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Incorporating social preferences into the ecological limits of hydrologic alteration (ELOHA): a case study in the Yampa-White River basin, Colorado

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SUMMARY

1. River management involves satisfying societal preferences alongside environmental needs for a healthy river ecosystem. Environmental flows is a discipline that aims to define streamflow requirements that achieve desired social and ecological conditions in rivers.
2. The ecological limits of hydrologic alteration (ELOHA) framework takes a regional approach towards assessing relationships between human-caused river flow alterations and social–ecological benefits. ELOHA allows for, but does not specify, a social process with practical guidelines for incorporating social preferences into environmental flow management problems. Studies using the ELOHA framework are being performed around the world.
3. This study presents development of a decision support tool to prioritise river basin criteria and to rank river segments in order of combined hydro-ecological and social environmental flow needs. We integrate this tool with hydro-ecological components of an ELOHA application in the Yampa–White River basin in north-west Colorado. Stakeholder preferences were collected with a survey, and the analytic hierarchy process was applied to estimate the importance of five criteria identified as socially valued proxies of freshwater management in the basin. Analytical methods for multicriteria decision analysis were used to integrate the preference information with results from the ELOHA application to prioritise the basin river segments.
4. Our methods and results provide a means to facilitate stakeholder negotiation and future environmental flow policy analyses. By extending the existing ELOHA framework to include a social preference component, this approach is general and can be applied to environmental flow policy and management in other river basins.

Keywords: decision-making, environmental flows, multicriteria decision analysis, river management, social preference

Introduction

River management involves satisfying societal preferences alongside environmental needs for a healthy river ecosystem. Water supply, recreation, drinking water, flood protection and hydropower have long been societal objectives for river management. Environmental needs have gained importance as they are viewed in the practice of environmental flows, defined in the Brisbane Declaration (2007) as ‘the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems’ (http://www.watercentre.org/news/declaration).

The environmental flow concept represents a consensus among river scientists that water supply, water quality and the ecological integrity of rivers are largely influenced by variations in streamflow (Poff *et al.*, 1997; Richter *et al.*, 1997). Environmental flow requirements are estimated by statistically accounting for changes (i.e.

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alterations) in measurable streamflow quantities and linking these alterations to measured geomorphic and ecological processes. Quantification of flow–ecology relationships (Poff & Zimmerman, 2010) help to operationalise the concept that streamflow is a valuable indicator of a functioning river ecosystem and for biodiversity (Bunn & Arthington, 2002).

Hundreds of methods have been developed to estimate environmental flow requirements for valued ecological indicators of river ecosystems. Most are applied to regulated, single-site systems where human modifications have impacted riverine ecology (Tharme, 2003). The ecological limits of hydrologic alteration (ELOHA) framework (Poff *et al*., 2010) takes a regional and multi-site approach towards assessing relationships between human-caused river flow alterations and social–ecological benefits. ELOHA allows for, but does not specify, a social process with practical guidelines for incorporating social preferences into management problems that analyse flow–ecology relationships alongside stakeholder-defined preferences. Studies using the ELOHA framework are being performed around the world (Kendy, Apse & Blann, 2012; Reidy Liermann *et al*., 2012; McManamay *et al*., 2013; Mackay, Arthington & James, 2014; Tavassoli, Tahershamsi & Acreman, 2014).

The science and management of environmental flows is well-established (see *Freshwater Biology* special issue 'Environmental flows: Science and Management', 2010; Arthington, 2012). ELOHA is a widely embraced framework for global environmental flow management yet few publications have explicitly addressed the social process that is embedded in the framework. Finn & Jackson (2011) and Pahl-Wostl *et al.* (2013) suggest the inclusion of indigenous and governance-based preferences into ELOHA, respectively, but do not develop methods or present case studies for such a process. Where ELOHA has been implemented, setting water management standards is based solely on flow–ecology relationships (Kendy, Apse & Blann, 2012). These implementations lack not only social preferences, but also lack a formal decision support approach for evaluating social–ecological trade-offs.

For individual rivers, decision support approaches that have been developed integrate hydro-ecological response models with socio-economic management needs to systematically design alternative river management options. When used, they are largely applied to a single regulated river system using, for example, 'designer' flow regimes (Acreman *et al*., 2014). For such site-specific applications, optimisation methods are used to design management options that trade off ecological targets with water allocation objectives (Homa *et al*., 2005; Yang, 2011), human sustenance desires (King, Brown & Sabet, 2003) and multipurpose reservoir system objectives (Cardwell, Jager & Sale, 1996; Richter & Thomas, 2007; Barbour *et al*., 2011; Labadie, Zheng & Wan, 2012; Steinschneider *et al*., 2013; for a review, see Jager & Smith, 2008). The general application of optimisation into computerised decision support systems to allocate fresh water from multipurpose reservoir systems is rich (for reviews, see Labadie & Sullivan, 1986 and Labadie, 2004). Other methods such as Bayesian belief networks (Stewart-Koster *et al*., 2010) offer alternative probabilistic decision support frameworks.

Multicriteria decision analysis (MCDA) is a discipline that uses analytical techniques to systematically evaluate trade-offs associated with alternative river management options. MCDA is unique in that different management options with different performance measures and units can be prioritised based on transforming them into a common scale and incorporating social preferences into the trade-offs analysis. Previous case studies using MCDA to evaluate alternative environmental flow management options include Flug & Ahmed (1990), Hämäläinen, Kettunen & Ehtamo (2001), Shiau & Wu (2006), Alexander *et al.* (2006), Marttunen & Hämäläinen (2008), King & Brown (2010), Barton, Berge & Janssen (2010) and Beilfuss & Brown (2010).

This study has two specific aims: to develop a social process that extends ELOHA beyond solely hydro-ecological principles and to a more complete decision-making framework, and to use MCDA to evaluate trade-offs among social preferences and ecological needs in a multi-site, whole river basin. We developed a decision support tool to prioritise river basin criteria and to rank river segments in order of combined hydro-ecological and social environmental flow needs. For a case study, we complement a published application of ELOHA on the Yampa–White River basin in north-west Colorado. That application quantified hydro-ecological relationships and flows required to maintain biological, recreation and policy criteria at river segments throughout the basin. The decision support tool was developed to elicit preference information from stakeholders in the basin and implement a formal MCDA evaluation of the basin river segments as proxies of future flow management policy options.

Methods

Study basin and relevant social–ecological data

The Yampa and White rivers flow in a westerly direction in Colorado towards the Green River, a major tributary to the Colorado River (Fig. 1). The catchments, hereafter referred to as the basin, cover lands mostly in the public domain that are managed by federal agencies. Socio-economic beneficiaries in the basin are from the agriculture and tourist (e.g. fishing, boating and skiing) sectors. Portions of the tourist sector have a social preference to maintain environmental flows for ecosystem service benefits (e.g. trout fisheries, recreational white water).

The Colorado Water for the 21st Century Act (House Bill 2005-1177) called for the negotiation of water resource management in locally driven collaborative decision contexts. To facilitate this objective, 'basin roundtables' were created as groups of citizen stakeholders who reside inside the boundaries of each of the nine river basins in Colorado. As part of the multibasin non-consumptive fresh water needs assessment, the Yampa–White River basin roundtable sponsored the Nature Conservancy to perform an ELOHA application called the Yampa–White Basin Roundtable Watershed Flow Evaluation Tool Study (WFET) (Sanderson *et al.*, 2012a; https://www.conservationgateway.org/Files/Pages/yampawhitewfet.aspx).

The WFET used practical guidelines from the ELOHA framework to assess current flow-based conditions of social–ecological criteria at 12 pre-determined river segments throughout the basin. Three biological criteria were identified by the basin roundtable as valued sustainability measures to the basin and include trout fish (cutthroat, brook, brown, rainbow), riparian vegetation (native cottonwood) and warm water fish (bluehead sucker, flannelmouth sucker, roundtail chub). Two additional flow-based criteria were included in the ELOHA application: recreational white water boating opportunities and threatened and endangered (T&E) fish (Colorado pikeminnow, humpback chub, bonytail chub, razorback sucker).

To summarise the initial phases of the ELOHA application, a basinwide hydrological classification contrasted baseline and developed river flows at instream flow-monitoring locations, which were used to distinguish the 12 basin river segments (Fig. 1). The classification was performed to develop metrics appropriate for quantifying streamflow requirements for the trout, riparian vegetation and warm water fish criteria. The Indicators of Hydrologic Alteration method (Richter *et al.*, 1996) and accompanying software were used to estimate ecologically important streamflow metrics describing baseline and developed river flow conditions at the river segments.

Flow–ecology relationships for the biological criteria were established based on an extensive literature review and expert opinion case study for sites throughout the state of Colorado (see Sanderson *et al.*, 2012b). The risk

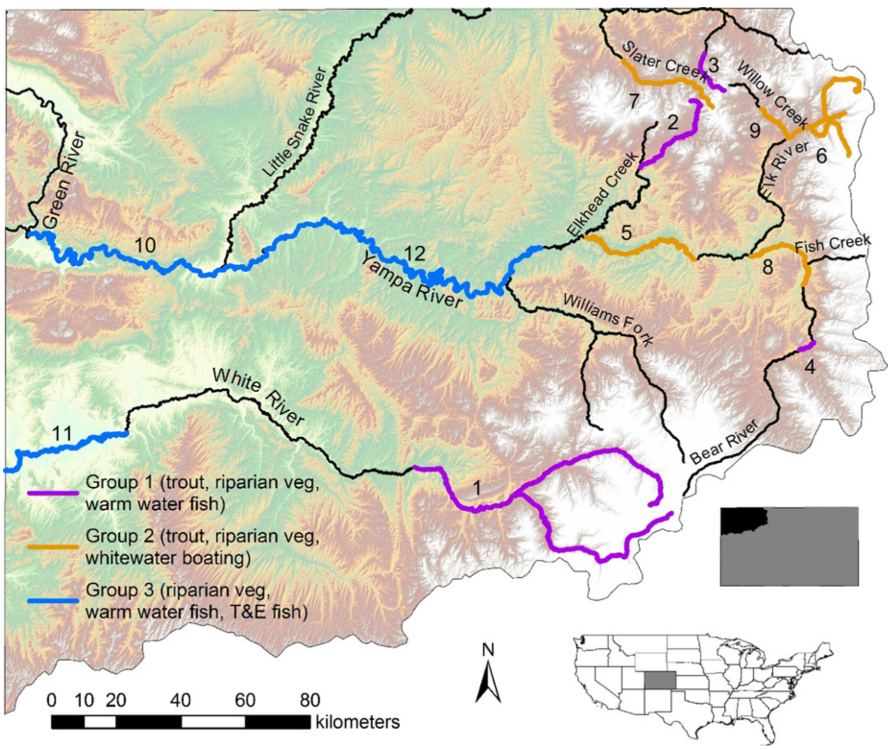

Fig. 1 Yampa–White River basin map with approximate river segment locations numbered. The river segments are partitioned into groups with the same criteria.

of deteriorating trout populations, riparian vegetation populations and warm water fish biomass was estimated by establishing different probability-based impairment classifications for these criteria. These were based on quantifying the relationship between per cent reductions in criteria metrics with flow modifications. In addition to estimating flow–ecology relationships of the biological criteria, preferred river flows for recreational white water boating were developed based on an American Whitewater recreation survey and geographic analysis (Sanderson *et al.*, 2012a). Lastly, designation of suitable flows for T&E fish was based on recommendations in the U.S. Fish and Wildlife Service's Programmatic Biological Opinion (USFWS, 2005) and related documentation.

Following quantitative analyses, expert opinion was used to assign a common linguistic classification of degrees of impairment to the five basin criteria, hereafter *impairment classes*, which represent the current flow-based status of each criterion at the basin river segments. A summary of the flow-related metrics and impairment classifications for each criterion is given in Table 1. The classification uses common terminology but impairment classes are not comparable across basin criteria because different quantitative flow-based metrics and methods were used to determine different degrees of impairment.

Preceding the completion of the WFET study, we participated in discussions with volunteer basin roundtable members to establish a working relationship and elicit ideas on how the results could be incorporated into a decision-making policy context. The group decided to target basin river segments that have the highest needs for environmental flow management, that is, river segments with high flow-based impairment. Based on this input and data available in the WFET, a decision analysis process (Fig. 2) and electronic support tool were designed to prioritise basin river segments. Following stakeholder-defined preferences, river segments that were prioritised by the tool are considered highly impaired and require environmental flow management. The decision analysis process required two components: estimating stakeholder-assigned importance (i.e. weighting factors) to the five basin criteria and integrating the criteria weighting factors into a prioritisation of the river segments using the published WFET data.

Prior to proceeding with the decision analysis, a common currency was needed for comparing the river segments with MCDA methods. To do this, impairment classes for each criterion were transformed into sets of fuzzy numbers ('fuzzy sets'; Zadeh, 1965) that represent an impairment score (right-hand column in Table 1). The assignment of fuzzy numbers is to generalise the order of impairment classes for analytical comparison using MCDA. Fuzzy numbers are arbitrary so long as they maintain ordinal scales in succession and correspond to stakeholder-defined preferences for comparing impairment classes in the decision analysis. Based on this and the objective to prioritise impaired river segments, highly impaired classes were given higher fuzzy numbers.

The 12 river segments were divided into three groups where each group of river segments included the same three criteria (Fig. 1): Group 1 are river segments that

Table 1 Information used to estimate impairment classes of criteria in the Yampa–White River basin (Source: Sanderson *et al.*, 2012a)

Basin criteria	Flow metric(s) (cubic feet per second)	Flow-based relationship	Impairment class	Fuzzy number
Trout	Mean annual flow (MAF)	Summer low flows <10% MAF	Very high	5
	Mean August flow	Summer low flows 10–15% MAF	High	4
	Mean September flow	Summer low flows 16–25% MAF	Moderate	3
		Summer low flows 26–55% MAF	Minimal	2
		Summer low flows >55% MAF	Low	1
Riparian vegetation	Mean annual peak daily flow	Dependent on geomorphic setting (confined vs. unconfined); links to a per cent range of flow alteration (different for each river segment)	Very high	4
	90-day maximum flow (wet years)		High	3
			Moderate	2
			Low	1
White water boating	Segment-specific flow ranges	Current streamflow ranges suitable for recreational usable days (different for each river segment)	High	3
			Moderate	2
			Low	1
Warm water fish	30-day low flow (July through November)	25–50% reduction in potential biomass	High	3
		10–15% reduction in potential biomass	Moderate	2
		<10% reduction in potential biomass	Low	1
T&E fish	U.S. Fish and Wildlife Service Programmatic Biological Opinion	Current streamflow < recommendation	High	2
		Current streamflow ≥ recommendation	Low	1

The linguistic classifications for each criterion were transformed into sets of ordinal fuzzy numbers for the decision analysis.

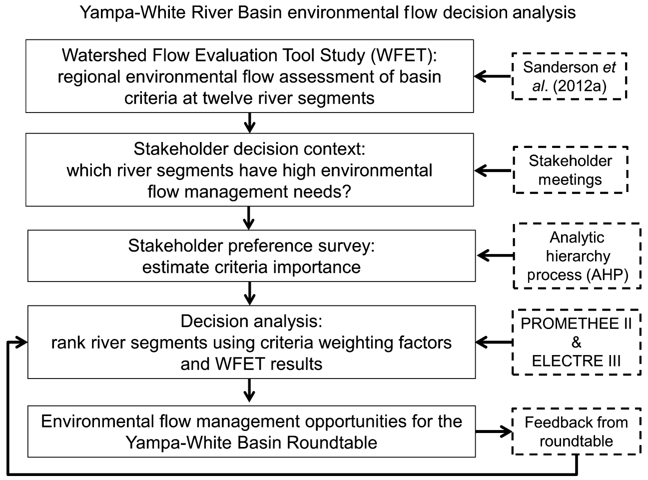

Fig. 2 A conceptual flow chart for the decision analysis.

estimated impairment class values for the trout, riparian vegetation and warm water fish criteria; Group 2 are segments that estimated values for the trout, riparian vegetation and white water boating criteria; and Group 3 are segments that estimated values for the riparian vegetation, warm water fish and T&E fish criteria. The current flow-based impairment status for each criterion at each river segment was taken from Sanderson *et al.* (2012a) and transformed into a corresponding fuzzy number. This information was used to populate an analytical evaluation table for each river segment group (Table 2).

Table 2 Evaluation table for using multicriteria decision analysis to compare river segments within each basin group

Group 1	Trout	Riparian vegetation	Warm water fish
Segment 1	1	2	1
Segment 2	5	1	3
Segment 3	4	1	1
Segment 4	1	4	1
Group 2	**Trout**	**Riparian vegetation**	**White water boating**
Segment 5	3	2	2
Segment 6	2	1	1
Segment 7	4	1	3
Segment 8	3	2	1
Segment 9	2	1	3
Group 3	**T&E fish**	**Riparian vegetation**	**Warm water fish**
Segment 10	1	2	2
Segment 11	1	2	1
Segment 12	1	2	1

The fuzzy numbers correspond to a current impairment status for each basin criteria (see Table 1).

Method to estimate basin criteria weights

Following development of the decision analysis process (Fig. 2), we estimated a priority vector of weighting factors for the basin criteria using the analytic hierarchy process (AHP) (Saaty, 1990) method. AHP breaks down a decision problem into a hierarchical structure that aids in the comparison of all pairs of elements within the $n-1$ levels of the structure. A three-level objective hierarchy was developed to aid in estimating criteria importance with AHP (Fig. 3). The overall objective focusses on non-consumptive freshwater uses (i.e. species conservation and ecosystem services). The subobjectives contribute to achieving the overall objective in different ways and were defined after the Environmental Protection Agency's pillars of sustainability (epa.gov/ncer/rfa/forms/sustainability_primer_v7.pdf). The five basin criteria are at the lowest level of the hierarchy.

To calculate a priority vector of criteria weights with AHP, preference judgements are produced for each pair of elements on one hierarchical level with respect to elements at the upper adjacent hierarchical level. Each paired judgement corresponds to Saaty's verbal scale (Saaty, 1990) and measures the intensity of importance of one element over another in paired comparison. For example, a verbal judgement of 'equal importance' means that two compared subobjectives such as the environment and economy are equally meaningful to achieve the overall objective. Likewise, judgements of 'moderate importance' mean that experience slightly favours one criterion over another. Saaty's verbal scale also includes judgements of 'strong importance', 'very strong importance' and 'extreme importance' with related linguistic meanings.

Verbal preference judgements made using the AHP method correspond to Saaty's ordinal number scale (Saaty, 1990). The translation of verbal judgements to numerical values allows them to be entered into an

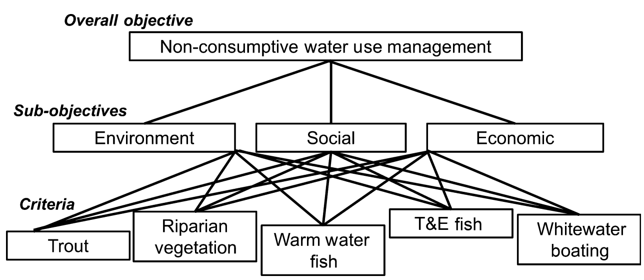

Fig. 3 A three-level objective hierarchy was used to design a stakeholder preference survey that estimated basin criteria weights with the analytic hierarchy process.

analytical reciprocal matrix for each $n-1$ levels of the objective hierarchy. The eigenvalue technique (see Appendix S1) was used to analyse each reciprocal matrix to converge to a vector of weights that corresponds to the elements on the subobjectives and criteria levels of the hierarchy.

Stakeholder preference survey

Stakeholder preferences of the 11-member 'non-consumptive needs' subcommittee of the basin roundtable were elicited in a survey from May to August 2013. The subcommittee was non-randomly chosen for the preference survey because they reflected a local context for water-use management in the basin. The surveys were distributed through email in Microsoft PowerPoint and Microsoft Word formats to all members of the subcommittee. Included in the survey was background information on the criteria that were evaluated in the published WFET study as well as definitions for each subobjective. To define the environment subobjective, the terms 'ecosystem services', 'air quality', 'water quality' and 'waste management' were used. Likewise, the terms 'human health', 'education' and 'sustainable communities' were given to define the social subobjective and 'jobs', 'supply and demand' and 'natural resource accounting in cost benefit analyses' were given to define the economic subobjective. In general, we wanted all respondents to approach the AHP questions with common background knowledge and terminology.

The survey then elicited stakeholder judgements about the strength of importance for each subobjective and criterion of the hierarchy (Fig. 3) based on pairwise comparisons of same-level elements using AHP questions and Saaty's verbal scale. AHP questions pertaining to subobjectives took the form: 'Which of the following objectives are more important with respect to the overall goal of sustainable non-consumptive freshwater use management in the Yampa–White basin?' Questions for criteria took the form: 'Which of the following criteria are more important with respect to the *social/economic/environment* objective in the Yampa–White basin?' In total, a single respondent was asked to make three paired judgements on the subobjectives and 30 paired judgements on the basin criteria. Two types of surveys were randomly delivered to the individuals with alternative ordering of criteria given in the AHP questions. The biocentric and anthropocentric types of criteria ordering was done as indirect controls for bias (e.g. Tversky & Kahneman, 1973) to the words that came first and more frequently in the pairwise comparisons.

Seven (of 11) surveys were returned and given unique identification numbers to hold the responders' identity confidential. The qualitative judgements of the seven respondents were translated into Saaty's number scale (Saaty, 1990) and used to populate reciprocal matrices in a Microsoft Excel spreadsheet. A 3rd-order reciprocal matrix was developed to calculate weights of the subobjectives, and a 5th-order matrix was developed for the five basin criteria. For the criteria, 21 matrices were developed corresponding to the seven responder answers for each of the three subobjective questions. The Alonso & Lamata (2006) method was applied as a special acceptance rule to reject reciprocal matrices that were not consistent (i.e. there was no logical pattern to respondent answers) (see Appendix S1).

We aggregated the valid stakeholder judgements (i.e. 17 of 21 respondent matrices passed the consistency test) through a series of steps to develop separate 3rd-order matrices corresponding to estimating criteria weights in each basin group. These steps included grouping individual judgements using the geometric mean of responses and using hierarchical additive weighting to generate a summary priority vector of criteria weights corresponding to each river segment group (see Appendix S1).

Methods to prioritise basin river segments

The PROMETHEE II (Brans, Vincke & Mareschal, 1986) and ELECTRE III (Roy, 1996) methods for MCDA were applied to rank the river segments in each basin group in order of their aggregated impairment status. Presented herein is a brief generalisation of the methods (for quantitative details, see Appendix S1).

The river segments are ranked in PROMETHEE II by comparing the fuzzy numbers (Table 2) of the criteria in pairs over all river segments in a basin group. A fuzzy membership function is defined in PROMETHEE II as the degree of truth that one river segment outranks another. The weighted membership function first calculates quantitative differences between all pairs of criteria fuzzy numbers in a basin group and then aggregates quantitative fuzzy criteria relationships (e.g. indifference, linear, Gaussian) (Brans *et al.*, 1986) and the criterion weight to map the comparison to the same dimensionless scale (0,1). Membership function values closer to unity offer stronger support that one river segment ranks higher than another in comparison.

To illustrate, the trout criterion is evaluated between river Segment 7 and Segment 6, which is a comparison between 'high' and 'minimal' hydro-ecological impairment, respectively (i.e. comparing fuzzy numbers 4 and

2 in Table 2, respectively). Upon strict comparison, Segment 7 is more impaired than Segment 6 and the fuzzy membership function for the paired comparison will be equal to unity. However, through development of a linear fuzzy criteria relationship, the membership function may be reduced to between zero and one. Defining this imprecision is based on linearly diminishing the difference between the two fuzzy numbers and therefore allowing flexibility in its contribution to the overall membership function. In succession, this corresponds to a reduction in the overall intensity of the quantitative difference in rank of river Segment 7 compared to others in Group 2. The technique uses a method similar to this philosophy to analytically aggregate all paired fuzzy number comparisons and leads to a final ranking of all river segments in each basin group. Like PROMETHEE II, the ELECTRE III method is based on mapping the strengths of the differences between criteria impairment of river segments to common scales using similar indices and establishing fuzzy criteria relationships.

Sensitivity analysis

A sensitivity analysis procedure was designed to yield several sets of river segment rankings within each basin group. The analysis was based on iterations of PROMETHEE II and ELECTRE III using different combinations of fuzzy criteria relationships and the AHP criteria weights (see Appendix S2). These iterations were conceived with volunteer basin roundtable member interaction and by conducting a qualitative assessment of the AHP results and were carried out in the Microsoft Excel spreadsheet that was designed for the project.

The first sensitivity iteration for each basin group was performed using equal criteria weights and no fuzzy relationships for the fuzzy numbers being compared. This simulated a situation where no stakeholder preferences are incorporated in the decision analysis and the river segment ranking is non-biased. Subsequent biased iterations integrated the AHP criteria weights with three fuzzy criteria relationships (e.g. indifference, strict preference, linear) that simulated stakeholder imprecisions about the current impairment classes of the criteria within each basin group. Indifference fuzzy relationships signify flexibility in certainty that adjacent fuzzy numbers (i.e. successive impairment classes) are equally preferable (e.g. there is no clear preference between 'high' and 'moderate' trout classes). Strict preference means that a distinct ranking exists if fuzzy numbers differ (e.g. a membership function equal to unity is assigned for a comparison between 'high' and 'moderate' trout classes). Linear fuzzy relationships mean that adjacent impairment classes maintain positive but not strict preference (e.g. a 'high' trout impairment class positively but does not strictly rank higher than a 'moderate' class; fuzzy membership value was equal to 0.5 for this relationship).

In total, five sensitivity iterations of each MCDA method were performed on basin groups 1 and 2. Three sensitivity iterations of the methods were performed on basin Group 3 because only three river segments were compared and flow-based criteria impairment was similar across the segments.

Results and discussion

Basin criteria weights

The preference survey yielded the following AHP results. Subobjective weights and criteria weights are given in Table 3. The results show that the environment subobjective was clearly the most valued among the stakeholder group (weight = 0.54) with respect to the overall objective of non-consumptive water-use management in the basin. For criteria, trout was the most valued in river segment groups 1 and 2, whereas T&E fish was the most valued in Group 3. Subobjective priorities among the criteria were consistent with this ordering, with the exception that riparian vegetation was found to be a slightly more valued criterion with respect to the environmental subobjective in Group 2. As a control

Table 3 Criteria weights for each subobjective and for each criterion per basin group

Basin criteria		Environment (0.54)	Social (0.18)	Economic (0.28)	Overall weights
Group 1	Trout	**0.42**	**0.58**	**0.62**	**0.50**
	Riparian vegetation	0.37	0.26	0.21	0.31
	Warm water fish	0.21	0.16	0.17	0.19
Group 2	Trout	0.38	**0.50**	**0.52**	**0.44**
	Riparian vegetation	**0.40**	0.22	0.20	0.31
	White water boating	0.22	0.28	0.28	0.25
Group 3	Riparian vegetation	0.27	0.38	0.35	0.31
	Warm water fish	0.15	0.22	0.28	0.20
	T&E Fish	**0.58**	**0.40**	**0.37**	**0.49**

Weights in bold are the highest in their respective basin group (see Fig. 1). Columns within each group sum to unity (1).

measure, we calculated the frequencies of answers to each survey type (biocentric versus anthropocentric) and concluded that individual respondent criteria weights did not relate to the sequencing of criteria in the preference survey.

The AHP weights indicate that the environment subobjective is a higher priority than social or economic subobjectives to the stakeholder group as it is perceived for non-consumptive freshwater management in the basin. Trout was the most valued criterion for groups 1 and 2 and T&E species for Group 3. 'Trout' is a collective term from the basin roundtable's perspective and includes endangered as well as introduced species for recreation. Trout are highly valued by upper-basin conservation and recreation beneficiaries. Based on *a posteriori* conversations with volunteer roundtable members, trout as an indicator of non-consumptive basin needs is understandably more important than most other indicators. To quote a roundtable member, the fact that trout was prioritised 'makes management sense' because it is highly preferred from tourist beneficiaries in the more populated upper-basin groups 1 and 2 (Fig. 1).

The designation that T&E fish are prioritised in Group 3, which comprise of downstream basin river segments, also makes sense to the stakeholders. In the lower basin, recreation is largely substituted with agriculture as a dominant beneficiary from the river and this type of freshwater use can significantly alter the river streamflow regimes and subsequently impact sensitive species in the lower basin. In addition, T&E fish are a national priority, which elevates their social perspective and priority.

It is apparent that the survey respondents could establish a clear judgement among basinwide objectives and criteria. This is noticeable, for example, with the riparian vegetation criterion that varies in weight among the subobjectives in Table 3. This is evident even though there is a clear trend in the highly prioritised criterion (trout) from each group across most subobjectives.

River segment priorities

The sensitivity analysis yielded different ranks of river segments within each basin group (Tables S2–S4 in Appendix S2). Table 4 gives the average over all sensitivity iterations for each basin group and shows that river segments 2, 7 and 10 received the highest priority in the respective groupings (Fig. 1). High rank indicates river segments with high environmental flow needs (i.e. river segments with highly impaired criteria).

The first sensitivity iterations used equal criteria weights and no assignment of fuzzy criteria relationships. This lack of stakeholder preference resulted in no distinct ranking between many pairs of river segments in groups 1 and 2. This result is important because little distinction is made when comparing the impairment classes of criteria in river segments when stakeholder preferences are not incorporated into a formal decision analysis.

Table 4 River segment rankings per basin group

Group 1	Segment 1	4th
	Segment 2	1st
	Segment 3	2nd
	Segment 4	3rd
Group 2	Segment 5	2nd
	Segment 6	5th
	Segment 7	1st
	Segment 8	3rd
	Segment 9	4th
Group 3	Segment 10	1st
	Segment 11	Tie: 2nd
	Segment 12	Tie: 2nd

High rank indicates high environmental flow needs.

The integration of stakeholder-driven criteria weights and fuzzy criteria relationships resulted in the same overall ranking among river segments in groups 1 and 2 for both MCDA methods. This result is important because we aimed to control for differences in the assumptions of each MCDA method and conclude that they did not have an overall impact on the results. The prioritisation of river segments in Group 3 was very similar, regardless of the inclusion of criteria weights or sensitivity iteration.

To summarise the results in the context of environmental flow management, we view the highest ranked segments 2, 7 and 10 (Fig. 1; Table 4) as highly impaired and are considered priority options for the basin roundtable to deliberate future site-specific projects and policies that support flow management intervention. Examples of such projects include the following: (i) potential flow modification projects from upstream impoundments and (ii) water rights transfer agreements from consumptive uses (e.g. water supply and agriculture) to non-consumptive uses (e.g. hydropower and recreation). Low ranking segments 1, 6, 11 and 12 are the least impaired and considered priority options for environmental flow preservation policies (e.g. conservation easements).

Intermediate ranks from the sensitivity analysis yielded interesting caveats for flow management in groups 1 and 2 (Tables S2 & S3 in Appendix S2). To give an example from Group 2 where both trout and riparian vegetation were highly preferred criteria, we noticed that Segment 8 was equally favoured to Segment 5 when uncertainty was included as a linear fuzzy relationship for all three basin criteria. Likewise, Segment 5 ranked higher in iterations where stakeholder preference was simulated as being strictly indifferent towards riparian vegetation. According to this sensitivity iteration, the AHP weights were integrated with stakeholder feedback to ask whether riparian vegetation should be considered a high management priority (i.e. given less flexibility to its current flow-based impairment status) and, if so, what outcome would it have on the ranking of the five river segments in the group. The ecological merit behind these sensitivity iterations is that managing for riparian vegetation may have an integrated positive effect for in-stream criteria in this group (i.e. 'the valley rules the stream'; Hynes, 1975). It was determined that if stakeholders allow uncertainty for trout impairment and are flexible to consider riparian vegetation as a preferred upper-basin criterion, then Segment 5 may be considered an important flow management priority in Group 2. This outcome was well-received through *a posteriori* conversations with volunteer basin roundtable members.

We stress here the importance of creating logical sensitivity iterations using *a posteriori* stakeholder feedback including discussions about the preference survey and in-person discussion of results. Because this was a collaborative effort, we tended to steer away from sensitivity analyses that were unimportant to the decision context and project goals. The feedback procedure is suggested as a means of gauging how many sensitivity iterations of the MCDA techniques are needed to develop a defendable rank.

In conclusion, to carry out a systematic social process conducive to the ELOHA framework for regional environmental flow assessment, a collaborative decision analysis and electronic support tool were developed to prioritise basin criteria and to rank river segments in support of stakeholder-defined environmental flow management preferences. The planning project produces a template that can be incorporated into future ELOHA applications in other geographical and governance contexts.

Our multifaceted decision analysis used multiple methods for MCDA to validate the decision support tool. However, the WFET study did not estimate impairment classes of all criteria at all basin river segments and we cannot provide a whole basin ranking. The decision analysis is limited to comparing river segments with similar criteria and, hence, no distinction can be made among low- and high-priority river segments across the three basin groups in Table 4. Comparisons among the basin groups and other river segments not used in the decision analysis require further investigation.

We consider the approach to constructing the objective hierarchy and preference survey to be an objective method for correcting and detecting potential stakeholder bias. The intent was for survey participants to ignore place-based knowledge of the river segments and to focus on basinwide non-consumptive use management. It is questionable as to whether the resulting criteria weights would have changed had there been a different hierarchical structure to the decision problem or different style of questioning. For example: Would the criteria weights have changed if the river segment options were made available to the stakeholders? Addressing this question would necessarily involve an element of geographical bias. Yet the resulting criteria weights ultimately make management sense based on *a posteriori* discussions and an understanding of ecological and socio-economic characteristics of the Yampa–White River basin.

The decision support tool was developed in Microsoft Excel versus other sophisticated MCDA packages for easy access and distribution among the scientists, analysts and basin roundtable members involved in the project. We are confident that future approaches will develop similar tools that are transparent and interactive and are applicable to environmental flow or ELOHA decision-making.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Detailed information on the methods is included. Fig. S1 explains the hierarchical additive weighting to estimate basin criteria weights.

Appendix S2. Table S1 explains the sensitivity iterations for river segment comparisons with MCDA. Tables S2–S4 give river segment ranks for all iterations of the sensitivity analysis per MCDA method and basin group.

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