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GETTING TO SCALE WITH ENVIRONMENTAL FLOW ASSESSMENT: THE WATERSHED FLOW EVALUATION TOOL

J. S. SANDERSON,[a]* N. ROWAN,[b] T. WILDING,[c] B. P. BLEDSOE,[e] W. J. MILLER[f] and N. L. POFF[d]

[a] *The Nature Conservancy of Colorado, Fort Collins, Colorado, USA*
[b] *Camp Dresser McKee Inc., Denver, Colorado, USA*
[c] *Department of Biology, Colorado State University, Fort Collins, Colorado, USA*
[d] *Department of Biology & Graduate Degree Program in Ecology, Colorado State University, Fort Collins, Colorado, USA*
[e] *Department of Civil and Environmental Engineering & Graduate Degree Program in Ecology, Colorado State University, Fort Collins, Colorado, USA*
[f] *Miller Ecological Consultants, Inc., Fort Collins, Colorado, USA*

ABSTRACT

Growing water demand across the world is increasing the stress on river ecosystems, causing concern for both biodiversity and people. River-specific environmental flow assessments cannot keep pace with the rate and geographic extent of water development. Society needs methods to assess ecological impacts of flow management at broad scales so that appropriate regional management can be implemented. To meet this need in Colorado, USA, we developed a Watershed Flow Evaluation Tool (WFET) to estimate flow-related ecological risk at a regional scale. The WFET entails four steps: (i) modelling natural and developed daily streamflows; (ii) analysing the resulting flow time series; (iii) describing relationships between river attributes and flow metrics (flow–ecology relationships); and (iv) mapping of flow-related risk for trout, native warm-water species and riparian plant communities. We developed this tool in two watersheds with differing geomorphic settings and data availability. In one of the two watersheds, the WFET was successfully implemented to assess ecological risk across the 3400-km^2 watershed, providing consistent watershed-wide information on flow-related risk. In the other watershed, active channel change and limited data precluded a successful application. In Colorado, the WFET will be used to evaluate the risk of impacts on river ecosystems under future climate change and water development scenarios (e.g. for energy development or municipal water supply). As water continues to be developed for people, the WFET and similar methods will provide a cost-effective means to evaluate and balance ecosystem needs at large scales. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: ecological limits of hydrologic alteration (ELOHA); natural flow regime; instream flow assessment; regional methods

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INTRODUCTION

With a rapidly expanding global population, demand for water is outstripping available water in many regions of the world (Arthington *et al.*, 2006). Water managers all over the world are challenged to provide reliable and affordable water supplies to meet this demand (Poff *et al.*, 2010). At the same time, there is a growing expectation that water development should not degrade the freshwater ecosystems that support our quality of life and our values (Acreman, 2001; Postel and Richter, 2003). Efforts to sustain rivers while supplying water for human needs are expanding with the realization that our societies are dependent on services that river ecosystems provide (Gleick, 2003; Millennium Ecosystem Assessment, 2003).

It is widely recognized that sustaining rivers requires managing for environmental flows (Postel and Richter, 2003; Annear *et al.*, 2004; Poff, 2009; Carlisle *et al.*, 2010; Poff *et al.*, 2010). Environmental flows are defined as the 'quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihood and well-being that depend on these ecosystems (http://www.riverfoundation.org.au/images/stories.pdfs/bnedeclaration.pdf). Methods for assessing environmental flows are essential for optimizing the simultaneous goals of water supply and ecosystem maintenance. Many data-intensive methods for environmental flow assessment are available (Bovee *et al.*, 1998; Tharme, 2003; Annear *et al.*, 2004; Arthington *et al.*, 2004) and have been implemented on thousands of kilometres of rivers worldwide (Postel and Richter, 2003), yet these rivers represent a tiny fraction of the rivers where assessment is needed. Unfortunately, the rate of water development in the world's rivers greatly exceeds the ability of scientists to assess effects on a river-by-river basis (Poff *et al.*, 2010). To meet the need for environmental flow assessment on par with the rapidity and large scale of water development, Poff *et al.* (2010) developed a new framework for assessing environmental flow needs at the regional scale. This framework is referred

*Correspondence to: J. S. Sanderson,, The Nature Conservancy of Colorado, Fort Collins, Colorado, USA.
E-mail: jsanderson@tnc.org

to as the 'ecological limits of hydrologic alteration' (ELOHA). To date, few efforts have comprehensively applied the ELOHA framework, although several have developed one or more components (Henriksen *et al.*, 2006; Kennen *et al.*, 2007; Apse *et al.*, 2008; CSIRO, 2008; Kennen *et al.*, 2009; Kennard *et al.*, 2010).

The arid southwestern USA exemplifies the tension between water supply and environmental needs. The Colorado River is the lifeblood of the region's society and economy (Committee on the Scientific Bases of Colorado River Basin Water Management, 2007). This river has the most complete allocation of its water resources of any river in the world and is also one of the most heavily regulated (U.S. Bureau of Reclamation, 2000). During just the last decade, the river's 1906–2003 mean annual discharge of $18.6 \times 10^9\,m^3$ (Christensen and Lettenmaier, 2007) has been exceeded by the demand for water to irrigate 1.4 million ha of farmland, sustain 30 million people and support other aspects of the basin's economy. The population, dependent on the river, is expected to increase 40% by 2035. At the same time, the river's ecosystems and the many species they support are already at risk. For example, of the 37 fish species present prior to water development (Carlson and Muth, 1989)—of which >70% are endemic—four are extinct and over two-thirds are at risk of extinction. Climate change is expected to exacerbate tensions over water. There is a broad consensus among climate models that this region will dry significantly in the 21st century (Seager *et al.*, 2007).

In 2005, the state of Colorado launched a statewide planning effort to assess needs for water supply in addition to 'non-consumptive' needs (fishing, boating and species conservation). A strong motive for the planning process was a projected population increase of 5 to 10 million residents by 2050 (Harvey Economics, 2008). For the water-supply assessment, well-established methods existed for quantifying water needs (CWCB, 2004). Methods also existed for quantifying non-consumptive needs (CWCB, 2007). However, non-consumptive methods were as follows: (i) designed for assessing individual river segments; (ii) primarily oriented toward fish (i.e. they did not address other ecosystem needs such as maintaining riparian areas); and (iii) expensive to implement (currently \$50 000–\$75 000 for results applicable to tens of kilometres), making it cost-prohibitive to apply them across all streams and rivers in a watershed.

To fill the need for a broadly applicable environmental flow assessment in Colorado, we applied the ELOHA framework to develop the Watershed Flow Evaluation Tool (WFET). At a cost of approximately \$200 000, a pilot project of the WFET was conducted in two watersheds in Colorado: (i) the Roaring Fork Watershed; and (ii) the Fountain Creek Watershed, which collectively include several hundred kilometres of streams and rivers. These two watersheds were selected because they offer contrasting scenarios of water management and data availability, and taken together they serve as useful test cases for application of the ELOHA framework. In the Roaring Fork Watershed, streamflows have been modelled throughout the watershed and there exists a moderate body of relevant literature about the relationship between river ecology and flow. The Roaring Fork Watershed pilot project demonstrated high utility and is being extended to a much larger geography. In the Fountain Creek Watershed, streamflow data were sparse, water management has caused rapid and on-going changes in channel morphology, and, because flows have been augmented rather than depleted, there is little relevant data to inform flow–ecology relationships. The Fountain Creek Watershed pilot project illustrated some challenges that will be faced during application of the ELOHA framework.

In this paper, we: (i) describe the technical methods used to develop the WFET; (ii) present results of the flow assessment from the Roaring Fork Watershed and the Fountain Creek Watershed; and (iii) discuss strengths and limitations of the tool and its possible applications. Also, because flow assessment to inform water management is necessarily done in a sociopolitical context, we discuss the sociopolitical dimensions that led to the success of this study.

STUDY AREA

Roaring Fork Watershed

The Roaring Fork River flows into the main stem of the Colorado River approximately 200 km below the headwaters of the Colorado River, at the town of Glenwood Springs, Colorado (Figure 1). The Roaring Fork Watershed is $3700\,km^2$. Flow originates primarily as snowmelt in headwaters above 4000 m and joins the Colorado River at 1740 m. Mean annual precipitation exceeds 1140 mm at high elevations (most arriving as snow) and is 400 mm in Glenwood Springs. Mean annual air temperatures are −1.3 °C and 6.6 °C at high and low elevations, respectively. The estimated mean annual flow at Glenwood Springs under natural conditions is $29\,m^3\,s^{-1}$.

The majority of the Roaring Fork Watershed is alpine tundra and subalpine and montane forests owned by the US Forest Service, although valley bottoms are heavily utilized for irrigated hay production and cattle pasture. Mean annual diversions of approximately $1.3 \times 10^8\,m^3$ are exported from the Roaring Fork River to the Arkansas River.

Fountain Creek Watershed

Fountain Creek is a tributary of the Arkansas River, with the confluence approximately 250 km below the headwaters of the Arkansas at the town of Pueblo, Colorado. The Fountain

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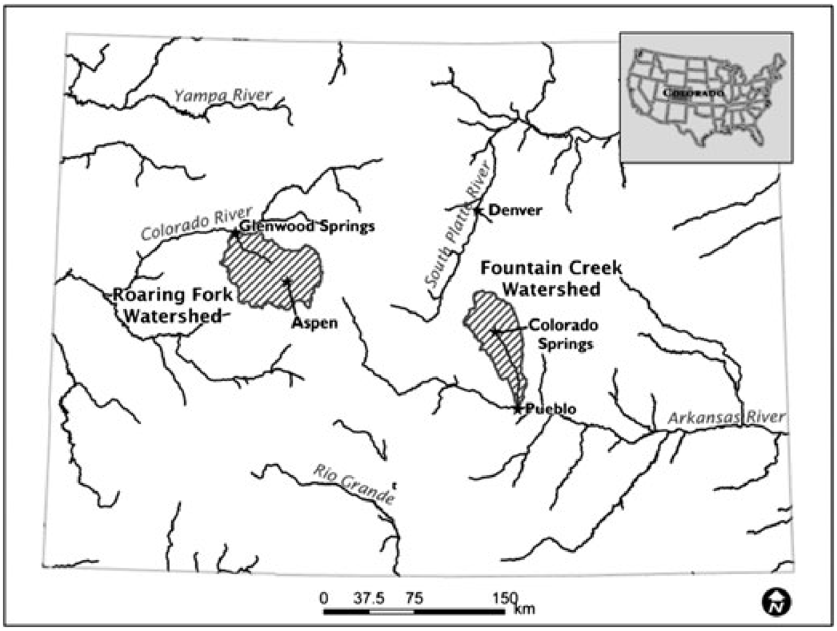

Figure 1. Locations of the Roaring Fork and Fountain Creek watersheds

Creek Watershed is 2400 km^2. Flow originates primarily as snowmelt in headwaters above 2400 m and confluences with the Arkansas River at 1400 m elevation. Mean annual precipitation ranges from greater than 540 mm at high elevations (most arriving as snow) to 300 mm in Pueblo. Mean annual air temperatures are 2.2 °C at high elevations to 11.1 °C at low elevations. The estimated mean annual flow under natural conditions is 1.7 $m^3 s^{-1}$.

Land cover is forest in the upper watershed, owned primarily by the US Forest Service, and shrublands and grasslands at lower elevations where most land is privately owned. Three major transbasin diversions move on average 1.9×10^8 m^3 $year^{-1}$ of water from the Colorado River to the Arkansas River, much of it via Fountain Creek.

THE ECOLOGICAL LIMITS OF HYDROLOGIC ALTERATION FRAMEWORK AND ITS APPLICATION IN COLORADO

The ELOHA framework applies knowledge gained from river-specific studies to regions as large as states, provinces, nations or large river basins, without requiring detailed, site-specific hydrologic or biological information for every river (Poff *et al.*, 2010). ELOHA synthesizes available hydrologic and biological data from rivers within a region to produce coarse-scale estimates of environmental flow needs useful in regional water planning. The ELOHA framework comprises both a scientific and social process. Hydrologic modelling and analysis provide an essential foundation for environmental flow analysis. In parallel with the hydrologic analysis, the response of ecosystem components to changes in specific streamflow statistics is described quantitatively in flow alteration–ecological response relationships (flow–ecology relationships). Applications of flow–ecology relationships are limited to particular hydrogeomorphic settings and to the geographic range of the ecosystem components they address. Any specific applications of the flow–ecology relationships, such as establishing targets for river management, are then balanced through a process that accounts for societal values and goals. We developed the WFET in a process that closely mirrored the ELOHA framework.

Hydrologic modelling and analysis

In the Roaring Fork Watershed, we used the State of Colorado's Stream Simulation Model (StateMod; CDWR and CWCB, 2009), a water allocation and accounting model, to estimate daily flow values for natural and developed conditions. Flows were modelled at 47 locations (nodes) in the watershed for a 31-year period (1975–2005). The 31-year period of record is sufficiently long to represent inter-annual variability in flow conditions (Kennard *et al.*, 2009).

StateMod has not been developed in the Fountain Creek Watershed, so flow analyses were restricted to US Geological Survey stream gauge locations. Only five locations had data for a sufficient period of record and data quality to be used in the analysis. One of these five gauges lacked a sufficient period of record, so the record was extended by synthesizing daily flow values using two upstream gauges. A double mass curve analysis (Stogner, 2000) was used to identify the timing of

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major changes in flow and the division of the flow record into natural and developed periods. The timing of these changes corresponded to the start of major water-supply projects.

We calculated changes in ecologically relevant flow metrics (Olden and Poff, 2003) between natural and developed conditions using the Indicators of Hydrologic Alteration (The Nature Conservancy, Arlington, VA, USA) software (Richter *et al.*, 1996). Because StateMod was developed for water supply analyses, not ecological assessments, we analysed model assumptions and output to determine which INDICATORS OF HYDROLOGIC ALTERATION metrics were compatible. For both watersheds, five metrics were chosen as compatible with one or more stream attributes and sufficiently accurate to be useful in the flow analysis: mean annual flow, mean August flow, mean September flow, mean January flow and mean annual peak daily flow.

Development of flow alteration–ecological response relationships

We quantitatively described flow–ecology relationships (Poff and Zimmerman, 2009) for six attributes across three geographic regions based on 108 studies (Table I; Camp Dresser & McKee, Inc. *et al.*, 2009). Flow–ecology relationships are expressed as either an expected departure of an ecosystem attribute from a reference condition as hydrologic conditions depart from natural or an expected status of an ecosystem attribute as a function of the magnitude of a hydrologic metric. Examples are as follows: (i) riparian plant communities were represented as percent change from reference condition as the magnitude of peak flow under developed conditions decreased relative to natural; and (ii) the expected suitability of a stream for trout or native fish was expressed as a function of late-summer flows standardized by mean annual flow. Continuous relationships were described for riparian plant communities and native fish west of the continental divide (Figure 2). For the continuous relationships, quantile regression was used to estimate the maximum rate of the response variable as a function of flow conditions, thus focusing the flow–ecology relationship on hydrologic conditions as a limiting factor in ecological response (Cade and Noon, 2003). Categorical relationships were described for trout and Great Plains native fish (Table II), based on, respectively, Binns and Eiserman (1979) and Tennant (1976), and were modified during a workshop conducted with several of Colorado's fish experts.

Table I. Number of studies used to develop flow alteration–ecological response relationships. 'Other' indicates ecosystem attributes not listed and/or studies from beyond Colorado

	Interior West	Rocky Mountains	Great Plains	Total
Fish	**19**	**18**	**15**	52
Riparian vegetation	**20**	1	**8**	29
Invertebrates	9	**9**		18
Vertebrates (birds, beaver)	4			4
Terrestrial invertebrates	2		1	3
Algae	2			2
Total	56	28	24	108
Other				44

Geographic regions based on CEC (1997), which generally correspond with Bailey *et al.*'s (1994) ecoregions (Central Shortgrass Prairie, Southern Rocky Mountains and parts of three ecoregions that fall into the 'Interior West'). Numbers in bold font indicated attributes and regions used in the WFET pilot projects.

Flow–ecology relationships varied across regions and were applied only where a species or ecosystem would be expected to occur. There exists a pronounced geoclimatic contrast moving west to east in Colorado from the Interior West, across the Rocky Mountains, to the Great Plains, so we used an existing classification of these ecological regions as an informal framework for the development and application of flow–ecology relationships (Level I ecoregions; CEC, 1997). Flow–ecology relationships applicable to the largest portions of both the Roaring Fork Watershed and the Fountain Creek Watershed were those developed for Rocky Mountains. Additionally, risk for a given attribute was mapped only where that attribute was expected to occur (e.g. risk for cottonwood-dominated riparian areas was mapped only below 2900 m, above which cottonwoods generally are not found) (Carsey *et al.*, 2003).

Mapping of attribute risk levels

Using the five flow metrics, we calculated the hydrologic metric required to determine risk for riparian plant communities, trout and native fish. Because invertebrate flow–ecology relationships were derived from data collected for headwater streams (mean annual flow rate ≈ 0.1–$1.0\,m^3\,s^{-1}$), their general applicability was considered limited and they were not included. We identified three to five risk classes for each attribute. For continuous relationships, cut-offs between risk levels were determined largely by expert opinion, informed by visual interpretation of data distribution. For categorical relationships, boundaries between risk levels were implicit in the categories.

Because the limited number of flow–ecology relationships may not capture all aspects of river health, four flow metrics were calculated and mapped directly (mean annual flow, mean January flow, mean August flow and one-day peak flow). No risk categories were defined for these metrics, but

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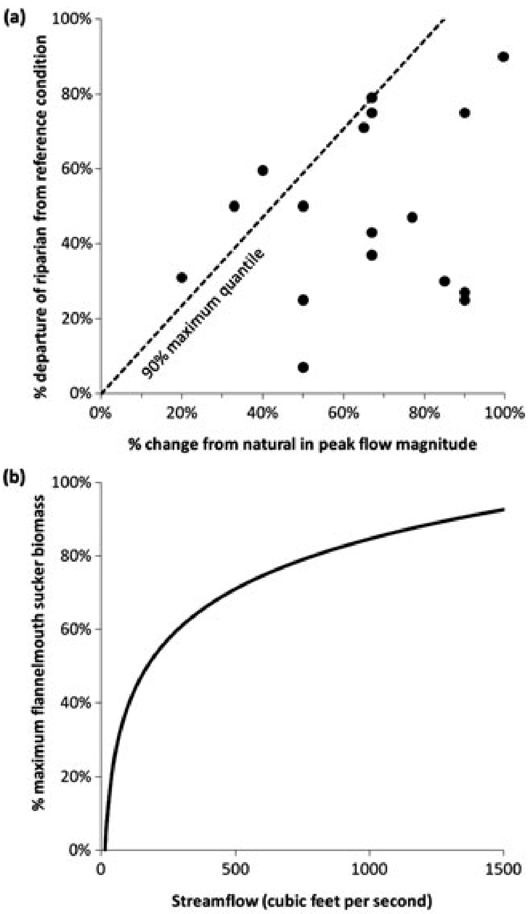

Figure 2. Continuous flow–ecology relationships for (a) riparian plant communities and (b) flannelmouth sucker

degree of alteration was mapped as minimal, moderate or high based on expert-derived hypothetically expected ecological response to a given level of flow alteration.

With the nodes categorized, we then inferred the risk class for stream segments in between nodes to generate a network map (Figure 3). Generally, a segment was assigned the risk class of the downstream node, although exceptions were made where knowledge of an upstream reservoir or major diversion was an obvious demarcation.

Flow–ecology relationships for Fountain Creek have a substantial degree of uncertainty because of the following: (i) data supporting these relationships are derived from instances of stream depletion, not augmentation; and (ii) channel conditions and geomorphic processes in Fountain Creek have changed because of flow augmentation and instability of the sandy channel. Because of these uncertainties, we also examined sediment transport capacity and long-term erosion potential downstream of Colorado Springs since 1980 using magnitude–frequency analysis (Wolman and Miller, 1960) to estimate the time-integrated sediment load transported through the channel. At-a-station hydraulic geometry characteristics, grain-size distributions and flow resistance for segments proximate to the nodes were compiled from previous studies (URS Group Inc., 2007). The GEOTOOLS (Engineering Research Center, Colorado State University, Fort Collins, CO, USA) software package (Bledsoe *et al.*, 2007) was used to perform the magnitude–frequency analysis with the Brownlie (1981) and Wilcock and Kenworthy (2002) sediment transport relationships using both 25 and 30 logarithmic bins. Erosion potential risk was calculated as the ratio of natural to developed erosion potential, where a ratio of <2 was considered low risk, 2–4 moderate risk and >4 high risk.

Comparison to site-specific modelling

Existing data from site-specific modelling of hydraulic habitat at a location on the Roaring Fork River was used to assess how well the WFET results for trout conform to results from the Physical Habitat Simulation System

Table II. Categorical flow alteration–ecological response relationships for (a) trout and (b) native warm-water fish occurring east of the continental divide

Rating	Summer low flow (% of mean annual flow)	Description
(a)		
0 (worst)	<10	Inadequate to support trout.
1	10–15	Potential for trout support is sporadic.
2	16–25	May severely limit trout stock every few years.
3	26–55	Low flow may occasionally limit trout numbers.
4 (best)	>55	Low flow may very seldom limit trout.
(b)		
0 (worst)	<10	Severe habitat degradation.
1	10–30	Poor or minimum habitat.
2	30–40	Fair or degrading habitat.
3	40–50	Good habitat.
4	50–60	Excellent habitat.
5 (best)	>60	Optimal/outstanding habitat.

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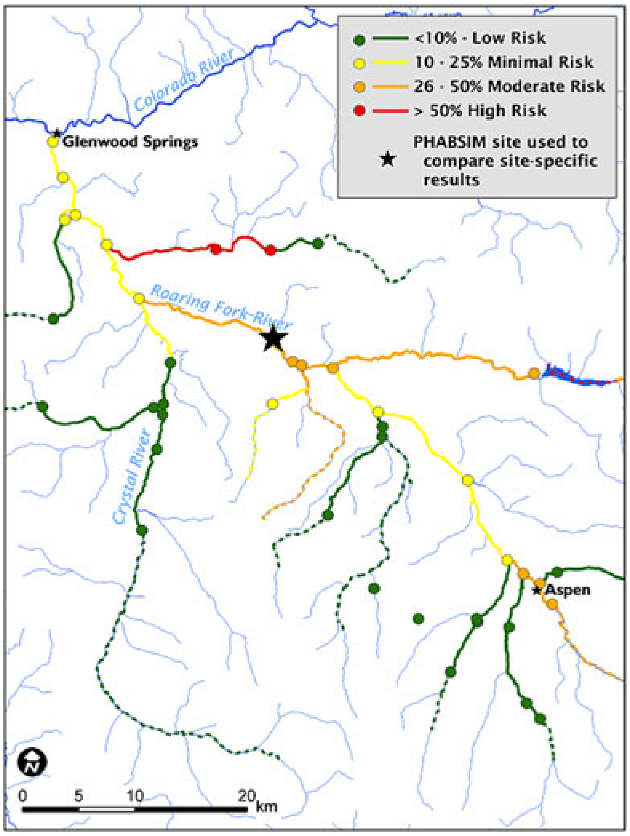

Figure 3. Watershed Flow Evaluation Tool results illustrating the geographically extensive assessments of flow-related risk to riparian plant communities under developed conditions. Low-risk (green) river segments occur in drainages with few diversions. The high-risk (red) river segment occurs below Spring Park Reservoir that substantially reduces the peak flows needed to sustain riparian plant communities. Moderate-risk (orange) river segments result from out-of-basin diversions higher in the watershed and management of a large reservoir

(PHABSIM, US Geological Survey, Fort Collins Science Center, Fort Collins, CO, USA; Waddle, 2001). Changes in habitat availability for rainbow and brown trout were modelled for natural and developed flows. Degree of change in habitat availability was then compared to WFET results. Conversely, the WFET predictions for moderate-risk and high-risk levels were evaluated using the PHABSIM results to determine the corresponding change in trout habitat.

The social process

A social process informed every aspect of the WFET development. The need for a non-consumptive assessment was laid out in legislation (Colorado General Assembly, 2005). This legislation established 'basin roundtables', which have authority to direct both the consumptive and non-consumptive assessments. During WFET development, regular information transfer occurred between the technical team developing the tool and roundtable members. Technical team members educated roundtable members on the bases of the WFET, underlying assumptions, hydrologic modelling, flow–ecology relationships and potential applications of the tool. At the same time, roundtable members educated the technical team on their needs for flow assessment and basin-specific information about hydrology and ecology. Roundtable members also continuously challenged the technical team to defend the validity of the WFET and to make the technical aspects of the tool comprehensible to roundtable members without technical training.

RESULTS

Roaring Fork Watershed

Flow alteration in the Roaring Fork Watershed includes one major dam (Ruedi Reservoir) and a network of transbasin diversions on headwater streams (e.g. Frying Pan-Arkansas Project). As a result, the mean annual flow at the lowest point in the basin (at the confluence of the Roaring Fork River with the Colorado River at Glenwood Springs, CO) has decreased 18% relative to natural conditions. Flow alteration is not uniformly distributed, either spatially or temporally. Change in mean annual flow ranged from <10% decrease in the Crystal River and several headwater streams to >50% decrease immediately below a reservoir and several transbasin diversions. At the locations of major transbasin diversions, mean annual flow has decreased >26%, with mean annual flows at one node having decreased >50%. Late-summer low flows decreased at all but one location where reservoir releases maintain higher-than-natural flows. At three nodes, low flows decreased >50% from natural. January flows generally increased, with two nodes (below a major reservoir and at Glenwood Springs) having increased >40%; three nodes experienced decreased January flows with none decreasing >20%. The one-day peak flow decreased >10% at 24 of the 47 nodes, with four nodes experiencing decreases >35%.

The predicted ecological risk resulting from these hydrologic changes varied depending on the stream attribute being considered. The August–September metric indicated that habitat suitability for trout was generally good under natural conditions (45 of 47 nodes were at low or minimal risk). The exceptions were two nodes on the west end of the study area that naturally fall into the 'significant risk' category for trout habitat. Under developed conditions, three nodes changed to moderate risk, yet 42 of 47 nodes remained at low or minimal risk for trout habitat degradation. Flannelmouth sucker is a native warm-water fish occurring in the lower Roaring Fork River and was chosen as representative of three declining species of native

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fish. All five nodes where flannelmouth sucker occur were found to be at minimal risk of degradation.

In contrast to fish, the alteration of peak daily flows was at moderate risk for change in riparian plant communities at nine nodes; two of these nodes were at high risk (39 nodes evaluated). The nodes with low ecological risk were typically in low-order streams with no transbasin diversions from the headwaters.

Fountain Creek Watershed

At all five nodes in the Fountain Creek Watershed mean annual flow has increased from natural to developed conditions. The two uppermost nodes increased 30–45%; the three lowermost nodes increased 180–200%. Winter, summer and peak flows have also increased, from 30% to 330%, depending on the flow parameter and the location.

All nodes were classified low risk for all attributes, but we consider these ranks unreliable because of known flow augmentation and associated channel changes. In contrast to these low-risk determinations, all four of the lowest nodes in the basin were determined to have high erosion potential. Overall, the erosion potential of sub-bankfull flows has been magnified approximately fourfold to fivefold downstream of Colorado Springs.

Comparison to site-specific modelling

Watershed Flow Evaluation Tool results compared favourably with site-specific estimations of fish habitat suitability. The results of the PHABSIM application on the mainstem of the Roaring Fork River indicated <1% difference in late-summer habitat conditions between natural and developed scenarios. The WFET results also predicted low risk to trout in the same river segment. When moderate-risk and high-risk flows as indicated by the WFET were run through the PHABSIM model, wetted area in river channel decreased 21–30% from natural, results that again indicated a favourable comparison between WFET and PHABSIM results.

DISCUSSION

The WFET for the Roaring Fork Watershed demonstrated how the ELOHA framework can serve to assess environmental flows assessment over an extensive geography with relatively modest investment. The Roaring Fork Watershed pilot project has lead to the funding of two additional projects that will extend the WFET across much of northwest Colorado, an area covering over 50 000 km^2. The utility of the Roaring Fork Watershed effort rested on the availability of essential technical components. An existing hydrologic model was available to calculate a 31-year record of natural and developed daily flows. Although this hydrologic model was not developed for ecological analyses, it proved sufficient for most of the applications we originally envisioned. The Roaring Fork WFET was also dependent on available data to describe relationships between flows and the river ecosystem. The level of accuracy achieved using available data was sufficient to support planning assessments at a watershed scale, a scale that is unattainable using only detailed site-specific studies, which are costly and take considerable time per site.

The Fountain Creek Watershed effort was hampered foremost by limited flow data (five stream gauges in a 2400-km^2 watershed) and no hydrologic model available for extending this spatial coverage. Additionally, we found few data on ecological response to flow augmentation, which is the primary flow impact in Fountain Creek. Finally, flow–ecological response curves developed during this effort are premised on channels in dynamic equilibrium. In lower Fountain Creek, augmented flows have destabilized the channel with the potential for further erosion of the bed and banks. We had insufficient information to understand the ecological implications of these channel changes.

Watershed Flow Evaluation Tool applications, limitations and future directions

For the Roaring Fork Watershed, the WFET provided useful insight into the flow-related ecological risk across the basin. The primary output from the pilot project was a series of maps that clearly and quickly convey risk for several ecosystem components. Such a watershed-wide perspective was not possible before.

Knowledge of flow-related risk can be useful for both research and water use planning. For research, a basin-wide map can provide a basis for studies of flow–ecology relationships across a spectrum of flow alteration. For water use planning, many potential uses exist. WFET results can be used to screen for high-risk areas that need site-specific investigation of flow requirements or, conversely, to identify areas where flows are intact. In Colorado, the WFET will be used to assess impacts to rivers that can be expected under future climate change and water development scenarios (e.g. for energy development or municipal water supply). Given the regional nature of the WFET, it can support large-scale assessments of impacts from a suite of projects spread over an extensive area. For both existing and future water-supply projects, the WFET has the potential to support strategic decision-making about project placement and design, as well as system-wide operations to optimize ecological outcomes. This can aid developers interested in finding the path of least resistance before committing to the expense of a full impact assessment.

The WFET advances watershed-scale flow assessment, but it cannot do everything. We were able to describe flow–ecology relationships for only three ecosystem attributes,

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leaving considerable scope for future method development as datasets become available. For example, mapping of the riparian metric was constrained to the elevation limit of narrowleaf cottonwood, so the WFET provides no information on riparian plant communities at higher elevations. In future applications, we expect to partially address these shortcomings by incorporating sediment transport and geomorphological considerations into flow–ecology relationships. We also expect that the WFET and other ELOHA applications will create a foundation for and encourage research explicitly focused on flow–ecology relationships.

For all of its strengths at broad scales, the WFET cannot replace fine-scale, site-specific assessments. For example, in locations where a quantitative flow prescription is needed to guide water management, site-specific methods should be used to better account for local conditions. The WFET will not replace the ecological and hydrological analyses needed during impact assessments (e.g. under the National Environmental Policy Act), but may help guide the selection of sites and variables for subsequent detailed assessment.

The social process

Colorado is typical of many western US states where ongoing water consumption for agriculture and industry combined with increasing population is pushing the limits of a finite water resource that may decrease with climate change (CWCB, 2004, 2007, 2010). A significant drought throughout the region in 2002 added urgency to plan for the future, resulting in the passage of the Water for the 21st Century Act (Colorado General Assembly, 2005). Despite tensions among people using the water for diverse and sometimes conflicting purposes, the notion that sustaining healthy river ecosystems is essential to human well-being is widely acknowledged (Gleick, 2003; Millennium Ecosystem Assessment, 2003), and this notion was expressed in Colorado's water planning legislation.

This backdrop was critical to the success of the Roaring Fork WFET pilot project. Many viewpoints from all parts of the political spectrum were allowed representation in discussions to date. From the onset of the non-consumptive needs assessment, stakeholders in each river basin were given substantial authority to decide how the assessment would be conducted. In the Colorado basin, where the Roaring Fork Watershed is located, the stakeholders included agricultural water users, municipal water suppliers and many individuals (including some from the former two groups) with a strong interest in the protection of rivers for their fishing, boating, amenity and ecosystem values. The technical development of the WFET also involved participants from a range of backgrounds, including private contractors, academics, a non-governmental organization and a state agency. This diverse group, with support and encouragement from the Colorado Water Conservation Board, was clearly committed to both maintaining water supplies for human needs and protecting the natural environment. Both the legislative mandate and constant give-and-take among project collaborators were essential to the success of the Roaring Fork WFET effort. Ultimately, it must be the basin stakeholders and our broader society that collectively decide the desired state of our aquatic ecosystems. The purpose of technical tools developed by scientists, like the WFET, is to provide the information needed to achieve this state.

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