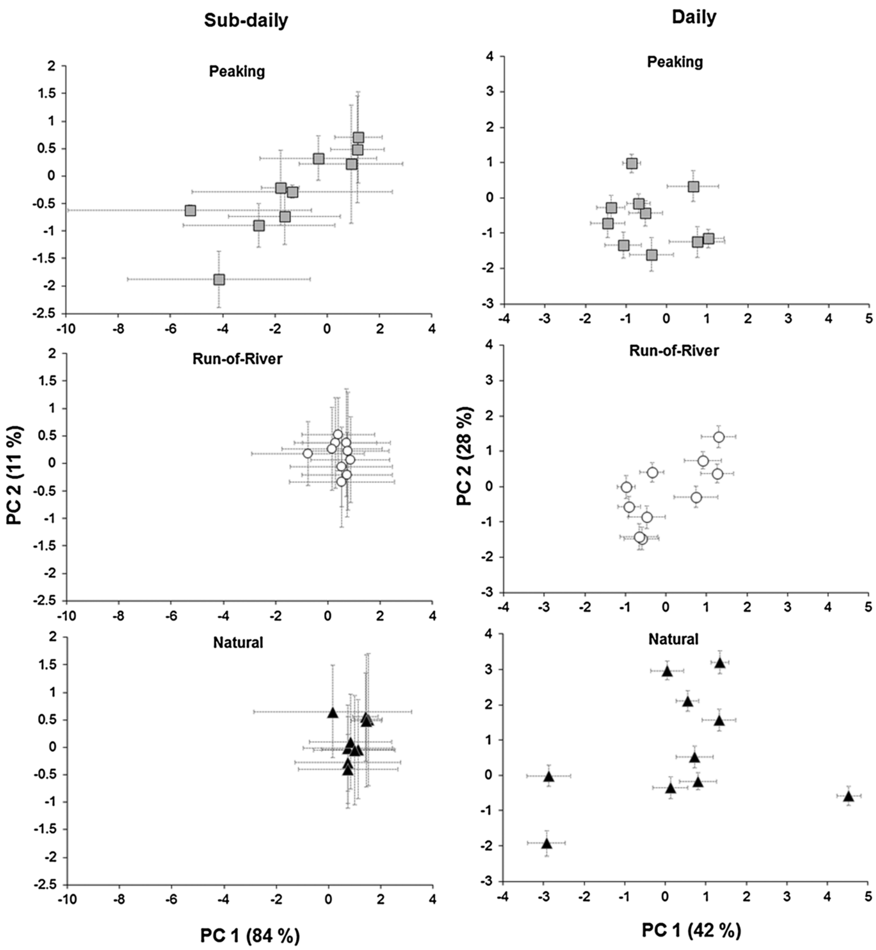

Figure 5. Plots of PC1 versus PC2 for principle components analysis of sub-daily and daily flow metrics for three types of stream flow regimes—natural, run-of-river and peaking. Each point represents the mean of 25th, 50th, 75th and 95th percentile values for a single stream with associated variation (error bars) representing 1 SE

(e.g. Knight *et al.*, 2008; Carlisle *et al.*, 2011), but far fewer studies have used metrics calculated from sub-daily data to explain variation in ecological patterns resulting from flow alterations (Roy *et al.*, 2005; Helms *et al.*, 2009). Although examples of hydrologic classifications using daily discharge are very common (Poff, 1996; Kennard *et al.*, 2010b; McManamay *et al.*, 2012), hydrologic classifications that utilize sub-daily data are rare (Sauterleute and Charmasson, 2012). Results of the PCA suggest that similarities in sub-daily variation exist among streams of a common type or operational category, which implies that sub-daily discharge could be used to classify streams. We suggest that isolating different temporal components of hydrologic variation across various scales may be essential for hierarchical stream classification approaches.

An obvious advantage of sub-daily discharge data is its high temporal resolution. The 15-min interval data contain 96 times more observations than daily-averaged data. Typically, at least 15 years of daily discharge information is required to reduce uncertainty in daily metrics to support studies evaluating spatial variation in hydrology (Kennard *et al.*, 2010a). In addition, spatial comparisons of gauges also require at least 50% temporal overlap in hydrologic records (Kennard *et al.*, 2010a). Many gauges may fail to meet the strict screening criteria required for daily hydrologic analyses, thereby leaving many analyses incomplete (Olden *et al.*, 2012). We suspect that repeatable patterns in sub-daily hydrology are evident within much shorter time frames and analysis of sub-daily flow variation can be accomplished with a shorter hydrologic record than that needed to assess seasonal or annual patterns.

Sub-daily information can generate high resolution statistics, yet it can be aggregated up to coarser resolutions to support hierarchical analyses. For example, fully assessing the role of hydrologic variation on a given population may require determining flow-ecology relationships at multiple temporal scales. Sub-daily flow variation may influence

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short-term habitat use (Schwartz and Herricks, 2005), migration (Carmichael *et al.*, 1998), feeding ability (Barwick and Hudson, 1985) and spawning success (Grabowski and Isely, 2007), while habitat creation (Trush *et al.*, 2000), growth (Peterson and Jennings, 2007), and recruitment (Rulifson and Manooch, 1990) may be influenced by hydrologic variation at seasonal or annual scales.

Cumulative frequency plots like those presented here represent the distribution of each hydrologic metric calculated for each day, rather than daily statistics for many years. Cumulative frequency plots can be used to define envelopes of normal operations for any metric for a particular flow regime or stream type. This type of analysis can be used to determine which characteristics of altered flow regimes (e.g. reversals, rise rates and daily ranges) are most similar and different from unaltered streams, and the percentage of time stream flows falls within an altered state. If particular flow characteristics can be related to ecological responses or resource management goals, then project operations could be modified to control specific flow characteristics within various temporal windows. For example, successful juvenile rearing of a particular fish species might depend on some flow characteristic that is defined by a limited range of variation. A change in operation that specifically targets that characteristic or metric might be the most efficient way to alter flow to successfully address this environmental need.

Sub-daily metrics provide new opportunities for research in assessing spatial patterns in hydrology and flow-ecology relationships. In terms of assessing spatial hydrology, multiple hydrologic classifications have been created using daily discharge information. A hierarchical approach to hydrologic classification may include utilizing sub-daily information along with daily flow data. Determining how sub-daily measures vary within and among basins on the basis of climate and landscape characteristics can be informative in predicting finer-resolution hydrology for un-gauged streams.

Establishing connections between the temporal resolution of flow metrics and biologic, geomorphic and physio-chemical receptors is an area of much needed research. Explicitly accounting for temporal resolution may help isolate the magnitude and timing of acute hydrologic events. For example, sub-daily metrics capture the peak magnitude and rising limb of flood events. These metrics are often lost in daily averages and are likely to be more relevant in assessing geomorphic changes, such as bedload scouring and creation of sandbars and gravel beds. Behavioural responses by fish to flooding typically occur within seconds to minutes (David and Closs, 2002; Schwartz and Herricks, 2005; Cocherell *et al.*, 2012). In addition, the shape of the hydrograph (e.g. the rising limb) may be just as important as the full magnitude in isolating ecohydraulic relationships, such as invertebrate drift (Wilcox *et al.*, 2008) and bedload transport (Mao, 2012). Daily fluctuations in temperature and other water quality parameters are directly dependent on within-day flow variation (Bevelhimer *et al.*, 1997; Caissie, 2006; Zolezzi *et al.*, 2011).

A research need exists for studies that evaluate differences between natural and human-influenced hydrology. One of the greatest justifications for researching sub-daily flow variation is that anthropogenic activities have the most obvious effects on hydrology at short temporal scales. In addition, we contend that alterations at the sub-daily scale have equal and perhaps greater detrimental consequences to aquatic ecosystems than coarser temporal scales, because these types of alterations induce conditions to which most organisms are maladapted (Cushman, 1985). For example, in the case of intense urbanization and hydropower peaking, dramatic increases and decreases can occur within minutes (Brown *et al.*, 2009; Cushman, 1985). Similar to unpredictable increases in flow, dramatic decreases in flow can occur because of withdrawals for uses such as hydraulic fracturing (Entrekin *et al.*, 2011). These decreases may only be captured by assessing sub-daily flow variation. In summary, sub-daily flow statistics provide a great deal of promise in the future of hydrologic applications, including assessing hydrologic alterations.

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