A SPATIAL ASSESSMENT OF HYDROLOGIC ALTERATION WITHIN A RIVER NETWORK

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ABSTRACT

Maintaining natural hydrologic variability is essential in conserving native riverine biota and river ecosystem integrity. Hydrologic variation plays a major role in structuring the biotic diversity within river ecosystems as it controls key habitat conditions within the river channel, the floodplain, and hyporheic (stream-influenced ground water) zones. Alterations in streamflow regimes may modify many of these habitat attributes and impair ecosystem connectivity. We demonstrate use of the 'Range of Variability Approach' for assessing hydrologic alteration at available streamgauge sites throughout a river basin. We then illustrate a technique for spatially mapping the degree of hydrologic alteration for river reaches at and between streamgauge sites. Such maps can be used to assess the loss of natural hydrologic variation at a river basin scale, thereby facilitating river restoration planning. © 1998 John Wiley & Sons, Ltd.

INTRODUCTION

The structure and persistence of native biotic communities within river ecosystems is strongly influenced by both spatial and temporal variation in environmental conditions (Poff and Ward, 1989; Stanford *et al.*, 1996). Spatially complex riverine environments present diverse habitats along longitudinal, lateral, and vertical dimensions (Ward, 1989; Stanford and Ward, 1992), offering the possibility for spatial segregation of species and guilds, size classes, and life stages (Schlosser, 1991; Stanford *et al.*, 1996; Poff *et al.*, 1997). Temporal variation in streamflow, water temperature, dissolved oxygen concentration, transport of sediment and organic matter, and other environmental conditions continually modify the suitability of particular aquatic habitats, imposing an 'environmental regime' on those habitats. Environmental regimes influence the composition and structure of aquatic communities in three important ways: (1) by shaping environmental conditions and their variation within particular habitats; (2) by shaping the distribution and evolution of the mosaic of habitats; and (3) by influencing the movements of organisms between habitats.

The streamflow regime is a driving force in river ecosystems (Stanford *et al.*, 1996; Poff *et al.*, 1997). Streamflow controls key habitat parameters such as flow depth, velocity, and habitat volume. The often strong connections between streamflow, floodplain inundation, alluvial ground water movement, and water table fluctuation mediate the exchange of organisms, particulate matter, energy, and dissolved substances along the four dimensions of river systems: upstream–downstream, channel–hyporheic (ground water), channel–floodplain, and the temporal dimension (Amoros and Roux, 1988; Ward, 1989; Stanford and Ward, 1992; Ward and Stanford, 1995a). Flow is often tightly coupled with other environmental conditions as well, such as temperature and oxygen, channel morphology and substrate particle sizes (Sparks, 1992, 1995; Allan, 1995; Ward and Stanford, 1995b; Stanford *et al.*, 1996; Poff *et al.*, 1997; Richter *et al.*, 1997). Alteration of natural streamflow regimes modifies the

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distribution and availability of riverine habitat conditions, with adverse consequences for native biota (Poff *et al.*, 1997).

Evaluating flow alteration at a river network scale

The long-term daily streamflow records available for many larger (third order and up) streams and rivers in developed nations present an opportunity to evaluate flow alterations associated with human perturbations such as dams and water diversions. The approach we suggest for assessing hydrologic alteration is based on the differences in streamflow regime characteristics between two defined time periods at a given streamgauge (Richter *et al.*, 1996, 1997). If the years of record at a streamgauge can be divided into a period of more natural or less altered (e.g. pre-development) streamflow conditions, and a period of more altered (e.g. post-development) conditions, then it is possible to measure the degree of alteration in streamflow regime that has taken place between these two periods (Richter *et al.*, 1996).

Richter *et al.* (1997) recently described the application of such flow assessments to river ecosystem management efforts. Flow management or restoration targets were prescribed on the basis of natural variability in streamflow characteristics, using a method named the 'Range of Variability Approach' (RVA). As a management tool for regulated or developed rivers, the objective of the RVA is to guide efforts to restore or maintain the natural streamflow regime of a river using the range of natural variability in thirty-three different ecologically relevant flow parameters as the basis for setting management targets (Table I). Using the RVA, river managers strive to keep annual values of each hydrologic parameter within a targeted range of values that defines some portion or all of the natural range of variability in the parameters (e.g. Figure 1). These RVA management targets should be based, to the extent possible, on available ecological information. At the same time, the RVA is meant to enable river managers to define and adopt readily interim management targets before conclusive, long-term ecosystem research results are available. An adaptive management approach, whereby interim management targets and management actions are prescribed and implemented, system response is monitored, and management targets and the prescribed flow regime are adjusted based on monitoring results and ecological research, is fundamental to successful application of the RVA.

The RVA target range for each hydrologic parameter is usually based upon selected percentile levels or a simple multiple of the parameter standard deviations for the natural or pre-development streamflow regime. The management objective is not to have the river attain the targeted range every year; rather, it is to attain the targeted range at the same frequency as occurred in the natural or pre-development flow regime. For example, attainment of an RVA target range defined by the 25th and 75th percentile values of a particular parameter would be expected in only 50% of years (see Figure 1 for example).

The degree to which the RVA target range is not attained is a measure of hydrologic alteration. This measure of hydrologic alteration, expressed as a percentage, can be calculated as:

$$((\text{Observed} - \text{Expected})/\text{Expected}) * 100$$

wherein 'observed' is the count of years in which the observed value of the hydrologic parameter fell within the targeted range; 'expected' is the count of years for which the value is expected to fall within the targeted range. Hydrologic alteration is equal to zero when the observed frequency of post-development annual values falling within the RVA target range equals the expected frequency. A positive deviation indicates that annual parameter values fell inside the RVA target window more often than expected; negative values indicate that annual values fell within the RVA target window less often than expected.

The calculations for the RVA are based upon hydrologic data collected at a point (streamgauge), and therefore really only measure hydrologic alteration in a temporal (rather than a spatial) dimension at that point. However, such point-based data and evaluations usually reflect hydrologic conditions and processes over a wider and longer area of the river. For instance, hydrologic conditions evaluated at a streamgauge should strongly reflect conditions in the lateral (river–floodplain) dimension as well as in the channel–hyporheic dimension, unless barriers to natural hydrologic connectivity such as levees or drainage ditches have been constructed. Streamgauge data also provide information on hydrologic conditions extending

Table I. Summary of hydrologic parameters used in the RVA, and their characteristics

General group	Regime characteristics	Streamflow parameters used in the RVA	Examples of ecosystem influences
1: Magnitude of monthly discharge conditions	Magnitude, timing	Mean discharge for each calendar month	Habitat availability for aquatic organisms Soil moisture availability for plants Availability of water for terrestrial animals Availability of food/cover for fur-bearing mammals Reliability of water supplies for terrestrial animals Access by predators to nesting sites Influences water temperature, oxygen levels, photosynthesis in water column
2: Magnitude and duration of annual extreme discharge conditions	Magnitude, duration	Annual maxima one-day means Annual minima one-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means Number of zero-flow days 7-day minimum flow divided by mean flow for year ('base flow')	Balance of competitive, ruderal, and stress-tolerant organisms Creation of sites for plant colonization Structuring of aquatic ecosystems by abiotic vs. biotic factors Structuring of river channel morphology and physical habitat conditions Soil moisture stress in plants Dehydration in animals Anaerobic stress in plants Volume of nutrient exchanges between rivers and floodplains Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments Distribution of plant communities in lakes, ponds, floodplains Duration of high flows for waste disposal, aeration of spawning beds in channel sediments
3: Timing of annual extreme discharge conditions	Timing	Julian date of each annual one-day maximum discharge Julian date of each annual one-day minimum discharge	Compatibility with life cycles of organisms Predictability/avoidability of stress for organisms Access to special habitats during reproduction or to avoid predation Spawning cues for migratory fish Evolution of life history strategies, behavioral mechanisms
4: Frequency and duration of high/low flow pulses	Magnitude, frequency duration	No. of high pulses each year No. of low pulses each year Mean duration of high pulses within each year Mean duration of low pulses within each year	Frequency and magnitude of soil moisture stress for plants Frequency and duration of anaerobic stress for plants Availability of floodplain habitats for aquatic organisms Nutrient and organic matter exchanges between river and floodplain Soil mineral availability Access for waterbirds to feeding, resting, reproduction sites Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
5: Rate/frequency of hydrograph changes	Frequency, rate of change	Means of all positive differences between consecutive daily values Means of all negative differences between consecutive daily values No. of flow reversals	Drought stress on plants (falling levels) Entrapment of organisms on islands, floodplains (rising levels) Desiccation stress on low-mobility stream edge (varial zone) organisms

upstream and downstream of the gauge location. Using point-based data to assess conditions upstream and downstream of a gauge location requires rules for determining the distance of up- or downstream applicability of the streamgauge-based data or measures of alteration. This article presents an example set of such rules in the case study.

Once point-based data have been analyzed and their spatial applicability determined, mapping of hydrologic alteration can provide a visual portrayal of the spatial extent of hydrologic alteration. A number of different strategies for mapping hydrologic alteration could be employed using the results of the RVA analysis at each streamgauge. One strategy is to categorize the numerical measures of hydrologic alteration into a few qualitative classes, assign a different mapping pattern to each alteration class, and then display each mapped river segment with the appropriate pattern based on the level of hydrologic alteration detected within that river segment. This mapping strategy is used to illustrate the case study.

Ideally, the definitions of qualitative classes, e.g. highly or moderately altered, should correspond to differing degrees of ecological impact associated with hydrologic alteration. For example, if the dependence or tolerance of a particular species for specific values of each hydrologic parameter were known, the classes of hydrologic alteration could be scaled and defined accordingly. However, such tolerances or dependencies are seldom known for more than a few species within an ecosystem, and for those species such knowledge is nearly always limited to just a few hydrologic parameters (Sparks, 1992; Richter *et al.*, 1996, 1997). Without compelling ecological justification, and unless policy or regulatory constraints dictate a narrow focus, it is recommended that qualitative classes of hydrologic alteration not be based on the needs of one or a small set of individual species. Rather, simply sub-dividing the range of possible alteration values into a small set of arbitrarily defined classes may adequately describe relative degrees of hydrologic alteration at the river network scale.

CASE STUDY

The application of the RVA method for assessing and mapping hydrologic alteration on a river basin scale is demonstrated by evaluating the impacts of dam construction on hydrologic variability in two major rivers in the upper Colorado River basin in Colorado and Utah (USA). The upper Colorado River drainage basin, situated above Lake Powell, Arizona (Figure 2), encompasses 761 343 square kilometers in Arizona, Colorado, New Mexico, Utah, and Wyoming. The Colorado and Green Rivers are the two largest rivers draining the upper basin.

The large river–floodplain ecosystems of the upper basin provide habitat for four species of federally listed fish, namely bonytail chub (*Gila elegans*); humpback chub (*Gila cypha*); razorback sucker (*Xyrauchen texanus*); and Colorado squawfish (*Ptychocheilus lucius*), along with numerous rare and imperiled riparian and riverine wetland community types. The history and current status of the endangered fish recovery program, and recommendations for flow management to sustain the fish, are summarized in Stanford (1994).

Surface water diversions from the Colorado and Green Rivers began as early as the mid-1800s. However, the cumulative effect of these diversions pales in comparison to flow alterations associated with dam construction in the basin. Dam construction began with Eden Reservoir on Big Sandy Creek, Wyoming, in 1910. In the four decades from 1937 to 1977, 25 additional large reservoirs were constructed in the Colorado/Green river basins.

The primary intent in presenting this case study (without rigorous analysis of early water diversion or climate effects) is to demonstrate a technique for assessing hydrologic alteration on a river network scale. The magnitude of pre-1937 impacts have not rigorously examined (associated primarily with surface water diversion for irrigated agriculture), so the RVA targets used in this case study should be further evaluated before being considered as appropriate management targets for the Colorado and Green River systems (see recommendations in Richter *et al.* (1997) for application of the RVA in river ecosystem management). Additionally, some of the streamgauge records used for defining the RVA targets or the magnitude of

hydrologic alteration are as short as 9–16 years. For setting operational management targets, a regional analysis of the sensitivity of hydrologic parameter values to varying record length, based upon data from least-altered 'reference' basins, should be used as a means for determining minimum necessary record length (Richter et al., 1997).

Eight streamgauging sites located along the Colorado River (five sites) and Green River (three sites) were selected for analysis of hydrologic alteration associated with dam construction in the upper basin (Figures 2 and 3). These gauging sites were selected based upon the availability and length of streamgauging records for both the pre-dam and post-dam periods. For each of the eight streamgauging sites, note the inclusion of the date of construction of both the first and last dams built within the basin area contributing to that streamgauge site; Figures 2 and 3 identify the 26 dams considered in this analysis. The pre-dam period for any given streamgauge was then defined as the period from the beginning of data collection until the construction of the first dam within the contributing basin; the post-dam period began after completion of the last dam within the basin and extended to the most recent year of data. Because Eden and Stagecoach Reservoirs impound less than 5% of the overall drainage areas contributing to the nearest downstream streamgauging sites on the Green River, their influence on Green River flows was neglected in the analysis that follows. Inclusion of these two reservoirs would have had the undesirable effect of substantially shortening pre- or post-dam periods for the Green River gauges at Jensen and Green River, Utah.

For each of the eight streamgauge records, we computed the 25th and 75th percentile values for each of the 33 hydrologic parameters used in the RVA, based upon the available pre-dam record (Figure 3). These values were taken as the lower and upper limit, respectively, of the RVA target range for each parameter (e.g. Figure 1). The values for the measure of hydrologic alteration were then calculated as described previously.

Results of RVA analysis

The results of the RVA analysis are summarized in Table II. Only the results for six hydrologic parameters (from the full set of 33 RVA parameters) are reported here. Overall, these six parameters were the most greatly affected by reservoir development and operation in the upper basin. The annual values for each of these six streamflow parameters are generated in the RVA as follows:
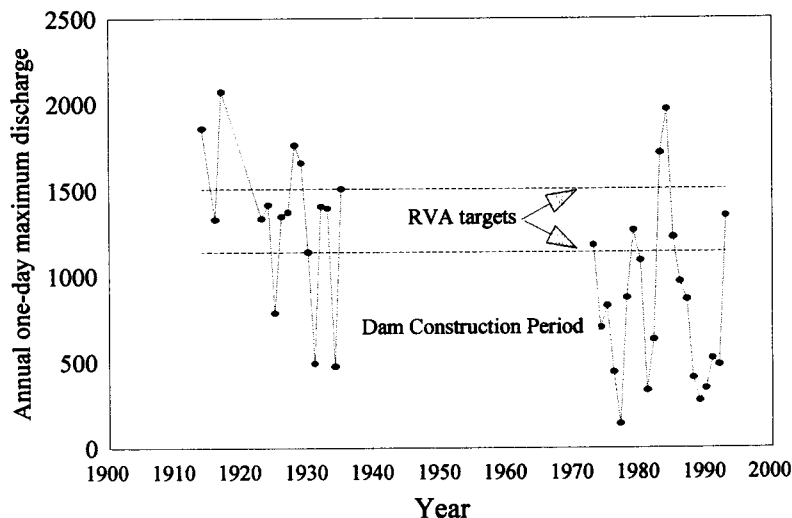

Figure 1. This plot of annual maximum one-day flood magnitudes (in cubic meters per second) for the Colorado River at Cisco, Utah, illustrates dam-induced flood control effects. Hypothetical streamflow management targets for the one-day flood magnitudes using the Range of Variability Approach are illustrated as 'RVA targets.' Because the targeted range illustrated here is based upon the 25th and 75th percentile levels of the annual one-day flood series, the management goal would be to maintain 1-day flood levels within this range during 50% of years
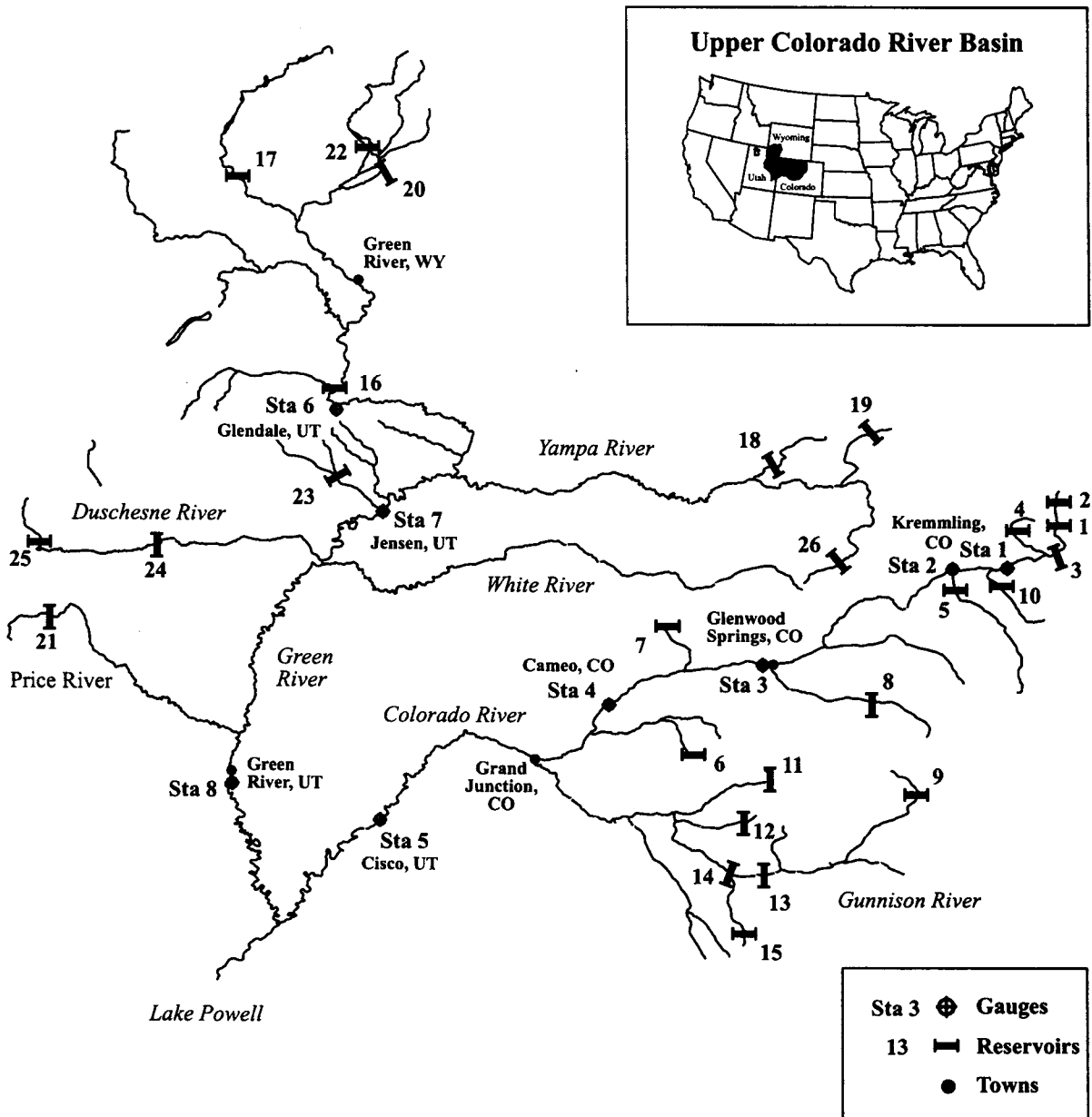
Figure 2. Upper Colorado River basin location map, illustrating locations of the eight streamgauge sites and 26 dams evaluated in this study. Streamgauge identification numbers correspond to Figure 3. Dams or reservoirs identified by number, along with dates of construction: (1) Shadow Mountain, 1946; (2) Lake Granby, 1950; (3) Grand Lake, 1946; (4) Willow Creek, 1953; (5) Green Mountain, 1943; (6) Vega, 1959; (7) Rifle Gap, 1967; (8) Ruedi, 1968; (9) Taylor Park, 1937; (10) Williams Fork, 1939; (11) Paonia, 1962; (12) Crawford, 1962; (13) Blue Mesa, 1966; (14) Morrow Point, 1968; (15) Silver Jack, 1971; (16) Flaming Gorge, 1963; (17) Fontenelle, 1963; (18) Steamboat Lake, 1966; (19) Elkhead 1977; (20) Eden 1910; (21) Scofield, 1961; (22) Big Sandy, 1952; (23) Steinaker, 1961; (24) Starvation, 1970; (25) Strawberry, 1973; (26) Stagecoach, 1989

Annual maxima and 30-day low flows: These parameters identify the highest daily mean discharge and lowest 30-day average discharge for each year.

High pulse durations: These are defined as periods in which the hydrograph rises above the 75th percentile of all pre-dam daily values. In each year, the average duration of high pulses is computed.

Timing of annual maxima and minima: The dates of occurrence for both the annual maximum and minimum discharge are identified by Julian date.

Frequency of hydrograph reversals: This parameter counts the frequency at which the hydrograph switches from a rising period to a falling period (and *vice versa*) within each year.

On the Colorado River, dam regulation has had the greatest impacts on annual 1-day flow maxima and 30-day flow minima; on the Green River, impacts have generally been greatest on 30-day minima and the frequency of hydrograph reversals. However, the spatial distribution of impacts varies considerably for each of the six parameters (Table II).

For each streamgauge site, the average hydrologic alteration scores across all parameters were computed (Table II). These averages were used in mapping hydrologic alteration.

To map hydrologic alteration, we divided the range of possible (absolute) average values for hydrologic alteration (0–100%) into three classes of equal range and assigned each class a distinct pattern: (i) 0–33% (light grey) represents little or no alteration; (ii) 34–67% (medium grey) represents moderate alteration; (iii) 68–100% (dark grey) represents a high degree of alteration (see also Table II).

Because the measurement of hydrologic alteration is point based, i.e. measured at the streamgauge, mapping conventions are necessary for characterizing whole stream reaches based on the point data. When the measure of hydrologic alteration at a particular streamgauge site is greater than 67%, it is assumed that this high level of alteration should extend upstream to the location of the first upstream dam. The highly altered zone is also extended downstream from the streamgauge to the first confluence with a major tributary. Minimally or moderately altered zones (hydrologic alteration of 0–33% and 34–67%, respectively) are handled in a similar fashion as highly altered zones downstream of stream-gauges, but may extend upstream to either the location of the first dam, to the location of the first dammed major tributary, or to a contact with a highly altered zone. Figure 4 portrays the distribution of these three zones of hydrologic alteration along the Colorado and Green Rivers. Using these mapping conventions, it was not possible to assess hydrologic alteration in the two gaps along the mainstem rivers, i.e. between the confluences of the Duschesne and Price Rivers with the Green River, and the reach immediately upstream of Grand Junction on the Colorado River.
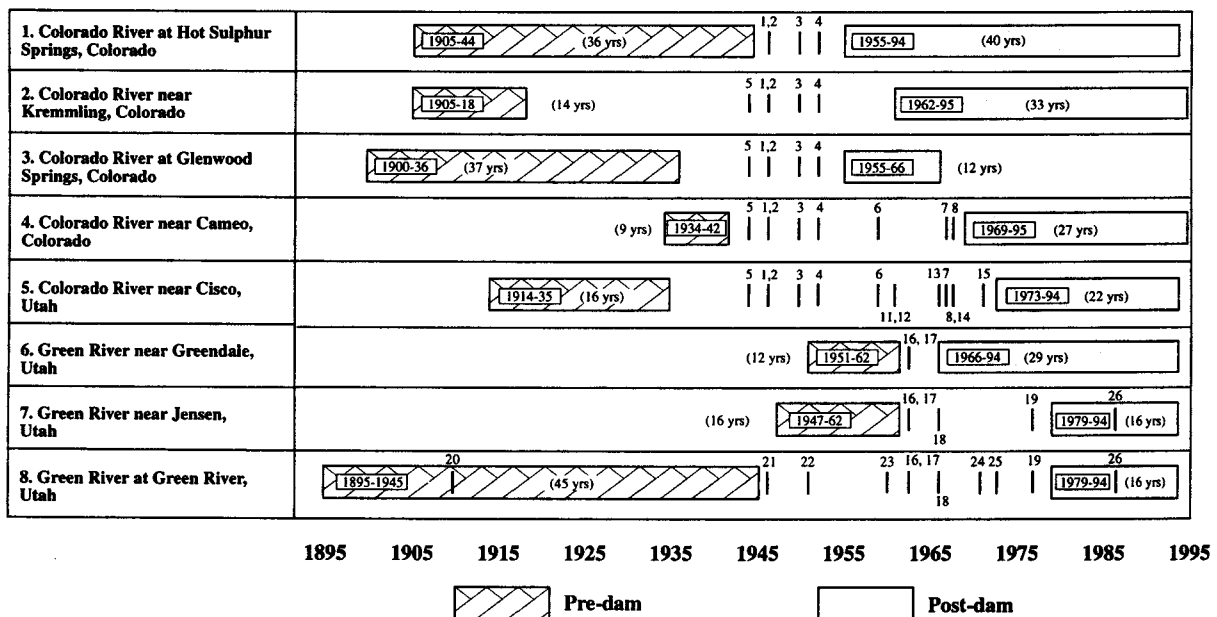

Figure 3. Periods of record for streamgauges used in this analysis. Cross-hatched bars represent the pre-dam period, shaded bars represent post-dam period. The total number of years of record available for these pre- and post-dam periods are specified in parentheses within each bar. The construction dates for each reservoir are identified within each interlude between pre- and post-dam periods; enumeration of each dam corresponds to Figure 2

Table II. Measures of hydrologic alteration[a] at eight streamgauges

Streamgauge	1-day maxima (%)	30-day minima (%)	Date of annual maximum (%)	Date of annual minimum (%)	High pulse duration (%)	No. of hydrograph reversals (%)	Average (%)
1. Colorado River at Hot Sulphur Springs, CO	−91 (H)	−95 (H)	−57 (M)	+24 (L)	−69 (H)	−48 (M)	64 (M)
2. Colorado River near Kremmling, CO	−89 (H)	−58 (M)	−68 (H)	+43 (M)	−84 (H)	−89 (H)	72 (H)
3. Colorado River at Glenwood Springs, CO	−69 (H)	−69 (H)	−23 (L)	+54 (M)	−38 (M)	−23 (L)	46 (M)
4. Colorado River near Cameo, CO	39 (M)	−83 (H)	−8 (L)	−33 (L)	−17 (L)	0 (L)	33 (L)
5. Colorado River near Cisco, UT	−68 (H)	−43 (M)	−60 (M)	−52 (M)	−43 (M)	−19 (L)	48 (M)
6. Green River near Greendale, UT	−82 (H)	−100 (H)	−70 (H)	−88 (H)	−82 (H)	−100 (H)	87 (H)
7. Green River near Jensen, UT	−22 (L)	−100 (H)	−11 (L)	−11 (L)	−22 (L)	−100 (H)	44 (M)
8. Green River at Green River, UT	−53 (M)	−55 (M)	−6 (L)	−6 (L)	−10 (L)	−100 (H)	38 (M)
Colorado River averages[b]	71	70	47	41	50	36	
Green River averages	52	81	29	35	38	100	

Degrees of hydrologic alteration are denoted by H, high; M, medium; and L, low.
[a] A positive deviation indicates that annual parameter values fell inside the RVA target window more often than expected (e.g. > 50% of post-dam years); negative values indicate that annual values fell within the RVA target window less often than expected (e.g. <50%).
[b] Average values are based upon absolute values of each deviation.

Dams along the Green and Colorado Rivers have had the general effect of substantially reducing the annual range of variation in flow magnitudes. Annual snowmelt floods have been substantially lessened in most years (Figure 1, Table II), and the duration of high flow pulsing is now much more variable (Figure 5, Table II) with very long pulses during high flow years and very short pulses during low flow years. The extended flood pulses during high flow years result from attempts to control flood damages, which lessen flood peaks but spread them out in time. Shorter high pulses result when dam operators respond to potential water shortages by capturing the spring flood waters for later use in irrigation and domestic water supply or hydropower generation. High flow pulses are a critical aspect of the lateral connectivity between a river and its floodplain, and reduced duration of these high pulses during less-than-average water years is thought to be diminishing the ecological function of floodplain wetland areas as nursery and feeding habitats for the endangered fishes of the Colorado and Green Rivers (Stanford, 1994). Large floods play an important role in structuring the morphology of river channels, in preventing the encroachment of riparian vegetation into overflow sloughs and main channel margins, and in preparing spawning beds (Harvey et al. 1993), but geomorphically-effective floods now occur far less often (Table II, Figure 1). Additionally, the timing of annual maxima must be synchronized with the life cycle requirements of the fish, such as the spawning season. Timing shifts of only 2 to 3 weeks in the Colorado River below Grand Junction (Figure 6) may be desynchronizing high flows with spawning and juvenile rearing periods for the endangered fishes in the Colorado River.

The late summer and winter seasonal use of the captured water for irrigation and power generation, combined with the effects of irrigation return flows to the rivers, results in higher late summer flows in river segments downstream of the reservoirs than would have occurred in the pre-dam low-water periods (Figure 7). Changes in low flow can alter migrational patterns and increases in low flows can affect competition between species or increase the bioenergetic demands of aquatic organisms during quiescent periods (Schlosser, 1991; Stanford, 1994).

From a river network perspective, the severe effects of Flaming Gorge Dam (dam no.16 in Figure 4) on the Green River are indicated in the alteration of low flows and the frequency of flow reversals all the way downstream to Green River, Utah (see Station 8: Figure 4, Table II). The inflow of the Yampa River above Jensen mitigates impacts on 1-day maximum discharge, the timing of the annual maxima and minima, and high pulse durations. However, additional dams on the Duchesne and Price Rivers cause further flood regime alteration in the lowermost reach of the Green River. Dams in the upper Colorado basin are likewise having significant impacts on all hydrologic parameters, but these effects generally attenuate with distance downstream toward Cameo, CO. Low flow (30-day minima) alterations persist below Cameo, however. Numerous dams in the Gunnison River basin are altering the lowermost reaches of the Colorado River, particularly with respect to the 1-day maxima and its timing, and the timing of annual minima (Table II).

DISCUSSION

It is considered that the technique demonstrated here for mapping hydrologic alteration provides powerful insights into the spatial distribution of hydrologic impacts within river networks. For example, hydrologic alteration in the lower end of the Colorado River below its confluence with the Gunnison River is well illustrated by deviations in the one-day maxima, the timing of maxima and minima, and high pulse durations (Figure 4, Table II). However, this hydrologic degradation in the lower Colorado River may not have been fully appreciated without this type of analysis, because the primary cause of this degradation is most likely the dammed tributaries of the Colorado River, and these dams are all located at considerable distance upstream of the Cisco streamgauging site.

This was the first effort to map hydrologic alteration using the results of the RVA analyses. It was quickly realized that the scarcity of long-term measurement records will limit the utility of this approach.
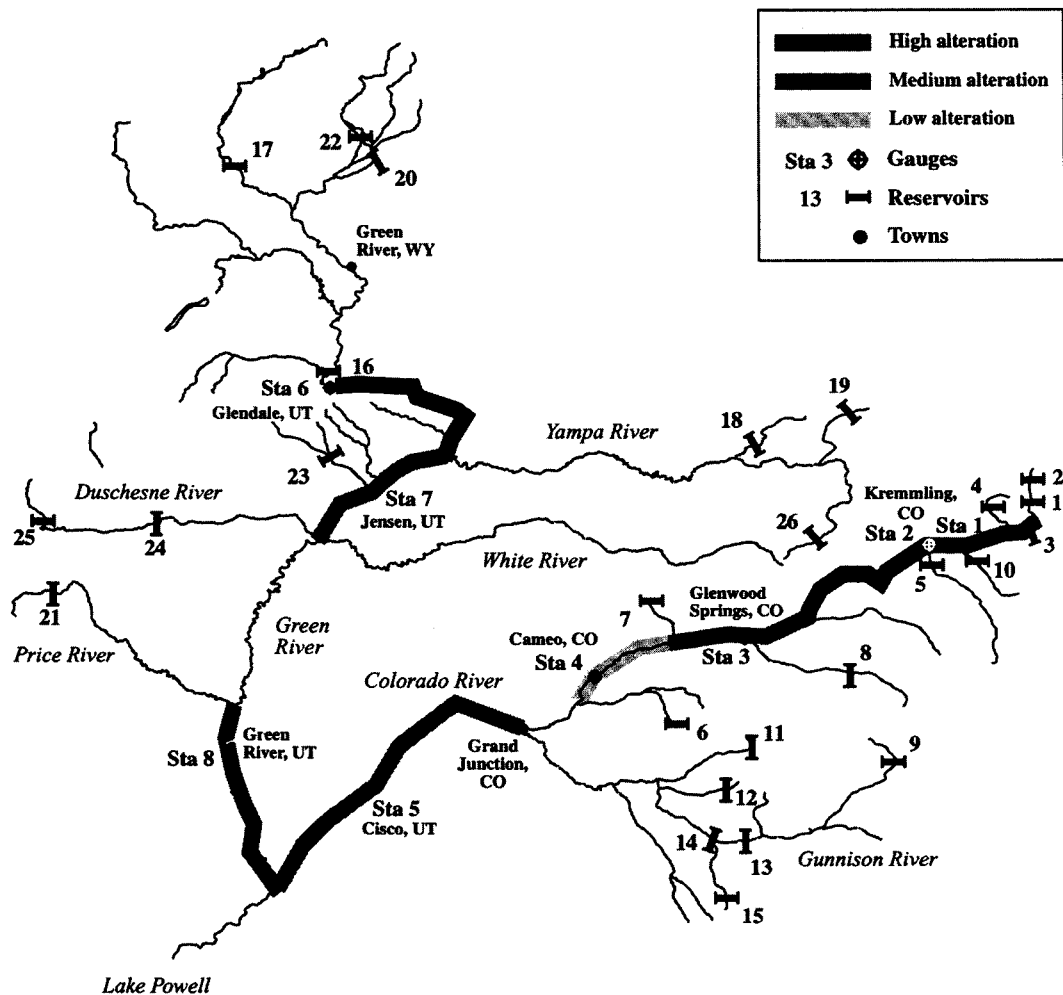
Figure 4. This map illustrates the spatial distribution of averaged hydrologic alteration across all six hydrologic parameters summarized in Table II. Light grey zones represent river segments exhibiting relatively unaltered conditions (hydrologic alteration values of 0–33%). Medium grey zones represent moderately altered river segments (hydrologic alteration values of 34–67%). Dark grey zones represent highly altered river segments (hydrologic alteration values of 68–100%)

By applying the hydrologic analysis on a river network basis, it was possible to identify river reaches within which streamgauging should be initiated or re-instated. When streamgauge records are short for either the period used to define RVA target windows, or for the post-impact periods (or both), the validity of any assessment of hydrologic alteration must be carefully considered. In Richter *et al.* (1996, 1997), a number of possible approaches are suggested for extending record length through use of statistical relationships developed between other streamgauges in a region, or by using hydrologic simulation models. Clearly, the sensitivity of RVA results to record length in differing ecoregional settings needs to be evaluated (Richter *et al.* 1997).

While gaps in available data may limit the applicability of the RVA method to the study of hydrologic alteration in some river basins, it nevertheless can provide significant insights into river integrity in suitably gauged systems. The breadth of parameters included in the RVA makes it an especially potent tool for river ecosystem management. In particular, the information acquired by studies of this type, specific to the upper Colorado River basin, can provide ecosystem managers with vital information for
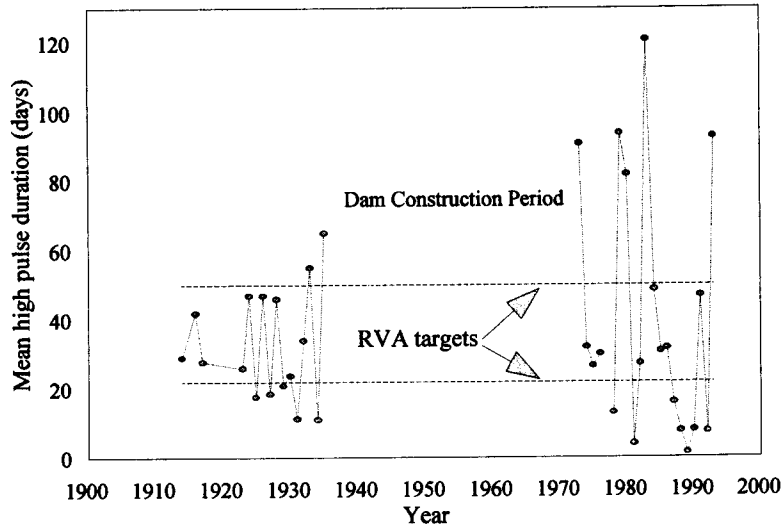
Figure 5. This plot of mean annual high pulse duration for the Colorado River at Cisco, UT illustrates the increased variability in annual pulses associated with dam operations

guiding efforts to restore or maintain system integrity. Analysis of RVA findings can pinpoint reaches within which alterations to the streamflow regime are disrupting or might disrupt overall system connectivity, or pinpoint reaches for which gauging activities need to be improved to provide crucial guidance; and can help identify precisely what is wrong hydrologically and what human activities are causing the disruption. Use of such tools is thus vital to efforts to conserve riverine biological diversity.
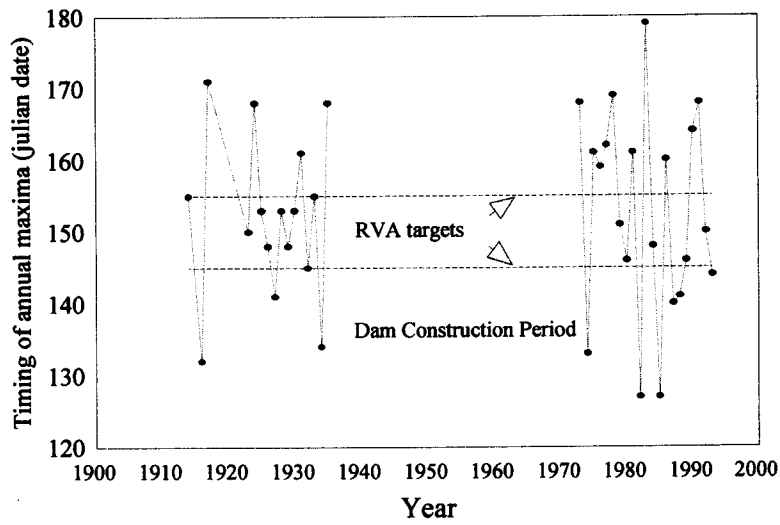
Figure 6. This plot illustrates changes in the timing of annual 1-day maximum discharge (m³/s) on the Colorado River near Cisco, UT

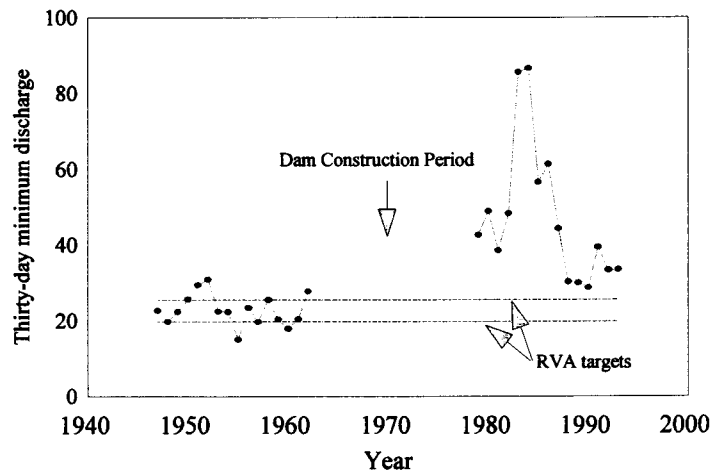Figure 7. This plot of 30-day minimum discharge (m³/s) on the Green River near Jensen, Utah, illustrates increases in low flows attributable to operations of Flaming Gorge Dam

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