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CONSTRUCTING AN INTERDISCIPLINARY FLOW REGIME RECOMMENDATION[1]

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ABSTRACT: It is generally agreed that river rehabilitation most often relies on restoring a more natural flow regime, but credibly defining the desired regime can be problematic. I combined four distinct methods to develop and refine month-by-month and event-based flow recommendations to protect and partially restore the ecological integrity of the Cache la Poudre River through Fort Collins, Colorado. A statistical hydrologic approach was used to summarize the river's natural flow regime and set provisional monthly flow targets at levels that were historically exceeded 75% of the time. These preliminary monthly targets were supplemented using results from three Poudre-specific disciplinary studies. A substrate maintenance flow model was used to better define the high flows needed to flush accumulated sediment from the river's channel and help sustain the riparian zone in this snowmelt-dominated river. A hydraulic/habitat model and a water temperature model were both used to better define the minimum flows necessary to maintain a thriving cool water fishery. The result is a range of recommended monthly flows and daily flow guidance illustrating the advantage of combining a wide range of available disciplinary information, supplemented by judgment based on ecological principles and a general understanding of river ecosystems, in a highly altered, working river.

(KEY TERMS: aquatic ecology; fish habitat; river restoration; sediment transport; stream temperature; watershed management.)

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INTRODUCTION

Rivers in the arid western United States played a key role in population settlement; their extensive water development continues to support irrigated agriculture as well as municipal and industrial demands that are increasing as populations grow. In the last half century, however, instream demands for fishing, recreation, public health, aesthetics, and a host of other recognized ecosystem goods and services have begun to compete, in part, with traditional out-of-stream uses on these "working rivers" (Postel and Richter, 2003).

Much scientific research has been devoted to quantifying and valuing instream (or environmental) flows (e.g., Loomis, 2000; Petts, 2009). Formulating environmental flows has been relatively successful in many streams and rivers where existing extractive demands have not precluded instream uses, or where water management infrastructure could be re-operated to provide environmental flows with little or no impact to traditional users (Postel and Richter, 2003). In other cases where competition for water has been

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more intense, formulating environmental flows has proven complicated, costly, and rife with technical concerns (Annear *et al.*, 2004). In some cases, millions of dollars have been spent over decades with controversy still lingering regarding the accuracy, suitability, and comprehensiveness of the methods used; the equity of the water allocation decisions reached; and the potential need for adjustments as more knowledge is attained (Poff *et al.*, 2003). Nonetheless, efforts remain underway worldwide to develop broadly applicable, regional, or river-specific environmental flow recommendations to support the ecosystem goods-and-services rationale even in situations where competition remains intense, signaling the increasing value ascribed to instream uses by our society and the expectation that it is possible to achieve a sustainable balance among instream and out-of-stream uses (Silk and Landry, 2007; Richter, 2009).

Although a variety of methods have been developed to formulate environmental flow recommendations, in one way or another they all recognize that a river's flow regime is *the* key driver in successfully maintaining river, floodplain, and stream margin wetland ecosystems (Poff *et al.*, 1997; Bunn and Arthington, 2002; Nilsson and Svedmark, 2002; Whiting, 2002). Streamflow is intimately related to many critical physiochemical components of rivers, such as channel geomorphology and water temperature, and can be considered a master variable that limits the distribution, abundance, and diversity of many aquatic plant and animal species (Resh *et al.*, 1988; Poff *et al.*, 1997). The major mechanisms linking the flow regime to ecosystem consequences are reasonably well understood. However, few rivers remain in their natural state, and predicting and quantifying the exact ecological responses of any given flow alteration in any specific river reach are not yet within the grasp of today's scientific community.

In light of the uncertainty regarding flow recommendation development for altered riverine environments, Arthington *et al.* (2006) have argued that rivers fall into two categories; one that warrants large, ongoing adaptive management assessments, and a second "for which site-specific biotic and hydrologic data neither exist nor will be forthcoming in the short term." This dichotomy is more properly viewed as a spectrum, with the two categories defining logical endpoints (see Tharme, 2003, for a broad perspective); there are many rivers for which extensive (and expensive) adaptive management processes may not be currently feasible, but enough biotic, hydrologic, and other data do exist to, in effect, validate or supplement much less-expensive statistical methods – at least as a starting point.

In this article, I illustrate such an approach for the Cache la Poudre River in Colorado using several kinds of detailed empirical information to "ground truth" or fine-tune a relatively simple hydrology-based statistical approach. I believe that integrating knowledge from a variety of disciplines can help avoid the oversimplification that Arthington *et al.* (2006) believe would result in further river degradation if a flow recommendation were based on statistical techniques alone.

My objective for this case study was to develop an initial flow recommendation for the Poudre River through the city of Fort Collins that would be sufficient to maintain the key environmental processes and services indefinitely, be resilient in the face of recurring flow-related stresses, and still meet most societal needs and expectations (Meyer, 1997). It is my hope that crafting a flow regime to meet this objective will serve to help educate the public regarding the current state of the river, offer a baseline by which to evaluate the relative benefits and/or costs of new water development proposals, and highlight opportunities to improve the existing flow regime.

Study Area

The Poudre River flows out of the Rocky Mountains eastward to join the South Platte River near Greeley, Colorado (Figure 1). The watershed for this popular trout fishing and rafting river covers about 4,900 km^2, ranging in elevation from the continental divide at 4,130 m down to 1,400 m. Given the extent of mountainous terrain in the upper basin, snowmelt dominates the runoff. There are numerous transbasin imports to the Poudre River (Case, 1995), including a large delivery through nearby Horsetooth Reservoir. Combined natural flows and imports result in an average annual discharge of approximately 1,357 Mm^3 near the river's egress from the mountains, although annual volumes vary widely. Total outflow to the South Platte is approximately 493 Mm^3, indicative of the high agricultural and municipal demands on the river (Evans and Evans, 1991; U.S. Army Corps of Engineers, 2008). Diversions began in the 1860s, with most major diversions occurring upstream of Fort Collins (Laflin, 2005). Prior to extensive water extraction and some reservoir development, large spring/summer runoff volumes percolated into the gravel/cobble alluvium floor, recharging shallow aquifers that sustained fall/winter base flows as well as a fringing cottonwood (*Populus deltoides*) riparian zone; the snowmelt hydrograph, and the physical mountains-to-plains transitional setting resulted in a unique species assemblage, with some fishes adapted to swift, cold water and others adapted to slower and warmer conditions (Fausch and Bestgen, 1997).

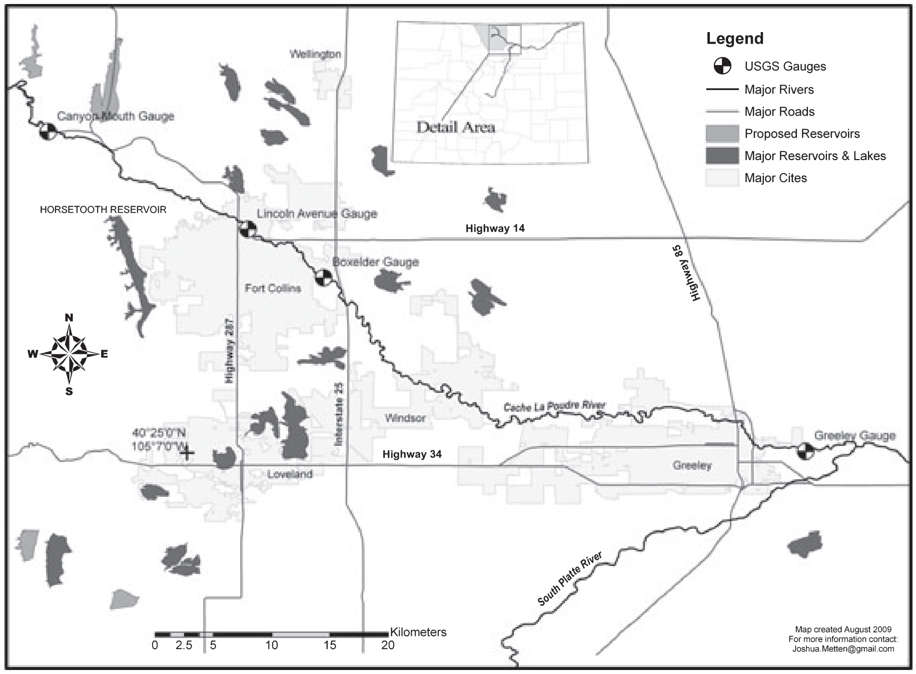

FIGURE 1. Schematic of Study Area Showing the Plains Portion of the Cache la Poudre River, Major Cities, U.S. Geological Survey (USGS) Gaging Stations, and Other Features Referenced in the Article.

Although the Poudre River once supported a thriving trout fishery throughout its entire length, at least in many years (Bartholow, 1991), water extraction and accompanying increases in summer water temperature have constricted the distribution of coldwater fishes such that they are found only in isolated spots below Fort Collins (Rico Moore, Cache la Poudre River Foundation, 2010, personal communication), probably associated with occasional cool water springs and seeps. Today, as well as in the past, the river supports a unique thermally transitional fauna as it warms and flows onto the plains. The river's thermal regime is discontinuous due to the infusion of relatively cold water (8-11°C) released intermittently from Horsetooth Reservoir's discharge canal during the irrigation season. When Horsetooth is releasing to the Poudre River and/or on days with relatively cool meteorological characteristics, the thermal regime is sufficiently cool to support a sustainable (if hatchery supplemented) population of rainbow and brown trout (*Oncorhynchus mykiss* and *Salmo trutta*) and the food base on which these species exist through the Fort Collins reach (Bartholow, 1991). (Although rainbow and brown trout are not natives of Colorado, they are used here as surrogates for the native trout they have replaced, both ecologically and economically.) However, when Horsetooth releases are low and/or on meteorologically hot days, water temperatures can be well above the 15-17°C optimum for these species; temperatures can also exceed 24°C for brief periods at the Lincoln Avenue gage site (Keith Elmund, city of Fort Collins, 2008, personal communication), conditions that are highly stressful to these fishes in terms of growth and condition at a minimum, and that may be lethal if prolonged (Brungs and Jones, 1977; Elliott, 1994).

Extensive water and land development has resulted in significant morphological changes (e.g., channel straightening, incision, and narrowing) over the last century due to flow diversions, urbanization, channelization, aggregate mining, and, together with the introduction of nonnative species, has significantly altered the riparian and aquatic fauna (Fausch and Bestgen, 1997; Ayres Associates, 2008). In 1986, most of the river's mountainous reach was federally designated as Wild and Scenic (http://hdl.handle.net/10217/21499); the remaining 72 km of the plains reach has been federally designated as a National Heritage Area in acknowledgment of the river's pivotal role in the development of Colorado's water law and delivery system. Three state wildlife areas lie along or adjacent to the river in the plains reach, some sheltering warm water sloughs created in inactive oxbow channels that harbor pockets of native wetland plant species. On a landscape level, riparian zones such as those found along the Poudre account for only 3% of Colorado's land area but represent essential habitat for over 50% of Colorado's bird species (U.S. Army Corps of Engineers, 2004).

The city of Greeley has previously dredged portions of the Poudre River because sediment entering the river, often through bank erosion, is no longer flushed from the system due to infrequent and reduced peak flows. Sediment aggradation (build up) has decreased channel conveyance leading to an increased risk of flooding. Further, river reconnaissance (U.S. Army Corps of Engineers, 2004) has shown that the stream corridor and important riparian zones need costly restoration; that wildlife migration has been disrupted; that channel narrowing has removed connections to historically adjacent wetlands, oxbows, and side channels; and native plant, fish, and wildlife species have been lost whereas nonnative species such as Russian olive (*Elaeagnus angustifolia*) and tamarisk (*Tamarix* spp.) have invaded. Known sediment problems may not be confined to Greeley; after a 1997 flood on the Poudre River, Shields (1997) offered anecdotal evidence that flood conveyance has been constrained due to channel aggradation at the Interstate-25 bridge over the Poudre River constructed in 1965 due to water withdrawals and other land use practices; floods, he says, now risk overtopping the highway.

Although some aspects of the natural environment of the Poudre River have been extensively studied, no one has cataloged the full range of impacts observed on the river, though Wohl (2005) did cover general impacts to a variety of Front Range rivers. Strange *et al.* (1999), however, report that on the highly altered South Platte River into which the Poudre River drains: (1) riparian habitats have been so extensively modified that at least four bird species have been lost through hybridization with nonnatives; (2) the river had the highest ammonia and nitrate concentration and the second highest phosphorus concentration among 20 major rivers sampled by USGS, all leading to water-quality violations; (3) native riparian vegetation loss was associated with increased algal abundance and loss of benthic macroinvertebrates; and (4) flow regime modification has resulted in declines of six native fish species considered for listing as Threatened or Endangered, and establishment of 18 exotics. Dennehy *et al.* (1998) expand on the water-quality and channel conditions in the South Platte basin, noting that: (1) subsurface irrigation return flow is a major nonpoint source of nitrate, dissolved solids, and pesticides in the South Platte River's lower reaches; (2) wastewater treatment plant effluent contributes large loads of phosphorous, nitrate, and ammonia; (3) large diversions in the basin result in less dilution for measured contaminants, which now violate EPA's aquatic life criteria; and (4) surface and groundwater reuse has increased salinity in the lower South Platte River and surrounding alluvial aquifer, negatively affecting both irrigation and drinking-water supplies. Collectively, using multiple lines of evidence, Dennehy *et al.* (1998) conclude that large portions of the South Platte basin, including some lower reaches of the Poudre River, are moderately to significantly degraded.

Although existing diversions from the Poudre River are extensive, several water extraction projects are currently proposed to further develop the water within the Poudre. Proposed projects involve both unappropriated water as well as water exchanges – water that is traded from one point of diversion to another, usually downstream to upstream – ultimately for storage in new or expanded reservoirs and delivered primarily to growing municipalities (U.S. Army Corps of Engineers, 2008). These project proposals have generated considerable controversy, in part because the Poudre River remains a highly valued resource for those who live nearby and regularly recreate along or in it. The public has assigned high willingness-to-pay values for flow maintenance or supplementation in the Poudre River, with an aggregate estimated value in Fort Collins alone between \$283 and \$425 million depending on the metric used (Loomis, 2008).

Controversy notwithstanding, there has been no effort to date to institute an adaptive management process on the Poudre River. However, there have been several aquatic studies making it a good candidate for the development of a sound, science-based environmental flow recommendation.

General Approach for the Poudre River

Tharme (2003) catalogued the spectrum of assessment methods being used to develop environmental flow recommendations or standards. Methods categorized as hydrology- or habitat-based made up the bulk of the assessments representing 30% and 28% of the total, respectively. Hydraulic-based methods made up another 11%, combination methods 17%, and the remaining 14% were termed holistic or "other." My approach for the Poudre River may be classified as a combination type in that I begin with a hydrology-based method and then weave in habitat and hydraulic-based information from available Poudre-specific empirical studies as outlined below.

Hydrology-based environmental flow methods in many ways tend to be the simplest and fastest to develop and apply. They are compelling because there is a strong and growing consensus (1) that rivers need a flow regime that is relatively natural to fully sustain native biodiversity for aquatic, riparian, and wetland ecosystems (Resh *et al.*, 1988; Power *et al.*, 1995; Poff *et al.*, 1997; Richter, 2009); (2) that deviations from natural (or between any two regimes) may be quantitatively measured by examining several fundamental attributes of the regimes (namely, flow magnitude, frequency, duration, timing, and rate of change) that attempt to describe the full range of seasonal and interannual hydrologic variation (Richter *et al.*, 1996; Olden and Poff, 2003; Henriksen *et al.*, 2006); and (3) that it is possible to designate thresholds from these metrics or otherwise scale flows in various ways to protect ecological values and instream utility (*Reiser et al.,* 1989; Richter *et al.*, 1997; Gippel, 2001). The assumptions generally are (1) that prealteration streamflow patterns establish the context for and provide proper guidance to manage ecological systems today; and (2) that flow variability is a vital attribute of ecological systems (Landres *et al.*, 1999). Several sets of authors have argued that when faced with scant information, maintaining streamflow between ±1 SD of the median natural flow is appropriate: Richter *et al.* (1996) proposed establishing initial flow limits by defining high and low flow boundaries at the 75th and 25th percentile of all preimpact monthly flows. Richter *et al.* (1997) further expanded on that reasoning, detailing a method they called the "Range of Variability Approach." This method establishes initial flow management limits at the 25th to 75th percentile range around the median monthly natural flows for a reference time period. Since the Richter *et al.*'s (1997) proposal, more scientists have advocated approaches that focus on percentile thresholds (Whittaker and Shelby, 2000; Arthington *et al.*, 2006; Richter *et al.*, 2006; Rathburn *et al.*, 2009). Although there is no universally agreed percentage of annual or monthly flows sufficient to maintain the ecosystem integrity of altered rivers (Gippel, 2001), I have nonetheless chosen a scaling technique to identify a range of monthly flows as initial targets for a flow recommendation that captures at least some of the natural variability that shaped the Poudre River's ecosystem.

Hydraulic-based environmental flow methods can also range from relatively simple (e.g., wetted perimeter) to more complex rating methods that, for example, calculate flushing flows. It is well established that annual peak flows dominate many river processes, especially channel morphology and riverbed community integrity (Scott *et al.*, 1996; Bunn and Arthington, 2002; Nilsson and Svedmark, 2002; Richter *et al.*, 2003; R. Milhous, USGS retired, 2008, personal communication). High pulse flows shape a channel's physical character, including pool and riffle distribution, bank structure, and channel width, and they determine the size distribution of stream bed substrates (sand, gravel, cobble). High flows prevent riparian vegetation from encroaching into the channel and tend to prevent the establishment of nonnative invasive plants and animals. Normal water-quality conditions are restored by high flows after prolonged low flow periods, flushing away waste products and pollutants and generally providing for the cycling of nutrients. Flushing flows maintain pore space that helps aerate eggs and remove metabolic waste in spawning gravels as well as sustain a resilient macroinvertebrate community in the hyporheic zone below the streambed. High flows scour silt along river margins that otherwise would become prime habitat for the invertebrate hosts of the whirling disease parasite. Very high flows enhance riparian wetlands for waterfowl and amphibians, often by raising near-stream groundwater levels. The distribution and abundance of large woody debris that creates habitat for many organisms is strongly influenced by high flows, which also provide important dispersal and reproductive triggers or cues to the aquatic community. It is reasonable to expect that reductions in the frequency and magnitude of flushing flows enable more robust attached filamentous and green algal communities to persist through the warm summer period. Such an enhanced algal community could lower dissolved oxygen in the river at certain times, potentially reducing trout survival under adverse conditions (Thurston *et al.*, 1981). Using data primarily from the USGS gage above Boxelder Creek and in-channel substrate measurements, Milhous (2009) has estimated flows necessary to maintain the Poudre's channel substrate at one site above the Boxelder gage (Figure 1) that I use to modify my initial high flow targets. Because a minimum number of days of peak channel maintenance flows must be provided in high water years to maintain channel integrity, dislodge established vegetation, and prevent long-term sediment aggradation, I use guidance from Richter *et al.* (2003) to further define a high flow recommendation.

Tharme's (2003) second largest category of environmental flow methods was habitat-based. These methods use more detailed hydraulic measurements in conjunction with "suitability criteria" that characterize the relative utility of river depth, water velocity, substrate/cover, and potentially other measurable or observable attributes to predict the overall quantity of habitat for aquatic species, or utility for recreation, as a function of discharge. The most commonly cited example of this category is the Instream Flow Incremental Methodology (IFIM), and specifically its Physical Habitat Simulation (PHABSIM) software component (Reiser *et al.*, 1989; Stalnaker *et al.*, 1995), although a number of methods have arisen from the IFIM foundation (Tharme, 2003). For the Poudre River, I rely on Nelson (1987) who performed a relatively intensive PHABSIM study for two locations along the Poudre River: one representing a more narrowly confined channel, and one representing wider channel morphology. One of Nelson's products was a set of graphs depicting the amount of habitat available at different flow levels for several lifestages of cold and warm water fish (rainbow and brown trout, white sucker, carp), hydraulic wetted surface area, and several recreational activities (tubing, rafting, canoeing). Because Nelson's results indicate substantial functional similarity between the responses of the two trout species and the two warm water species to streamflow, for simplicity I have chosen representative relationships of each set from his results to test my initial low flow recommendations.

The second hydraulic method I incorporate involves another flow-dependent variable, water temperature. Like the flow regime itself, water temperature has long been viewed as a governing ecosystem parameter with profound niche outcomes (Magnuson *et al.*, 1979) that begin at the molecular level but ultimately express themselves at the community level (McCullough *et al.*, 2009). Temperature is critical in controlling the distribution and abundance of cold, cool, and warm water fish by triggering movement and spawning behavior, mediating growth and survival rates, influencing competitive interactions, and strongly influencing other water-quality attributes (Armour, 1991). I previously studied the summer thermal regime in the Poudre River from the canyon mouth to Interstate-25 (Bartholow, 1991) and demonstrated that a combination of flow and nonflow management alternatives could maintain suitable water temperatures for a sustainable trout fishery from the canyon mouth downstream to Fort Collins (Bartholow, 1991). In this analysis, I rely on my conclusions from the 1991 modeling study to further test and refine my initial low flow recommendations. It is important to note that my objective here is not to provide cold water all the way to the South Platte River, but rather to maintain the thermal transition zone.

As will become apparent, the data and methods I have touched on so far deal with only four of the five fundamental attributes of a flow regime: magnitude, frequency, duration, and timing; none have explicitly considered the rate of flow changes. Erratic and high volume flow variations are considered quite detrimental to the aquatic system. They can disrupt spawning activities, reduce species richness and standing crop, interfere with seedling establishment, and cause fish and invertebrate stranding (Bunn and Arthington, 2002; Nilsson and Svedmark, 2002). Further, downramping (abrupt termination of high discharges) may contribute to bank slumping, leading to increased fine sediment accumulation in the channel, and large rapid rises in flow can certainly be a public safety hazard. Although I have found no published studies concerning rate-of-change information on the Poudre River, I have supplemented my flow recommendation with further hydrologic data analyses from which I develop additional environmental flow guidance.

METHODS

In the sections that follow, I first develop the components necessary to craft a comprehensive data-based flow recommendation using the various methods. I then combine them using the guidance from others as well as the assumptions and supplemental rationale offered.

Hydrologic-Based Flow Targets

To develop the initial hydrologic-based flow targets, I used two different sets of hydrologic data: the first to represent natural conditions, and the second to represent current conditions. Estimates of natural daily flows were available electronically from the Fort Collins water utility (Donnie Dustin, city of Fort Collins, 2006, personal communication) that were calculated starting with USGS gage data from the canyon mouth (No. 06752000), adding back all measured upstream diversions while subtracting all measured transbasin imports. In other words, natural flows in this article refer to predevelopment conditions. As supplied, these data covered a 20-year period, water years (October through September) 1976 to 1995. I noted some problems with these data, in particular small negative flow estimates for a few days in several years, that I adjusted by averaging the flow estimates on either side. The second dataset was the measured daily USGS gage record for the Lincoln Avenue gage (No. 06752260) in downtown Fort Collins covering the same water years. The assumption made in comparing these two datasets side by side is that natural losses or accretions between the canyon mouth and the Lincoln Avenue gage are minimal. Except for occasional large rainstorms that do not greatly affect monthly means, this assumption is met.

I used the National Hydrologic Assessment Tool (HAT) (Henriksen *et al.*, 2006) software (Version 3.0) to import, process, and display the two daily flow records. HAT was recently developed by the USGS as an upgrade of the Indicators of Hydrologic Alteration (IHA) software originally put together for The Nature Conservancy by Richter *et al.* (1996). Both IHA and HAT were designed to analyze flow regimes, identify hydrologic alterations due to human activities in a flow time series, and aid in setting environmental flow standards. For this analysis I utilized HAT's

TABLE 1. Monthly Flow Summary From the HAT Software.

Month	Estimated Natural Flow (m^3/s)			Lincoln St. Gage Flow (m^3/s)		
	25th Percentile	Median	75th Percentile	25th Percentile	Median	75th Percentile
January	1.36	1.81	2.52	0.11	0.34	0.85
February	1.61	1.84	2.12	0.11	0.23	0.91
March	1.81	2.72	3.40	0.08	0.14	1.19
April	3.71	5.61	9.46	0.11	0.28	3.96
May	19.12	30.76	37.61	2.55	4.87	9.54
June	31.86	55.90	72.81	7.79	21.01	31.35
July	12.12	19.06	30.50	2.44	3.12	8.04
August	4.70	6.46	11.19	0.88	1.27	1.67
September	2.66	3.74	4.98	0.37	0.57	0.96
October	2.46	2.95	3.82	0.14	0.23	0.91
November	2.01	2.61	3.17	0.14	0.23	0.93
December	1.59	2.10	2.66	0.11	0.17	0.74

Note: The 25th percentile flows for the estimated natural flow regime was the starting point for the hydrology-based flow recommendation.

summarization capabilities to calculate each year's mean monthly flow for the 20-year record and compute the median as well as the 25th and 75th percentile values for each month (Table 1).

I next constructed a monthly flow range that maintains the monthly median at the 25th percentile of the estimated natural flows, but scales the accompanying 25th and 75th percentile values around the new median proportionately with the natural flow pattern. As an example, May's 25th percentile natural flow, 19.12 m^3/s, is about 62% of its median 30.76 m^3/s, and the 75th percentile, 37.61 m^3/s, is about 122% of its median. These unrounded percentages multiplied by May's 25th percentile flow (19.12 m^3/s) result in the scaled values 11.89 and 23.36 m^3/s, which become the new 25th and 75th percentile flow targets. Applying this same method for all months resulted in the initial monthly environmental flow recommendations shown in Table 2.

TABLE 2. Initial Monthly Hydrologic-Based Flow Recommendation (m^3/s) Developed Such That the Median Flows Are the Same as the 25th Percentile of the Estimated Natural Flows Given in Table 1.

Month	25th Percentile	Median	75th Percentile
January	1.02	1.36	1.90
February	1.42	1.61	1.87
March	1.22	1.81	2.27
April	2.46	3.71	6.26
May	11.89	19.12	23.36
June	18.15	31.86	41.49
July	7.70	12.12	19.40
August	3.43	4.70	8.16
September	1.90	2.66	3.54
October	2.07	2.46	3.20
November	1.56	2.01	2.44
December	1.19	1.59	2.01

Hydraulic-Based Flow Targets

Milhous (2009) estimated that the flow necessary to adequately scour and flush sediment from the bed of the Poudre River between Fort Collins and Greeley is approximately 58.06 m^3/s. Unfortunately, he did not specify exactly how often (how many days or how many years) flushing should occur to maintain the substrate, but he reported that from 32 recent years of record (1975-2006) at the Boxelder gage (No. 06752280), measured flows of the magnitude he recommends occurred during 12 years, about a 1-in-3 frequency. He also noted that there was a seven-year sequence during the recent drought (2000-2006) when no flushing would have occurred. In the absence of more specific flushing frequency guidance from Milhous (2009), I rely on Richter *et al*. (2003) who recommend certain peak flow-specific metrics for channel flushing, discussed below.

Water temperature is the second hydraulic-based information set I incorporated. The central conclusion to my 1991 study was high water temperatures were often associated with low river flows, and that a summer supplemental flow of approximately 2.97 m^3/s would be required on an average of 30 days a year to maintain a suitable thermal regime through Fort Collins. These supplemental flows would keep water temperatures below about 23.3°C, a value chosen to represent the approximate daily maximum temperature which, if regularly exceeded, decidedly lowers the probability of a self-sustaining fishery (Bartholow, 1991). The average base flow at the Lincoln Avenue gage during July and August of the year I examined was about 1.22 m^3/s, meaning that flows would need to be about 4.19 m^3/s on the hottest summer days to maintain cool water temperatures.

Habitat-Based Flow Targets

A selection of Nelson's (1987) results is presented in Figure 2, where the *Y*-axis represents the amount of "habitat area" for lifestages of two fish as well as recreational tubing. I chose brown trout spawning and carp (*Cyprinus carpio*) fry as lifestages for cold and warm water exotic fish, respectively. Though carp fry emerge in the spring or summer and brown trout spawn in the fall but emerge during spring high flows, both have lifestage-specific habitat requirements. (Not shown in Figure 2, the habitat vs. flow relationship for rainbow trout spawning in the spring is essentially identical to the brown trout fall spawning curve.) I am unaware of any studies documenting which lifestages of these species may be habitat limited in the plains portion of the Poudre River, but it seems evident from Nelson's results that the lifestages I selected are especially responsive to flow magnitude and may indeed regulate population-level responses.

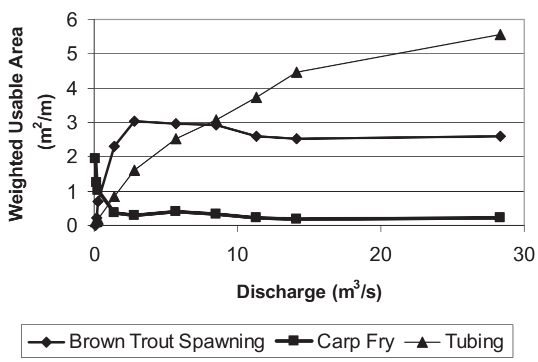

FIGURE 2. Selected Results From Nelson (1987) Showing That Carp Fry Habitat Is a Maximum Only at Low Flows Whereas Brown Trout Spawning and Tubing Are a Minimum at Low Flows and Increase as Flows Increase. Values shown here were approximated from published results representing the amount of "suitable habitat" for the species seasonal lifestage or activity.

Figure 2 shows how the habitat availability differs markedly for brown trout spawning and carp fry in response to both low and high flows. Slow and shallow flows below about 1.42 m^3/s are best for carp fry; any reduction in peak spring or summer flows will tend to benefit carp in the Poudre River. In contrast, deeper and faster flows above 2.83 m^3/s are best for brown trout in their fall spawning activity. Recreational tubing was chosen as a single surrogate for the recreational activities Nelson modeled, including rafting and canoeing, since they all exhibit an almost uniformly linear relationship, increasing from zero flow.

Rate of Change-Based Flow Method

Dealing primarily with mean (or median) monthly flows overlooks potentially critical inter-day flow phenomena common on the Poudre River. Figure 3 is one example of how markedly daily flows can vary depending upon starting and stopping irrigation diversions and Horsetooth Reservoir releases.

Using 30-min flow values from the USGS and Colorado Department of Water Resources instantaneous data archives supplied by the city of Fort Collins (Donnie Dustin, 2009, personal communication), I calculated the absolute and percent variation in daily

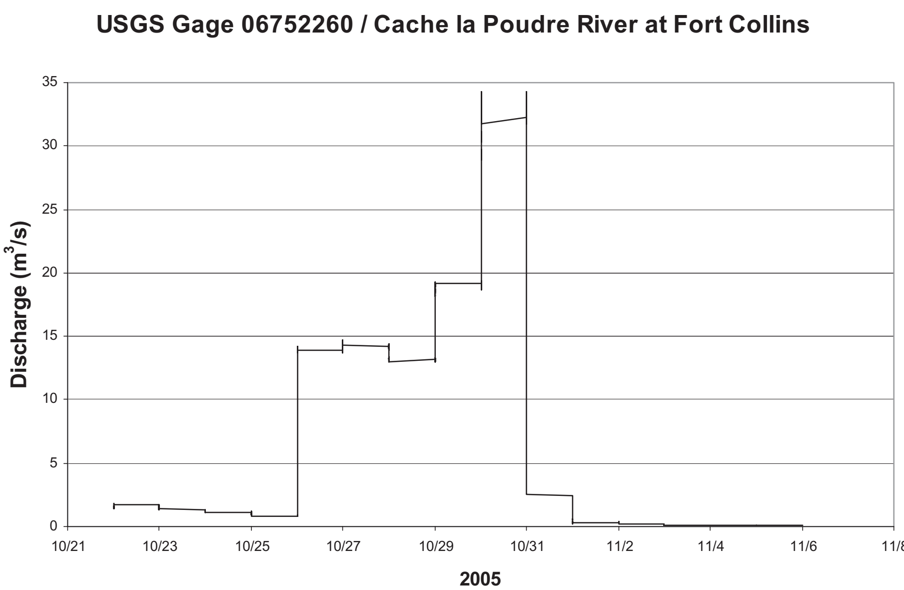

FIGURE 3. Example of Intra-Day and Day-to-Day Poudre River Flows Recorded in 2005 at the Lincoln Avenue Gage. Flows rose from <1 m^3/s to about 14 m^3/s on October 26, eventually rising to over 34 m^3/s on October 31, and then dropping to 0.1 m^3/s over the next few days. (http://ida.water.usgs.gov/ida/available_records.cfm?sn=06752260, *accessed* July 2009.)

[(maximum minus minimum)/maximum] flows at both the canyon mouth and Lincoln Avenue gages for March through October of water year 2007.

Variations were large and erratic through the year for both stations using both metrics, especially during peak runoff and after August. Mean daily variation was 24% at the canyon mouth and 49% at Lincoln Avenue, although the range and standard deviation were large at both stations. The 75th percentile of the relative variation in daily canyon mouth flows was 31% for the available dataset. Although I cannot distinguish natural and manmade flow fluctuations at the canyon gage using these data, I assume that the variation at the canyon mouth better reflects ecologically relevant conditions because there are many fewer upstream diversions.

Combining the Results

My goal at this point was to examine both the initial hydrologic-based flow recommendation shown in Table 2 as well as results from the other Poudre-specific empirical studies and my own data analysis to see how to combine the information into a coherent, justifiable environmental flow recommendation.

Looking first at substrate maintenance flows, Milhous (2009) estimated that the flow needed to scour fines from the Poudre River's bed was 58.06 m^3/s. This flow is slightly above the June estimated median natural flow of 55.90 m^3/s, but well below the 75th percentile natural flow for the same month. The natural flow dataset confirms that daily flows of 58.06 m^3/s or larger, occurred in 15 of the 20 years examined at the Lincoln Avenue gage, consistent with the common assumption that bankfull flows occurring every 1.5-2 years are effective in maintaining sediment balance and channel structure (Andrews, 1980). However, daily flows of 58.06 m^3/s or larger occurred when average monthly flows were >53.7 m^3/s. Thus, having median monthly June flows range only up to 41.49 m^3/s (Table 2) may not be sufficient to sustain the aquatic system and an allowance must be made to achieve flows at or above 58.06 m^3/s for channel flushing. But for how long should these substrate maintenance flows last?

Though they were writing about another basin, Richter *et al.* (2003) stated that one should exceed the minimum annual one-day maxima in all years, exceed the 25th percentile of the one-day maxima in three of four years, and exceed the median of the one-day maxima in half of the years. Though the HAT software has no equivalent metrics, making these calculations was straightforward. Specifically, the minimum annual one-day maxima to be exceeded in all years is 39.53 m^3/s, the 25th percentile of the one-day maxima to be exceeded in three of four years is 68.11 m^3/s, and the median of the one-day maxima to be exceeded in half of the years is 85.47 m^3/s. Further, among other metrics, Richter *et al.* (2003) suggest annual high flow durations exceed the 25th percentile in three of four years, but they offer no guidance on exactly how to define the daily duration of these flows. Flow duration recommendations for substrate maintenance have generally ranged from two to seven days, but have been as long as fourteen days (Tennant, 1976, as cited in Whiting, 2002).

I calculated the 25th percentile for the duration (number of days/year) for flows greater than several percentages of the peak daily natural flow in each of the 20 years I examined. The results showed that if the high flow period were defined as the number of days flows exceeded 90% of the peak one-day event, the flush should be 1.75 days long. If on the other hand, the definition included days with flows >75% of the peak, the flush should be almost six days long. Interestingly, there was no significant relation between each year's peak flow and the durations of high flows in that year, regardless of the percentage chosen, suggesting that a separate duration guideline need not be specified for wet, dry, and average years.

In an attempt to strike a middle ground between the Milhous (2009) flow recommendation and the Richter *et al.* (2003) more comprehensive guidance, and in the absence of more refined physical modeling, I estimate that requiring (a) an annual one-day maximum of 39.53 m^3/s in all years and (b) a two-day maximum of 58.06 m^3/s in three of four years would adequately achieve substrate maintenance objectives.

Nelson's (1987) hydraulic/habitat modeling results show that spring and fall flows below about 1.42 m^3/s will tend to benefit unwanted exotic fish (such as the common carp and other species) to the detriment of cool water trout. Because the 25th percentile monthly natural flows are all above this level except for a slight discrepancy in January, the median flow recommendations (Table 2) seem protective of desirable fish species. Nelson's recreational tubing results simply indicate that more water is better for recreation, at least up to some safety or bankfull level (Loomis, 2007), suggesting no changes to the initial flow recommendations.

Regarding the water temperature analysis, the median flow recommendations for July and August are 12.12 and 4.7 m^3/s, respectively, exceeding my estimate that 4.19 m^3/s must be available on the hottest days. Therefore, the summer mean monthly flow recommendations (at least for average and high flow years) seem appropriate as they stand. However, adding a requirement that summer *daily* flows must be ≥4.19 m^3/s on the hottest days to maintain cool water temperatures and sustain any trout in the reach, using coldwater releases from Horsetooth Reservoir to make up any river flow shortage, seems appropriate. Such a recommendation would apply in dry years in August, and potentially even on hot days in September.

Finally, keeping flow fluctuations below 30% in a single day seems warranted given the available data. However, it is clear that allowing a 30% flow decline could not be sustained for many days in a row. Further, such a rule says nothing about even shorter-term, intra-day flow fluctuations. For these reasons, using personal judgment based on my calculations and the need to prevent flows from declining extensively over many days, I suggest the following recommendation: No managed changes in streamflow >30% from day to day, none >15% in a six-hour period, and none >50% over any continuous seven-day period at any time of year.

Composite Flow Recommendation

My final recommended monthly flow ranges and supplemental guidance are shown in Table 3. The 25th percentile level would be representative of low flow years, the median (50th percentile) level would be representative of average flow years, and the 75th percentile level would be representative of high flow years. To put this flow recommendation in perspective, Figure 4 compares three monthly flow regimes for the Poudre River: natural (historical) flows, recent (current) flows, and the recommended flow regime.

DISCUSSION

The results of my analysis (Table 1 and Figure 4) quantify how today's flow regime has been diminished relative to the natural flow regime, particularly during the highest flow months of May through August. In each month, the upper bound (75th percentile) of the recently measured flows at the Lincoln Avenue gage is less than (or barely equal to) the 25th percentile natural flow. The current median flows for all months, especially May, June, and July, fall well outside the 25-75% natural flow range proposed by Richter *et al.* (1997). The natural flow paradigm (Poff *et al.*, 1997) suggests that the full range of seasonal and interannual hydrologic variation is necessary to completely maintain native biodiversity for aquatic, riparian, and near-stream wetland ecosystems. But water development supporting a different ecosystem, largely irrigated agriculture, has altered the Poudre River's flows, pruning away the original biological diversity, encouraging unwanted exotic species instead of species society prefers, and greatly reducing human recreation potential. Some portion of the ecosystem values that have been lost may be regained by restoring flows to the levels recommended herein, whereas further reduction in flows will likely lead to further loss of biodiversity and other ecosystem goods and services.

Yet we do not know, and may never know, exactly how to craft a flow regime that achieves a publicly championed and ecologically sustainable aquatic system for the Poudre River through Fort Collins. Integrating several approaches in the face of incomplete information has been termed a combination-type (or hybrid) methodology by Tharme (2003). Incorporating judgment, regardless of the methods applied, remains a necessary ingredient in adapting general results to site specific conditions (Petts, 2009). I have tried to do just that. I have assembled a set of monthly flow ranges supplemented with daily flow guidance intended to support a modified, but more functionally complete, aquatic and riparian ecosystem. I used available data, multidisciplinary analyses (hydrologic-, hydraulic-, and habitat-based), and personal judgment to incorporate seasonal and interannual

TABLE 3. Final Monthly Flow Range Recommendations (m^3/s) and Supplemental Guidance.

Month	25th Percentile	Median	75th Percentile	Additional Daily Guidance*
January	1.02	1.36	1.90	No managed changes in streamflow >30% from day to day, none >15% in a six-hour period, and none >50% over any continuous seven-day period at any time of year
February	1.42	1.61	1.87	
March	1.22	1.81	2.27	
April	2.46	3.71	6.26	
May	11.89	19.12	23.36	Annual one-day maximum ≥ 39.53 m^3/s in all years; three out of four year two-day maximum ≥ 58.06 m^3/s
June	18.15	31.86	41.49	
July	7.70	12.12	19.40	
August	3.43	4.70	8.16	Flow ≥ 4.19 m^3/s required if water temperature > 23.3°C
September	1.90	2.66	3.54	
October	2.07	2.46	3.20	
November	1.56	2.01	2.44	
December	1.19	1.59	2.01	

*The first Guidance note applies to all months, the second to May and June, and the third to August.

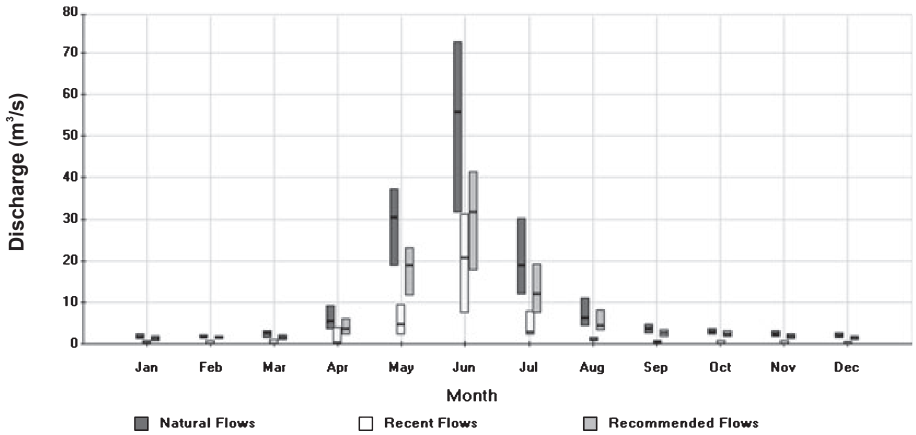

FIGURE 4. Comparison of Estimated Natural Flows, Recently Measured Flows at the Lincoln Avenue USGS Gage, and the Recommended Flow Regime Developed in This Article, Left to Right, Respectively, for Each Month. The bottom and top of each vertical bar delimit the 25th and 75th percentile range of monthly flows; the black horizontal bars indicate the monthly median. This graph illustrates that the recommended flows fall between the natural flows and the current flows in each month of the year and that the median of the recommended flows matches the 25th percentile of the natural monthly flows. These attributes are most easliy seen in the high-flow months; please refer to Table 3 for the precise numeric values for all months.

flow variability, supplement those initial flow recommendations by explicitly addressing the river's substrate maintenance (high flow) requirements, better define minimum daily flows to buffer cool water fish from domination by exotics, and reduce harmful intra-day and day-to-day flow fluctuations.

In crafting this flow recommendation, I explicitly chose options requiring less flow than other options I could have chosen. In particular, setting the median monthly recommended flow equal to the 25th percentile of the natural flows was a deliberate compromise for this "working river." I did this primarily because I acknowledge the difficulty in nudging the existing legal and institutional water management system from the status quo. Even though my stated objective is to achieve flows sufficient to maintain key environmental processes and services indefinitely, and be resilient in the face of recurring flow-related stresses, I recognize that existing uses also meet many societal needs and expectations. Relaxing the Richter *et al.* (1997) 25th to 75th percentile guidance allows low flow excursions in exceptionally water-short years in this highly modified river (a share-the-pain philosophy) yet still requires half of the monthly flows to be in a range recommended purely for ecological considerations. Opting to scale the monthly flows at the low end of the recommended range also recognizes that the channel has been highly altered after over a century of abstractions and urbanization, though the exact magnitude of shrinkage is unquantified (Ayres Associates, 2008). Although scaling the flow recommendation closer to natural flow magnitudes would likely increase the probability of a more natural, more fully functional ecosystem (Gippel, 2001), I must also acknowledge the reality that Colorado's instream flow legislation, as currently written, serves only "to preserve or improve the natural environment to a reasonable degree" [Colo. Rev. Stat. Section 37-92-102(3)], wording that seems to implicitly concede only modest, incremental change.

Aiming for pragmatism does not mean that the flow recommendation presented here could not be improved. There are several possibilities: (1) I used 20 years of daily flow data; although 15 years of data may be sufficient (Kennard *et al.*, 2009), a longer record might reduce any bias in the statistics calculated, potentially making flow recommendations more accurate – at least based on the climatic period the data represented. Looking back at the flow record that has been reconstructed from tree rings for the Poudre River by Woodhouse *et al.* (2004), the mean flow of the 20-year block beginning in 1976 represents about the 83rd percentile of all other nonoverlapping 20-year blocks back to the year 1626. However, the blocked data exhibit little variance overall – the 50th percentile flow for the same dataset is only about 10% lower than the mean 1976-1995 flow. In short, the time period I examined is only slightly wetter than the long-term average. (2) The fish habitat modeling techniques used by Nelson (1987) have evolved considerably since that time. Though it is unlikely that his results would change substantially, additional study would be required to incorporate newly developed species' habitat preferences, identify potentially limiting lifestages, and confirm or adjust his results. Examining habitat availability of native warm water species and invertebrates as a function of flow would serve to round out the habitat-based information. Specifically, there are several native fish for which habitat preferences and habitat distribution as a function of flow are just now being elucidated; this information should be incorporated into IFIM models. (3) Flow rate-of-change guidelines typically are derived for specific rivers based on their unique channel morphology. A ramping rate study could refine the daily or intra-day rate-of-change recommendations I have provided here, which are somewhat more liberal than have been recommended on other rivers (Whiting, 2002). (4) The study by Milhous (2009) provided a relatively wide margin of uncertainty surrounding his substrate maintenance flow estimate. More comprehensive studies covering more sites would be required to reduce that uncertainty. In addition, the flow regime recommended here for fine sediment flushing and riverbed surface maintenance may be insufficient in magnitude and duration to avoid an ongoing trend of willow encroachment and loss of channel capacity (Brian Bledsoe, Colorado State University, 2008, personal communication). Through field monitoring and preliminary modeling, Bledsoe has estimated that peak flows exceeding 84.96 m^3/s, lasting three to four days, and occurring on average every three or four years, may be necessary to maintain channel capacity and rejuvenate aquatic and riparian habitats, potentially including jurisdictional wetlands. Total sediment transport over time could be modeled to better assess the frequency and duration of high flows needed to maintain the channel. Broadly speaking, therefore, the flow recommendations I offer here must be viewed solely as preliminary until the critical relationships are better quantified with existing models, particularly for channel maintenance and riparian vegetation. Then, of course, active monitoring would be necessary to ensure that environmental objectives are being achieved and to aid in identifying any necessary adjustments.

One element of this flow recommendation potentially divides advocates for river restoration. Exceptionally high flows at certain times of the year have been associated with temporarily reducing trout standing crop, presumably due to flushing out juvenile life stages (Nehring and Anderson, 1993). However, Nehring has also shown that it is not necessary to have high brown or rainbow trout recruitment every year to maintain a thriving trout fishery, especially one managed as a catch-and-release (or low bag limit) fishery. In fact, lower recruitment by flushing "surplus" juveniles may beneficially avoid density-dependent trout growth stunting. Although I do not know whether trout recruitment may be limiting in the Fort Collins reach due to poor gravel quality or other factors, loss of eggs by dewatering is likely a greater threat than flushing fry (Kurt Fausch, Colorado State University, 2008, personal communication). For this reason, the recommendation for high annual substrate maintenance flows during the snowmelt runoff period seems sound (and would benefit recreational flows). After all, it is reasonable to assume that the aquatic community was once well adapted to the Poudre River's annual snowmelt pulse.

Just as complete restoration of the "working" Poudre River is unlikely in this human-dominated watershed, it is also important to note that partially restoring the flow regime alone is not likely to be sufficient to protect and enhance the river's ecological integrity (Booth *et al.*, 2004). Other water-quality factors, especially nutrients, must be considered (Baron *et al.*, 2003). Obsolete diversion structures should be removed, and active diversion structures must be re-engineered when replaced to improve recreational safety (Wright *et al.*, 2004; Donahue and Earles, no date) and permit at least minimal upstream migration for highly mobile aquatic species. Some provision for retaining large, woody debris, currently removed from the river for bridge safety reasons, must be made. Nevertheless, having reasonable instream flow targets is critical in furthering the goal of partially restoring the ecological integrity of the Poudre River. Crafting a recommended flow regime from interdisciplinary building blocks is an appropriate first step and may set the stage for incremental restoration.

If an environmental flow regime for the lower Poudre River were adopted, who would it be adopted by and how might it be implemented? Well over 100 years of water and storage rights almost fully constrain today's operations. I readily acknowledge that full implementation of the proposed flow regime would be a challenging and expensive long-term task. Nonetheless, some steps may be easier to accomplish than others. As noted, large daily and inter-day flow fluctuations often arise from abruptly adjusting diversions and reservoir releases. A sophisticated flow measurement system could be used to "learn" how to minimize and smooth operationally induced fluctuations through careful timing and infrastructure control without injury to existing water rights holders. Such a system would necessitate considerable collaboration among irrigation companies and reservoir operators, and, if done well, could set the stage for a more comprehensive institutional structure, outline any needed state legislation, and offer a platform to solicit funds to purchase, lease, or otherwise secure water donations sufficient to meet low flow objectives in most years. The institutional framework could evolve from a system of fragmented responsibilities and authorities into a more consolidated organization to negotiate and affect the efficient management of senior water rights, perhaps through water-sharing agreements with downstream water users depending on the water year type (low, average, high), and resolve the inevitable tensions that will arise due to competing objectives. The water year type could be determined from the closely monitored basin snowpack and reservoir carryover volumes in the early spring, a task already done by federal agencies, irrigation companies, and water conservancy districts. In other words, I foresee an incremental approach based on measurable successes, the ability to adapt to fresh information about the river and society's goals, and the public's acknowledged willingness-to-pay to achieve environmental objectives (Loomis, 2008).

Postel and Richter (2003) and Richter (2009) have characterized our water allocation dilemma well: as riverine science has advanced, society has become more aware of the ecological costs of water extraction. We now struggle to retrofit our social goals to include preservation of ecosystem health. The way to do that, these authors propose, is to reframe the competitive allocation paradigm into a framework of maximizing social benefits by putting ecosystem goods and services on the same footing as other human demands; promote efficient, integrated river and land management; and pursue incremental restoration with an eye on long-term sustainability. This major challenge is being tackled worldwide in ways that that will shape flows in rivers forever. This case study is but a tiny step in a far larger effort to begin a dialog for the Poudre River.

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