Economic–Engineering Method for Assessing Trade-Offs between Instream and Offstream Uses

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Abstract: Rivers provide multiple water uses and services, including offstream uses that are valued economically and instream uses, such as recreation and ecosystem preservation, that are rarely valued economically. In many countries, water rights allocate water to offstream uses, and dedicated minimum instream flows are the main instrument for instream water allocation. However, minimum instream flows do not ensure continuous reaches for recreation or aquatic habitats. An efficient allocation of water for instream uses requires quantifying the benefits obtained from those uses, so that trade-offs between instream and offstream water uses can be weighed against each other and properly considered. This study develops a generalizable, hybrid economic–engineering method to assess trade-offs between competing instream and offstream uses. Benefit curves measure recreation quality as a function of instream flow, and opportunity costs given by lost benefits of offstream uses generate supply curves for instream water. The method is applied to Chile's Maipo River. Instream water uses for recreation include kayaking and rafting. The principal offstream water use in the study reach is hydropower generation from the Alto Maipo Hydroelectric Project. Continuous length of boatable reaches and trade-offs between instream and offstream water uses are evaluated for normal and dry months and years. Results show that the opportunity cost of additional boatable reaches is sensitive to both drought and energy price. The cost of maintaining 34 km rather than 26.6 km of continuous boatable river is US$10 million in dry years when energy prices are high, and US$240,000 in normal years when energy prices are low. Results indicate that dry months and years, when water is scarce, have a greater number of optimal solutions between instream and offstream water uses. This is explained by the physical relationship between instream flow and continuous boatable distance for low flow values. The proposed approach could guide negotiation processes between instream and offstream water users, and can be applied elsewhere, provided a physically based assessment of instream water use benefit and an economic representation of offstream opportunity costs is available. **DOI: 10.1061/(ASCE)WR.1943-5452.0001026.** *© 2018 American Society of Civil Engineers.*

Introduction

Rivers provide water for multiple and competing uses. Offstream uses include water supply and hydropower generation through bypass reaches. Instream uses include aquatic ecosystems and recreational uses, such as navigation, rafting, kayaking, fishing, and swimming. However, with widespread water development, continued population growth, and climate change, many rivers cannot support all uses. Consequently, methods to assess the trade-offs between instream and offstream uses are needed. Offstream water uses have long been valued economically to quantify the benefit of diverted streamflow (Jenkins et al. 2003; Cai et al. 2003; Young and Loomis 2014). However, instream uses are not readily economically valued. Incorporating instream uses into frameworks and models that optimally allocate water is an ongoing challenge (Loomis et al. 2000; Jorda-Capdevila and Rodríguez-Labajos 2017). Advancing methods that quantify and analyze trade-offs between instream and offstream uses for efficient water allocation is needed to best manage rivers for multiple and competing water uses.

Numerous studies have described the relationship between human flow alteration and ecological response in rivers (Richter et al. 1996; Poff et al. 2010; Carlisle et al. 2011; Mims and Olden 2013; McCluney et al. 2014). Methods exist to estimate the streamflow needed for fish or to support aquatic ecosystems. Jowett (1997) analyzed and compared three methods to determine instream flows for fish and wildlife, including hydrologic (historical flow), wetted perimeter, and suitable habitat methods. These approaches are useful in water allocation planning for minimum instream flow requirements (Jager and Smith 2008). Although minimum instream flows are useful as constraints in water management models, they do not necessarily represent optimal flow levels to support ecosystems because organisms may be limited by factors other than streamflow such as water quality, channel structure, or food abundance (Vannote et al. 1980). Increasingly, models are developed that consider both ecosystem and human water use objectives explicitly (Sale et al. 1982; Cardwell et al. 1996; Homa et al. 2005; Yin and Yang 2011; Null and Lund 2012; Steinschneider et al. 2014; Kraft et al. forthcoming). This suggests that developing methods to quantify instream objectives in water resources systems models is an ongoing and needed direction for the future.

With regard to river recreation, Shelby et al. (1992) and Whittaker and Shelby (2002) estimated a relationship between recreation quality and flow by interviewing experts and river recreationists. Flow benefit curves for recreation were developed from aggregate evaluations defining the quality of a specific recreation activity with variable flow ranges. Results could not be applied

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to other rivers because flows and recreation depend on specific river locations. Hyra (1978) and Mosley (1983) determined minimum, maximum, and optimum depth, width, and velocity for recreation activities, derived mostly from expert judgment and surveys. In that case, hydraulic variables had similar characteristics independent of channel morphology, so results apply to any river. Hyra (1978) proposed a simple cross-section method in the shallowest reach to obtain minimum, maximum, and optimum depth and velocity combinations (expressed as weighted surface area), assuming that a single cross section can define minimum flow requirements. However, considering only one river reach does not adequately represent the quality of recreation as a function of flow along the river or consider the distance necessary to make activities such as boating or rafting feasible. A number of researchers have used boatable days or weeks in specific rafting reaches, which quantifies recreation use but not the quality of the resource. For example, Ligare et al. (2012) measured whitewater recreation in California's Sierra Nevada rivers by analyzing the number of weeks when flow levers are adequate to support recreation, based on minimum and maximum boatable flows, gradient, and flow regime. Martin et al. (2015) and Stafford et al. (2017) used a similar approach to quantify boatable days, and Carolli et al. (2017) developed a modeling approach using river depth as a primary driver of river recreation, supplemented by interviews with rafting guides for a river-specific method.

Young (2005) recommended that water allocation between competing uses be analyzed with economic techniques. Methods exist to value instream flows for recreation, including contingent valuation (Daubert and Young 1981), travel cost (Ward 1987; Loomis 1998), hedonic pricing (Birol et al. 2006), or estimating economic value using the opportunity cost defined by the shadow price on environmental flow constraints (e.g., Draper et al. 2003; Medellín-Azuara et al. 2007). The latter approach, however, estimates economic value as an opportunity cost only at one particular optimal solution instead of informing the trade-offs at alternative Pareto-optimal decisions under multiple, incommensurable objectives, some of which cannot be monetized.

This paper introduces a generalizable, hybrid economic–engineering method to assess the trade-offs between competing instream and offstream uses. This method is helpful when the economic value of instream water use is not readily available. The approach is unique because it develops a trade-off analysis based on a combination a physically based assessment of instream water use benefit with an economic representation of offstream opportunity costs. The method first develops physically based quality curves for instream water use for multiple sections along a river reach of interest as a function of instream flow. Morphological changes that affect depth and velocity and their effects on instream use quality are considered. Using these curves, instream use quality is estimated for each section, and categorized as acceptable, good, or optimal, based on predefined thresholds. Thus, the adopted metric represents potential rather than actual instream use. In addition, the opportunity cost for instream water is derived from the marginal opportunity costs of rival offstream water uses. We demonstrate our method using Chile's Maipo River as a case study, where instream recreation competes with a run-of-river, bypass hydropower project.

Chile's Water Code and Maipo River

Chile's Water Code was established in 1981 and recognizes water rights for consumptive and nonconsumptive offstream uses (Bauer 2004). However, interest in instream water uses has increased in the last two decades, and Universidad Austral de Chile (2000) developed a survey of instream water uses for the General Water Directorate (DGA). The 2005 reform of the Water Code established minimum environmental flows when new water rights are requested. Environmental impact assessments can further restrict water use by imposing higher minimum flows than those established by DGA. On the other hand, in an attempt to prevent speculation with water rights, the 2005 reform introduced a so-called nonuse payment imposed on water right holders if water is not diverted from the source. This instrument limits the possibility to maintain instream flows by purchasing rights in water markets.

The 2005 reform also introduced reserve flows, under which the state can deny a water right request even if enough water is available when (1) no alternative water source exists for drinking water supply for a community or (2) in exceptional circumstances when a nonconsumptive water right request conflicts with the national interest. The figure of reserve flows represents an opportunity for water allocation to offstream uses, particularly tourism and recreation. In this context, Aquaterra Ingenieros Limitada (2010) studied reserve flows for tourism for the DGA.

The Maipo River in central Chile is 250 km from headwaters to its outlet in the Pacific Ocean. The headwaters originate from the west slope of Maipo Volcano in the Andes Mountains at an elevation of 5,264 m. Climate in the watershed is montane-Mediterranean, with a pronounced wet season from April to October and a dry season from November to March. Snow level is approximately 4,500 m, and snowmelt makes up a considerable portion of streamflow in spring months. The Maipo River is 50 km southeast of Santiago, Chile's capital, and representative of water-scarce regions because there are multiple and competing water uses (Cai et al. 2006). Rosegrant et al. (2000) developed an integrated economic–hydrologic water model for the basin and evaluated demand management instruments, including water markets for agricultural, industrial and municipal water uses. More recently, Vicuña et al. (2018) explored water option contracts to maintain urban water reliability as a climate-change adaptation in the Maipo basin.

The 531-MW Alto Maipo Hydroelectric Project (AMHP) is currently under construction, with average expected power generation of 2,350 GWh/year (Baranao and Prácticas 2014). Water is diverted from run-of-river hydropower bypasses, reducing streamflow for whitewater kayaking and rafting for 34 km (Fig. 1). As a run-of-river plant without reservoir storage capacity, the AMHP informs the power system operator of its expected hourly power generation for planning purposes. This estimation typically considers some degree of subdaily peaking, taking advantage of the limited and short-term storage given by tunnels and penstocks (Haas et al. 2013). Nevertheless, water diversions at the intakes are fairly stable during the day. Downstream of the Alto Maipo Hydroelectric Project, the Maipo River and major tributaries are the primary urban and agricultural water supply for the Santiago metropolitan area (Cai et al. 2006).

Instream water uses for recreation include kayaking and rafting in the Maipo River, which varies from Class III to V+ rapids depending on river section and water level (Ocampo-Melgar et al. 2016). Numerous commercial rafting companies and private boaters use the river year-round, although the high season is September–April, when rafting companies schedule three trips per day (AES Gener 2012). Generally, boatable reaches are separated into three runs, the Class IV/V+ upper section, the Class IV/V middle section, and the Class III/IV lower section. The Maipo River is the most popular rafting and kayaking river in central Chile (International Rafting Federation 2015), with more than 2 million

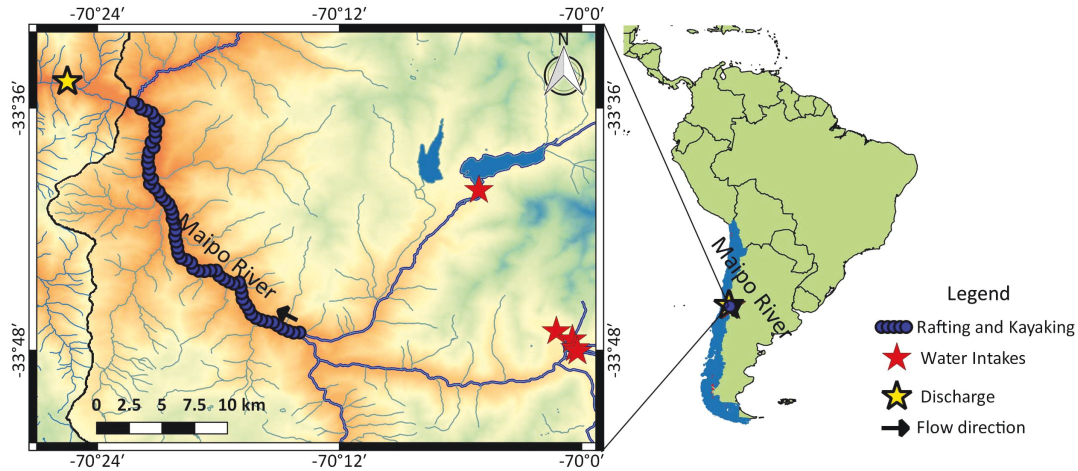

Fig. 1. Maipo River study region and Alto Maipo Hydroelectric Project intakes and return.

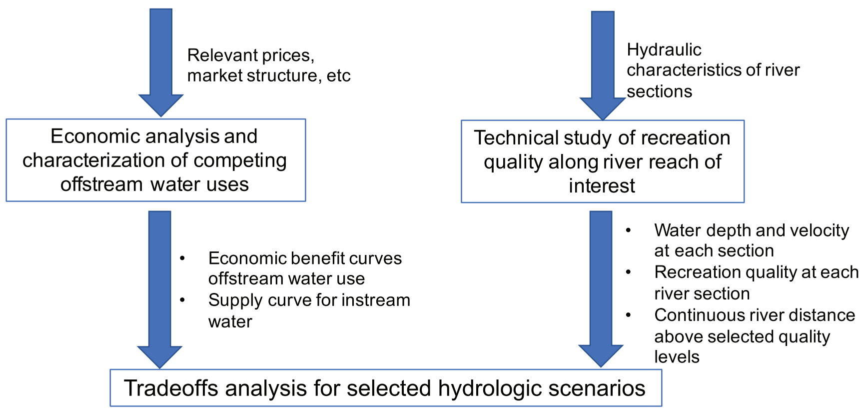

Fig. 2. Data and model flow of instream flow valuation for river recreation and trade-offs between instream and offstream water uses.

people visiting the river each year (Kayak River Stewards of Chile 2018) and approximately 2,900 people rafting per month (AES Gener 2012). Thus, the Maipo River provides recreational opportunities for the 6 million people in Santiago. Information on willingness to pay for rafting and kayaking in the Maipo River is unavailable. Commercial rafting companies, tourist businesses, and environmental groups have mounted opposition to the Alto Maipo Hydroelectric Project because it threatens streamflows for recreation and the environment (Bauer 2016). Defining the dynamic economic value of whitewater recreation is a first step in bringing hydropower, boaters, and other stakeholders to the table for negotiation.

As part of AMHP's Environmental Impact Assessment process, environmental flows on the order of 1 m^3/s were established based on fish habitat criteria, and verified for rafting (AES Gener 2008). The study assumed that rafting could take place in river sections at least 60 cm deep and 12 m wide. These conditions were checked for five sections along the reach where rafting currently takes place. Interestingly, the river reach of interest for rafting receives significant intermediate tributaries, and therefore some limited rafting opportunities exist regardless of the allocation to AMHP. Thus, extra allocation to instream water uses have the potential to improve recreation opportunities in the area.

Methods

Fig. 2 shows the data and model flow, with steps further described in this section. For a given streamflow, whitewater rafting and kayaking potential is measured as maximum continuous distance (MCD), measured in kilometers, with acceptable, good, or optimal boating conditions. Our method considers only offstream uses that compete with whitewater recreation. For example, we consider the longitudinal distance for recreation between diversions and return flows of hydropower bypasses (Fig. 3). We calculate the opportunity cost of offstream uses when water is allocated to instream recreation instead. Then we evaluate trade-offs between instream and offstream water uses to illustrate our method for water managers and stakeholders to prioritize efficient water allocations and facilitate decision making.

Instream Benefits as Function of Instream Flow

We estimate the benefit of instream uses, in this case whitewater river rafting, as a function of flow for the length of boatable reaches. This approach advances methods of valuing instream water uses without explicitly completing economic analysis to derive economic benefit curves of instream water uses. Specifically, this step

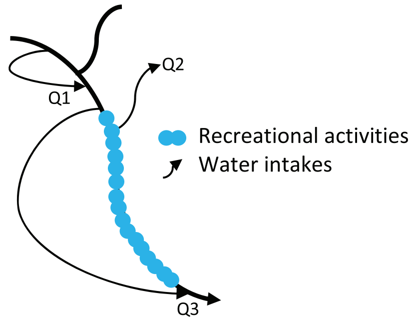

Fig. 3. Conceptual model of consumptive and nonconsumptive offstream water diversions, in which Q2 and Q3 diversions conflict with recreational activities, but Q1 diversion does not conflict.

consists of three main tasks: (1) evaluating recreation benefit as a function of depth and velocity, (2) describing the relationship between discharge and hydraulic river attributes (depth and velocity) for each river section, and (3) estimating whitewater recreation benefit as a function of instream flow for the length of boatable reaches (Fig. 2).

A given streamflow will present different hydraulic characteristics, and thus whitewater recreation quality, depending on channel morphology and river section. For a method applicable to any river with recreational activities, it is necessary to assume that whitewater recreation quality can be derived from hydraulic variables (velocity and depth) (Hyra 1978). Streamflow data and cross-section geometry at multiple river sections are needed to estimate velocity, depth, and width from hydraulic models, such as the Hydrologic Engineering Center's River Analysis System (HEC-RAS version 3.1.3). The hydraulic variables for whitewater recreation proposed by Hyra (1978) and Mosley (1983) have been applied in recent studies using habitat suitability analyses to estimate recreational flows, demonstrating the approach (King et al. 2000; AES Gener 2008; Aquaterra Ingenieros Limitada 2010; De Vincenzo and Molino 2013; Chávez-Jiménez and González-Zeas 2015; Gobierno de Chile 2016; Carolli et al. 2017).

Recreation quality depends on minimum, maximum, and optimal water depth and velocity, and is represented on a scale of 1 to 5 (Table 1) following Shelby et al. (1992) and Whittaker and Shelby (2002), who studied the relationship between flow and recreation quality using unacceptable, acceptable, and optimal ranges. Levels 1 and 2 indicate unsatisfactory conditions, when whitewater rafting is not possible. Level 3 indicates acceptable conditions, near the minimum or maximum depth and/or velocity for recreation use. Level 4 indicates satisfactory or good conditions, and Level 5 indicates optimal depth and velocity for whitewater recreation. Thus, the lower (and upper) limit to guarantee that recreational activities occur is represented by Level 3. Specific cross-section velocities and depths for minimum, maximum, and optimal rafting and kayaking levels for rivers generally are available (Hyra 1978; Mosley 1983; USACH 2016) (Table 1).

To estimate recreation quality as a function of depth and velocity, a number of assumptions were made. First, we assumed a linear relationship between recreation quality and depth or velocity based on Hyra (1978), who assumed a linear relation of recreation quality and surface area (obtained from depth and velocity data). Second, negligible depths and velocities were assumed to be unsatisfactory for recreation. Third, the maximum water depth for kayaking and rafting was unavailable (Hyra 1978; Mosley 1983), so we assumed that recreation quality is acceptable for all depths over 2 m

Table 1. Flow requirements for kayaking and rafting

Water requirements	Unsatisfactory thresholds (Level <3)	Minimum thresholds (Level 3, acceptable)	Optimal thresholds (Level 5)	Maximum thresholds (Level 3, acceptable)
D (m)	0–0.8[a]	0.8[a]	1.5–1.75[a,b]	>2
V (m/s)	0–0.5[a] and >4.5[b,c]	0.5[a]	1.0–3.0[b,c]	4.5[b,c]

Note: D = depth; and V = velocity.
[a]Data from USACH (2016).
[b]Data from Mosley (1983).
[c]Data from Hyra (1978).

(Table 1), because deep water typically does not limit whitewater recreation.

For a robust estimation of whitewater recreation quality throughout a river, we recommend using a representative number of river cross sections. We modeled velocity and depth hydraulic attributes for different flow magnitudes using HEC-RAS. Inputs to HEC-RAS were streamflow and cross-section geometry. HEC-RAS results were water velocities and depths to provide whitewater recreation quality and range at different flow levels.

Recreation quality, as a function of instream flow, was estimated as the minimum recreation benefit from water depth or velocity for every section of the river. To represent recreation quality as a function of flow throughout the river, our method introduces three indicators to integrate the results obtained for each section of the river. For each modeled flow level, we quantified

1. The lowest recreation benefit for each section of river. This indicator considers that there is not just one critical section (defined as the river section with the lowest recreation quality), but different flows result in different critical sections.
2. The percentage of river with acceptable recreation conditions (Level 3 and above).
3. The MCD of river with acceptable, good, and optimal recreation conditions. This is obtained by adding all river sections for acceptable, good, and optimal recreation conditions, then identifying the longest continuous reach. This last indicator assumes that between two sections with acceptable rafting conditions, the reach that joins them also has acceptable conditions.

These three indicators are not limited to one critical section, because recreation quality for different sections varies by flows. This is a contribution of our approach over earlier studies (Hyra 1978; Mosley 1983). For the Maipo River case study, we focused on the third indicator because it is integral for recreation activities that require continuity of the river, such as whitewater rafting and other navigation-based activities.

Supply Curve of Instream Water Uses

Supply curves for manufactured goods are defined by the marginal costs of production. Here, we use the opportunity cost of not diverting water for offstream uses to estimate the supply curve of instream water. In other words, the cost of recreational instream water is calculated as lost economic benefit from diverting less water for offstream uses. Therefore, the supply curve of instream water use corresponds to the marginal opportunity cost derived from the benefit curve of offstream water uses. Consequently, the economic benefit curve of offstream water use, as a function of diverted flow, is the basic economic information required by the method. Then, the marginal benefit curve is constructed for all feasible offstream flow levels, ranging from zero (no water is diverted)

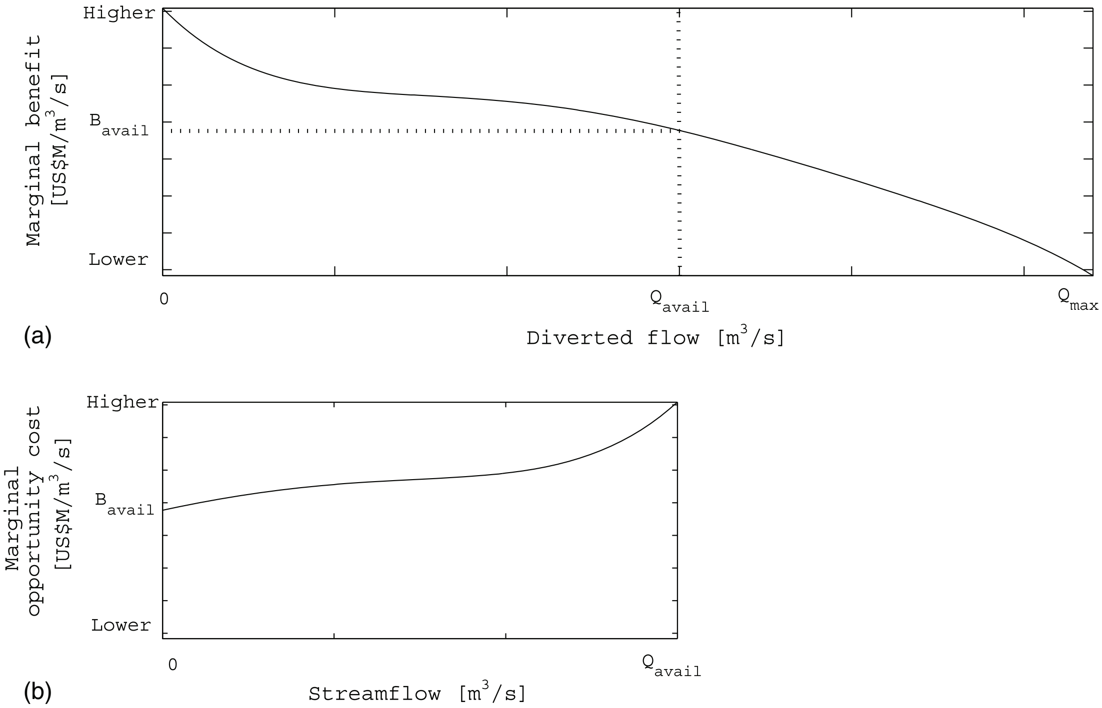

Fig. 4. (a) Conceptual marginal benefit of offstream water use; and (b) corresponding supply curve of instream water. $Q_{\max}$ = maximum turbine capacity (m^3/s); Q_{avail} = available water (m^3/s); and B_{avail} = marginal benefit at available water (million US$/m^3/s$).

to the maximum beneficial diversion [Fig. 4(a)]. In practice, only the portion of this curve up to the total available flow is relevant.

The supply curve of instream water is then obtained by truncating the marginal benefit curve at the available flow to be allocated to both uses, and switching the direction of the vertical axis [Fig. 4(b)]. The offstream opportunity cost and marginal benefit of offstream use curves are constructed for all possible water diversions for each month [Fig. 4(b)].

Marginal Economic Benefit of Offstream Water Uses

Economic benefits of offstream water use are commonly a part of hydroeconomic models (Harou et al. 2009), including urban, industrial, agricultural, and domestic use. For the example application, the economic benefit of offstream hydroelectricity was estimated using a method developed by Olivares and Lund (2012), which incorporates hourly price variability into revenue functions of hydroelectric projects. The method has two assumptions. First, hydropower generation takes place during hours when energy prices are highest. Second, turbines always generate at maximum capacity for a proportion of hours during the day equal to the ratio of the average monthly turbine flow to the maximum flow capacity of the plant. Considering the equations proposed by Olivares and Lund (2012), the economic benefit (B) of the hydroelectric project can be calculated as $B(C, f_v, h) = E_v \cdot \bar{P}(f_v)$, where C is the plant's flow capacity; f_v is the proportion of hours of operation (at full capacity), obtained as the quotient between release flow and the plant's flow capacity; h is the head; E_v is total energy that can be generated with a volume, V, of releases at constant head h; $\bar{P}(f_v)$ is the moving average of all prices exceeding $P(f_v)$; and $P(f_v)$ is the price duration curve (Fig. 5). Finally, the marginal benefit of offstream hydropower generation is estimated by taking the first derivative of the benefit function with respect to diverted flow.

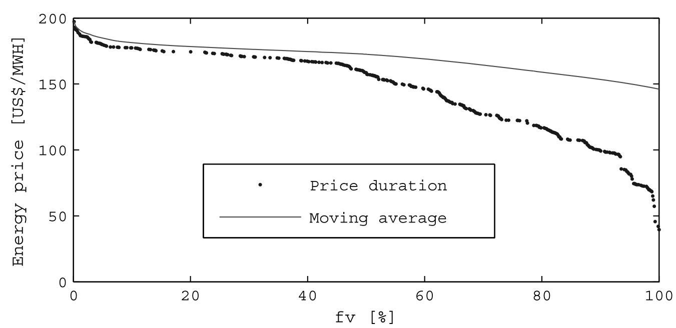

Fig. 5. Price duration curve and corresponding moving average for March.

Trade-Offs between Instream and Offstream Water Uses

Our method can identify alternative efficient water allocations between instream uses for recreation and offstream use. Offstream use potential—represented by the MCD with acceptable conditions for whitewater recreation—is compared with the corresponding opportunity cost of offstream use, in this case, hydropower. We combine the benefit curve of recreation (MCD) with the supply curve of instream water, both as a function of instream flow, to graphically identify efficient allocations of monthly mean streamflow. Adopting a Pareto efficiency criterion (Pareto 1896), efficient allocations are such that the instream use objective cannot be improved without reducing the offstream use benefit, and vice versa. As a result, our method identifies multiple optimal solutions for each month and each scenario, as do all multiobjective models (Cohon 2013).

Scenarios

Water management decisions, such as the allocation of water for instream or offstream uses, are typically based on water year–type designations (Null and Viers 2013; Rheinheimer et al. 2016; Null and Prudencio 2016). We define four scenarios, evaluated at a monthly time step, for a 30-year timeframe. Two scenarios represent normal and dry year types, providing monthly flows for 50% and 85% exceedance probabilities of average annual flow. Two additional scenarios represent normal and dry months using 50% and 85% exceedance probabilities of monthly flow frequency analysis. Hydropower operators care about this distinction because energy prices and operation rules vary depending on dry and normal month and year hydrologic conditions.

Results

Recreation Quality and Continuity as Function of Flow

River velocity, depth, and discharge for the Maipo River were available for 113 cross sections, spaced uniformly approximately every 300 m (AES Gener 2013). Fig. 6 shows examples of rafting and kayaking benefit curves for two of the 113 sections of the Maipo River (other sections had similar curves). These curves highlight the flow ranges with acceptable conditions for kayaking and rafting (above recreation benefit Level 3), and a smaller range of flows with optimal whitewater boating conditions (Level 5). Conditions above the segmented horizontal line support recreation, whereas conditions below are unsatisfactory. Different recreation benefit levels may exist in different river sections with the same streamflow due to the dependence of recreation benefit level on depth and velocity. Fig. 6 also illustrates recreation benefit levels for actual minimum instream flows (MIFs) imposed on the Alto Maipo Project as a result of the Environmental Impact Assessment (points on Fig. 6). MIFs are shown for 4 months in normal years and 4 months in dry years. Results show that MIFs in March and April during dry years provide acceptable recreational conditions in Section A, but unsatisfactory conditions in Section B. MIFs never provide optimal boating conditions, represented by a benefit level of 5.

Benefit curves of whitewater boating as a function of flow were constructed using recreation benefit levels for all 113 sections of the Maipo River. Rafting and kayaking require continuously suitable reaches, defined by a set of adjacent sections with suitable conditions for recreation. Because a given streamflow can define several continuous reaches with suitable conditions, the longest such reach represents the MCD. Fig. 7 shows the maximum continuous river distance that is available for rafting and kayaking at different flows and recreation benefit levels. Overall, flows exceeding 57 m^3/s provide fully connected, acceptable whitewater boating reaches in the Maipo River, whereas lower flows reduce whitewater recreation connectivity.

For acceptable boating conditions, there were large reductions in the continuous distance of whitewater recreation at some flow levels. For example, at approximately 40 m^3/s, kayaking and rafting was reduced by over 10 km (Fig. 7). In addition, the MCD with acceptable boating conditions always increased or remained equal with increasing flows. This is because sections that contribute to the MCD never had flows that exceeded the maximum thresholds for recreation. Fig. 7 also shows the maximum continuous river distance with good (Level 4) and optimal boating conditions (Level 5). However, for good and optimal boating recreation conditions, more flow does not always necessarily increase the connected length of kayaking and rafting runs, and may decrease connected distance. Increasing streamflow sometimes exceeded the maximum boating thresholds (Table 1), causing recreation benefit condition to drop to

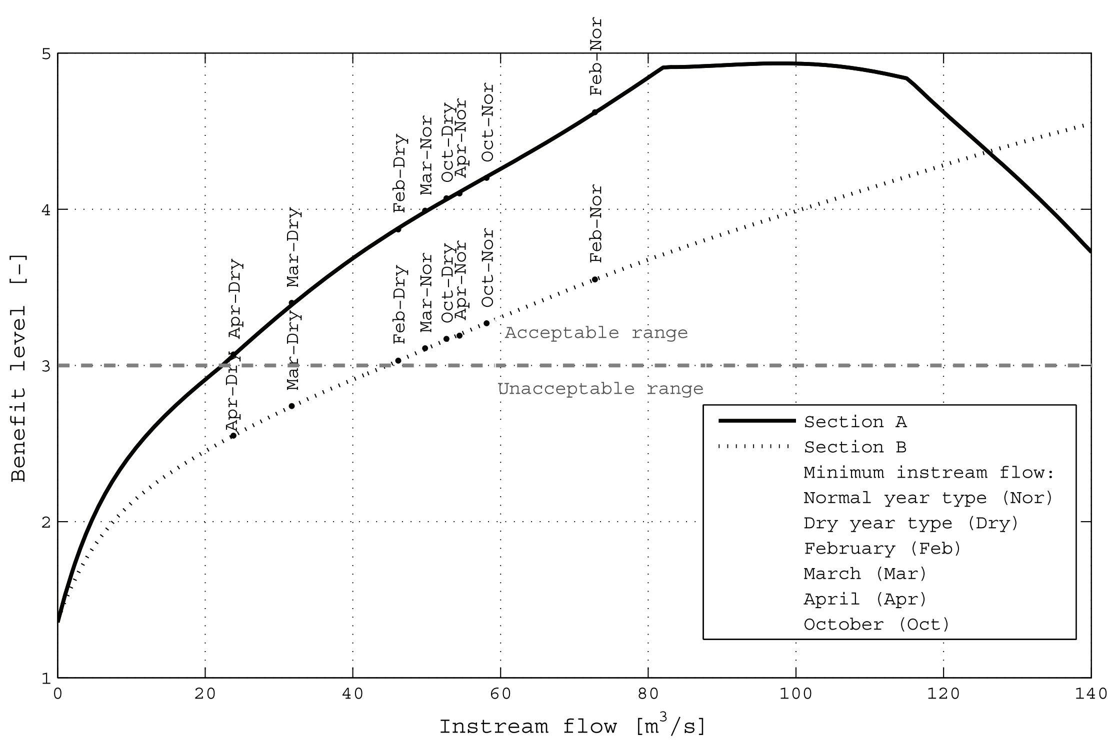

Fig. 6. Rafting and kayaking benefit curve for 2 of 113 sections of Maipo River, and minimum instream flows during February, March, April, and October for normal and dry years.

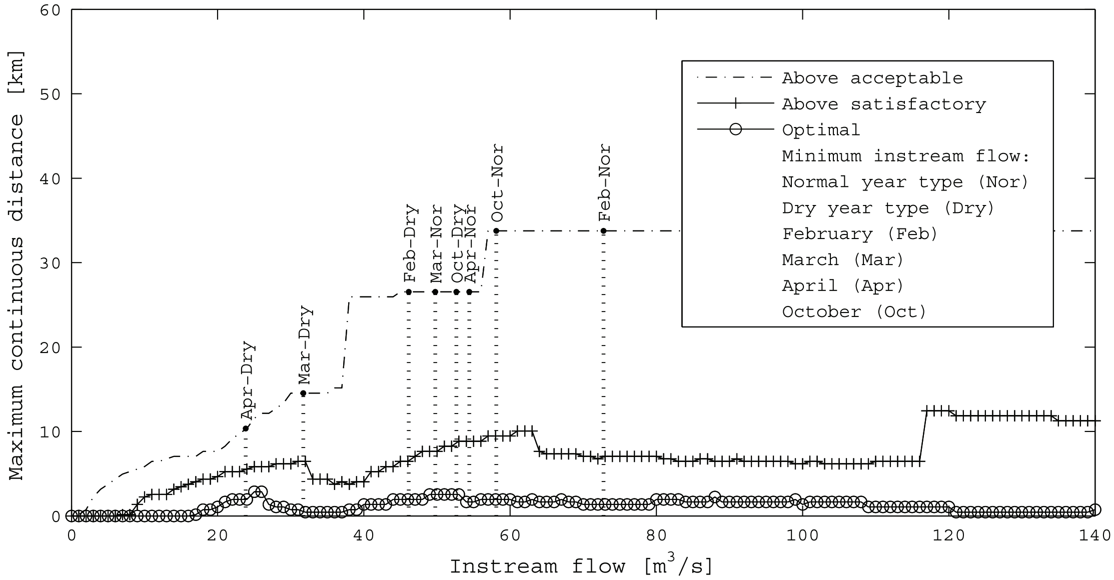

Fig. 7. Benefit curve of continuous distance available for rafting and kayaking in Maipo River with acceptable or higher recreation quality, and MIFs during February, March, April, and October for normal and dry years.

a lower level (e.g., into the acceptable range) at some sections, therefore reducing the continuous distance.

Fig. 7 includes MIF levels as points to illustrate maximum continuous boatable distance they provide as instream flow water allocation. October and February MIFs in normal years allow for fully connected rafting, although MIFs of other normal year months reduce the length of acceptable boating conditions by about 10 km, as do MIFs in February and October of dry years. MIFs in March and April of dry years produce less than 15 km of continuous distance with acceptable conditions for kayaking and rafting.

We also visualized continuous boating distance for each recreation benefit level (acceptable, good, and optimal conditions) as maps to highlight results from this approach (Fig. 8). With streamflows of 32 m^3/s, three unconnected reaches have acceptable conditions. The largest reach in the center corresponds to the MCD with acceptable boating conditions (14.6 km) in Fig. 7. Two additional but unconnected reaches with acceptable boating conditions are upstream and downstream. Interspersed in the boating reach with acceptable conditions are sections with good and optimal boating quality. These sections are connected by acceptable recreation conditions, and thus are boatable, although the total distance of good boating is 6.5 km and that of optimal boating is 0.5 km at this streamflow level.

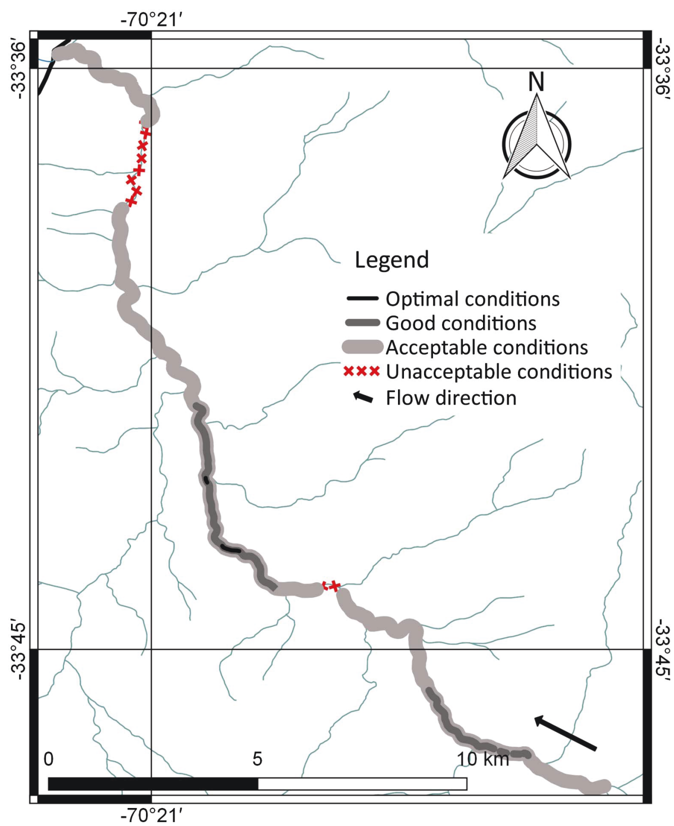

Fig. 8. Rafting and kayaking conditions throughout Maipo River for flow of 32 m^3/s. Maximum continuous distance with acceptable conditions = 14.55 m; maximum continuous distance with good conditions = 6.45 km; and maximum continuous distance with optimal conditions = 0.45 km.

Combining Recreation Benefits with Marginal Opportunity Costs

Once we estimated monthly mean flow diversions and monthly mean instream flow in the Maipo River, we calculated the instream water supply curve for wet and normal years, and wet and normal months. Fig. 9 shows an example of the instream water supply curve (marginal opportunity costs) and continuous whitewater recreation distance for spatially aggregated representative dry- and normal-year March streamflows. We found all possible noninferior solutions for dry and normal years—in other words, solutions that maintain continuous recreation benefits at the lowest opportunity cost. For example, a normal water year in Fig. 9(a) has two non-inferior solutions. The first maintains monthly mean flows of 50 m^3/s for 26.6 km of boatable river, with a total opportunity cost of zero. The second solution maintains instream flow at approximately 57 m^3/s for a 34-km boatable reach, with a marginal opportunity cost of approximately US$1.29 million per m^3/s. The total opportunity cost is US$8.67 million from the integral of the

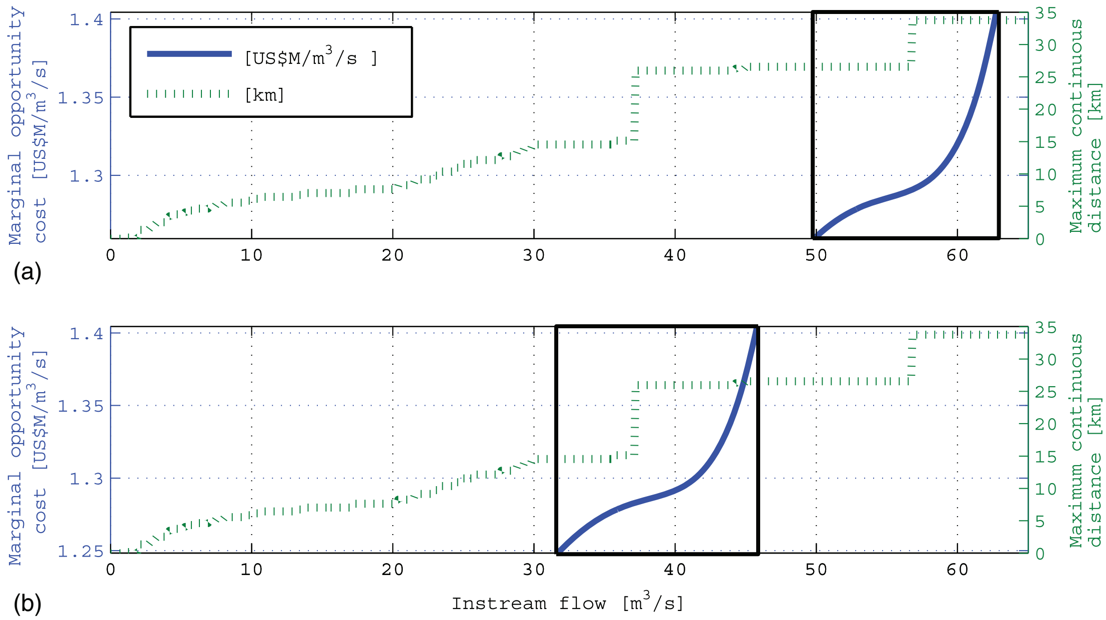

Fig. 9. Instream supply curve and continuous rafting and kayaking distance during March in (a) normal water year (63 m^3/s); and (b) dry water year (46 m^3/s). Range of hydropower diversions for each water year type is shown in box.

area under the streamflow supply curve. Streamflows exceeding 57 m^3/s have higher opportunity costs from foregone hydropower generation, but do not extend the distance at which conditions for rafting and kayaking are acceptable [Fig. 9(a)]. Water availability, and thus instream flows, are reduced in dry years, so that instream flows of 31.7 m^3/s provide 14.6 km of connected boatable conditions at a total opportunity cost of zero. There is a minor increase in connected rafting and kayaking distance near 36 m^3/s [Fig. 9(b)]. There is larger gain in connected boatable conditions, with another optimal solution at 37.2 m^3/s for a 26-km boatable reach, costing approximately US$1.28 million per m^3/s at the margin and approximately US$6.5 million in total. Increasing streamflows above 37.2 m^3/s does not lead to longer reaches for instream recreation in dry years.

Trade-Off Analyses

Fig. 10 illustrates trade-offs between instream uses for rafting and kayaking and offstream uses for hydropower generation for dry and normal years and dry and normal months. For simplicity, we show only 3 months in summer and fall (February–April) and 1 month in spring (October) when conflicts between instream and offstream water uses exist (SEIA 2008). For each scenario and month, all possible efficient solutions are included. Each solution suggests a MCD with acceptable and good river recreation conditions, and the respective opportunity cost of lost hydropower from the Alto Maipo Hydroelectric Project. The four scenarios present very different solutions because streamflow in the Maipo River differs significantly depending on dry or normal year and month types, and energy price varies by month. Dry years and months have more solutions compared with normal years and months. This is because water is scarcer, so conflicts between instream and offstream water uses are common. For example, Fig. 10 shows that normal years have two or fewer optimal solutions and normal months have less than three solutions for every month shown. For normal years, one solution always maintains the entire 34-km whitewater recreation distance (the maximum possible) with acceptable conditions and 10 km of whitewater recreation with good conditions.

In normal years, February and October have opportunity costs of zero to maintain the 34 km of whitewater recreation distance with acceptable conditions and 9.5 km with good conditions, because there is enough water to meet hydroelectric project and recreation demands. In normal months, it is possible to maintain the same distance with acceptable and good conditions at an opportunity cost of zero during February and at an opportunity cost of US$240,000 during October. However, in March and April, normal-year opportunity costs of the hydroelectric project are US$8.67 million and US$2.41 million, respectively, to connect and maintain 34 km for whitewater recreation with acceptable conditions and 9.5 km with good conditions. For normal months in March, there is an opportunity cost of zero to maintain the whole whitewater recreation reach with acceptable conditions and 9.5 km with good conditions, and for April it is only possible to maintain 26 km for rafting with acceptable conditions and 9.5 km with good conditions at an opportunity cost of zero.

On the other hand, for dry years and months there are always opportunity costs to maintain connected suitable recreation conditions. February and October are less critical months because it is possible to maintain 26.6 and 6.5 km of acceptable and good conditions for whitewater recreation, respectively, at no cost. However, to maintain 34 and 9.5 km of acceptable and good conditions, respectively, for rafting and kayaking during February in a dry year or dry month, opportunity costs increase to US$11.15 million and US$10.08 million, respectively. During October in a dry year and dry month, opportunity costs are US$1.2 million and US$0.24 million, respectively, to maintain the entire 34-km reach with acceptable boating conditions. Opportunity costs are lower in October than other months because energy prices during October are lower. For March and April, several noninferior, Pareto-optimal allocations exist. The maximum river length with acceptable conditions for recreation during March in a dry year is 26.6 km, at an opportunity cost of US$16.6 million, and is 14.6 km for April of a dry year, at an opportunity cost of US$7.1 million. The maximum

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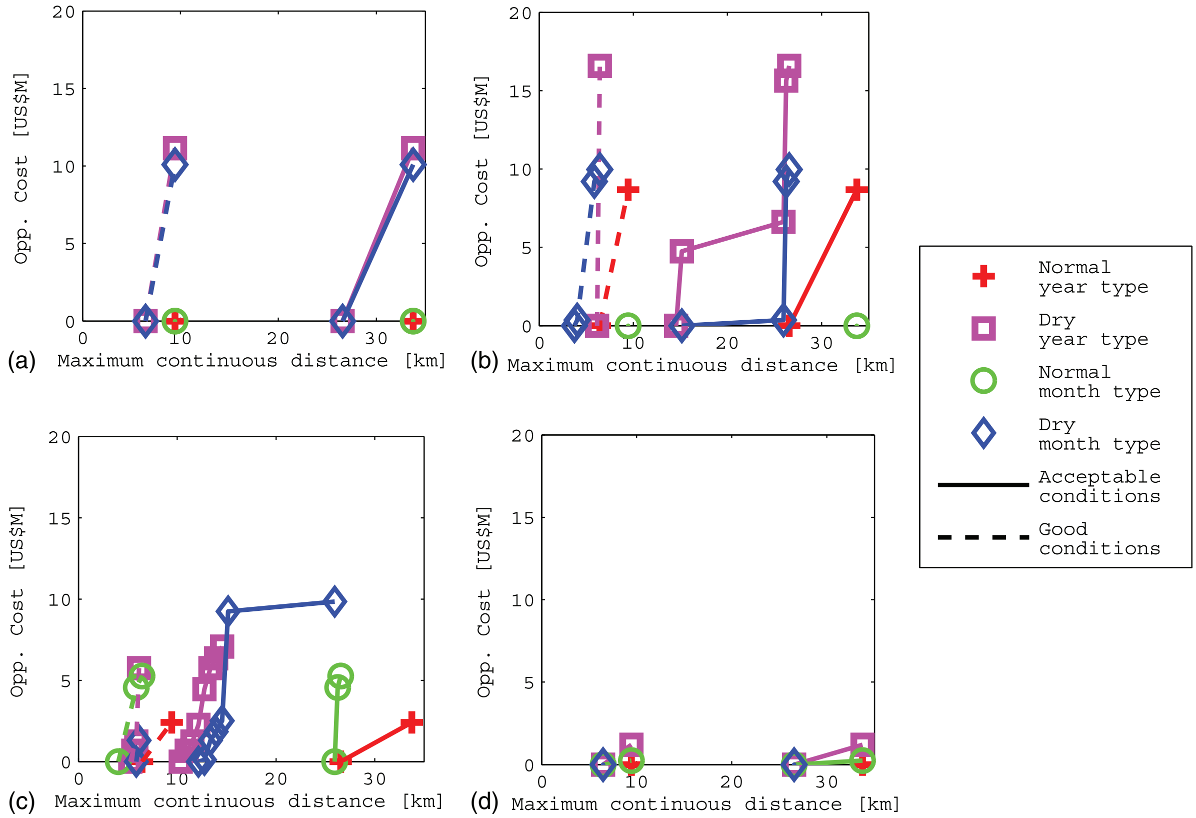

Fig. 10. Potential allocations (points) between opportunity costs of hydropower (million US dollars) and continuous distance of recreation with acceptable and good conditions (kilometers) for wet and dry months and wet and dry years during: (a) February; (b) March; (c) April; and (d) October.

river length with good conditions for recreation during March and April in a dry year is 6.5 km for both months, at an opportunity cost of US$16.6 million and US$5.8 million, respectively. During March in a dry month, it is possible to keep a maximum of 26.6 km for acceptable whitewater recreation, at an opportunity cost of US$10 million. During April of a dry month, 26 km of acceptable whitewater recreation comes at an opportunity cost of US$9.8 million. The maximum river length with good conditions for recreation during March and April in a dry month is 6.5 km, at an opportunity cost of US$9.9 million, and 6.2 km, at an opportunity cost of US$1.3 million, respectively.

Discussion

Instream water uses typically lack water rights and have little influence in water markets and allocations, as is the case in Chile, although instream uses are greatly affected by offstream allocations and pricing mechanisms (Colby 1990). Welfare economics in water policy evaluates multiple, competing instream and offstream uses to identify market failures for more-efficient and equitable water allocations (Booker et al. 2012). However, in the absence of demand-side economic characterization of instream water use, a welfare-economics approach cannot be applied, and alternative approaches need to be adopted.

Pareto-efficient solutions identify allocations when it is not possible to improve the benefit for one use without harming the other. When benefits do not have the same measurement units, results must be interpreted as a set of equally optimal trade-offs which may be presented to managers or stakeholders of the conflicting uses to inform efficient decision making (Cohon 2013). Specifically, Pareto-efficient allocation of water may maintain reaches of adequate length for recreation, in this case adopted as a measure of instream use benefit, at the lowest cost of lost hydropower generation.

In the Maipo River, different flow levels alter rafting reach length, quality, and opportunity cost. Results show that, in this system, continuous distance with acceptable recreation quality is monotonic with flow. Additionally, the increase in distance is smooth for relatively low flows but exhibits abrupt changes for larger flows. Physically, this is explained by the fact that for large instream flows, several boatable reaches of significant length can be identified (Fig. 8), and the maximum distance does not increase substantially until two or more adjacent reaches merge into one longer reach once a given instream flow value is exceeded. This threshold effect is not the case for small instream flows, in which the maximum distance can be increased by even modest increases in flow. On the other hand, lengths of good- and optimal-quality recreation respond more erratically to flow changes, even decreasing for some flow ranges.

Regarding the trade-offs, as expected, there is increased competition when water is scarce. It is easier to satisfy instream and offstream water demands during normal year types and normal months when water is more abundant and competition for water between uses is thus reduced.

Interestingly, trade-offs between length of river recreation and opportunity costs of instream flows for multiple hydrologic scenarios have a greater number of Pareto-efficient solutions in dry years and months. The number of Pareto-optimal solutions identified for each case is given by the breaks or corner points in the curve of MCD as a function of instream flow over the relevant range defined by the marginal opportunity cost curve. The MCD curve has many more breaks for low values of instream flows, up to about 30 m^3/s (Fig. 9). For greater instream flows, a few corner points can be identified, defining relatively large instream flow ranges in which additional flow gives no additional value in terms of additional distance.

The opportunity costs of foregone hydropower generation that we developed indicate that the trade-off required to ensure a quality recreation experience in the Maipo River is between US$0 and US$16.6 million, depending on month (water availability and energy price) and hydrologic river condition (dry or normal month or year). In contrast, it costs about US$32 to raft with a commercial outfitter in Chile's Maipo River. Assuming that an average of 2,900 people raft the Maipo River per month (AES Gener 2012), nearly US$93,000 per month is generated by Maipo River recreation. This is certainly a lower-bound willingness to pay, and it very likely involves some economic surplus to the users. Additionally, private rafters and kayakers also use the Maipo River, and recent conflicts between the Alto Maipo Hydroelectric Project and tourist businesses, environmental groups, and rafting companies (Bauer 2016) suggest additional aesthetic value. Thus, our method for estimating instream opportunity cost trade-offs brackets the known lower-bound willingness to pay of whitewater recreation, although opportunity costs for maintaining rafting flows would likely not be incurred by whitewater boaters.

Our method has some limitations that could be improved upon in future research. First, flow and cost estimates are on a monthly scale, so submonthly variability is not considered. It is possible that the recreation quality estimated for each month may not be realized for all days during the month, although averages should remain unchanged. Additionally, the method we adopted to estimate benefits of hydropower production at a monthly time scale assumes significant peaking capacity in the power plant. For a run-of-the-river plant, storage capacity is limited to subdaily regulation within the system's tunnels and penstocks. Therefore, we likely overestimated hydropower benefits and therefore opportunity costs. Second, predicting future water-year types and drier-than-normal months was outside the scope of this research, although future climate and energy demand forecasts could be used as inputs with our method. Our scenarios represent perfect hydrologic foresight, and thus results identify best-case solutions. In the real world, management decisions about water allocations for offstream and instream uses are made with real-world hydrologic uncertainty, and thus may underestimate or overestimate instream flows and trade-offs with offstream water demands. Finally, the metric herein adopted as a proxy for recreation quality actually represents recreation potential rather than actual use. Many alternative metrics exist to quantify whitewater recreation quality, such as number of rapids; difficulty of rapids; river access; and number of boatable days, weeks, or months. These metrics could be incorporated into future instream recreation value research to add nuance to recreation quality.

Conclusions

This paper presents a method to identify multiple potential, noninferior water allocations for competing instream and offstream water uses in different hydrological scenarios. The method is applicable to rivers where conflicts exist between economically valued offstream uses and noneconomically valued instream water uses. The approach combines an economic analysis to determine the opportunity cost of allocation to instream uses, with a technical analysis of potential instream recreation.

We applied our method to Chile's Maipo River to estimate the supply curve of streamflow for whitewater recreation (rafting and kayaking) and the offstream opportunity costs of hydropower generation. Conflicts exist between these two uses. We estimated recreation benefit as a function of streamflow for continuous reaches to guarantee that conditions for navigational recreation, such as rafting and kayaking, are acceptable. Our method estimates the opportunity costs of maintaining specific reach lengths and river recreation qualities based on reduced water diversions that conflict with recreation. We focused on recreation quality benefits by considering river morphology and how hydraulic characteristics change with streamflow. This implies that there is no single critical section in the river; rather, connectivity of acceptable recreation quality is desired. Results show that the opportunity cost of additional boatable reaches is sensitive to both drought and energy price. The cost of maintaining 34 km, as opposed to 26.6 km, of continuous boatable river is US$10 million in dry years, when energy prices are high, and $240,000 in normal years, when energy prices are low.

Our method is appropriate for places such as Chile, where water rights are allocated to offstream human water uses but instream uses are incipiently considered in water allocation by alternative instruments such as minimum instream flows or reserve flows. In other regions, this method could be applied to evaluate trade-offs for instream ecology, for example, where migratory species or metapopulations require connected aquatic habitats. Overall, the proposed approach and the results for the case study highlight promising policies to increase equity and efficiency between instream and offstream uses. In places where water rights are allocated to instream uses, the approach could incentivize water reallocation through water rights transfers or environmental water accounts.

References

AES Gener. 2008. "Actualización estudio de caudal ecológico proyecto hidroeléctrico hlto maipo (PHAM)." Accessed April 10, 2016. https://www.e-seia.cl/archivos/20081112.181332.rar.

AES Gener. 2012. "Seguimiento ambiental de proyecto hidroeléctrico alto maipo. Programa de monitoreo de indicadores sociales." Accessed April 12, 2016. http://www.altomaipo.com/Descargas/Documents/e577288406a39d694a58990da1f b91f1.pdf.

AES Gener. 2013. "Informe técnico del caudal ecológico del proyecto hidroeléctrico alto maipo." Accessed April 12, 2016. https://ewsdata.rightsindevelopment.org/files/documents/67/IADB-CHL1067_ 0FA8iVI.pdf.

Aquaterra Ingenieros Limitada. 2010. "Análisis de metodología y determinación de caudales de reserva turísticos. For Gobierno de Chile, Ministerio de obras públicas." Accessed March 30, 2016. http://documentos.dga.cl/ADM5269v1.pdf.

Baranao, P., and M. Prácticas. 2014. "Cumulative impact assessment—Alto maipo hydropower." In *Proc., 34th Annual Conf. of the Int. Association for Impact Assessment Conf.* Fargo, ND: International Association for Impact Assessment.

Bauer, C. J. 2004. "Results of Chilean water markets: Empirical research since 1990." *Water Resour. Res.* 40 (9): 1–15. https://doi.org/10.1029/2003WR002838.

Bauer, C. J. 2016. *The evolving water market in Chile's Maipo River Basin: A case study for the political economy of water markets project*. A report for the Rockefeller Foundation. Accessed December 10, 2017. https://static1.squarespace.com/static/56d1e36d59827e6585c0b336/t/5805460515d5dbb1ab599b91/1476740618944/Chile-Maipo-Bauer.pdf.

Birol, E., K. Karousakis, and P. Koundouri. 2006. "Using economic valuation techniques to inform water resources management: A survey and critical appraisal of available techniques and an application." *Sci. Total Environ.* 365 (1): 105–122. https://doi.org/10.1016/j.scitotenv.2006.02.032.

J. Water Resour. Plann. Manage., 2019, 145(3): 04018101

Booker, J. F., R. E. Howitt, A. M. Michelsen, and R. A. Young. 2012. "Economics and the modeling of water resources and policies." *Natural Resour. Modell.* 25 (1): 168–218. https://doi.org/10.1111/j.1939-7445.2011.00105.x.

Cai, X., D. C. McKinney, and L. S. Lasdon. 2003. "Integrated hydrologic-agronomic-economic model for river basin management." *J. Water Resour. Plann. Manage.* 129 (1): 4–17. https://doi.org/10.1061/(ASCE)0733-9496(2003)129:1(4).

Cai, X., C. Ringler, and M. W. Rosegrant. 2006. *Modeling water resources management at the basin level: Methodology and application to the Maipo River Basin*. Rep. No. 149. Washington, DC: International Food Policy Research Institute.

Cardwell, H., H. I. Jager, and M. J. Sale. 1996. "Designing instream flows to satisfy fish and human water needs." *J. Water Resour. Plann. Manage.* 122 (5): 356–363. https://doi.org/10.1061/(ASCE)0733-9496(1996)122:5(356).

Carlisle, D. M., D. M. Wolock, and M. R. Meador. 2011. "Alteration of streamflow magnitudes and potential ecological consequences: A multi-regional assessment." *Front. Ecol. Environ.* 9 (5): 264–270. https://doi.org/10.1890/100053.

Carolli, M., G. Zolezzi, D. Geneletti, A. Siviglia, F. Carolli, and O. Cainelli. 2017. "Modelling white-water rafting suitability in a hydropower regulated Alpine River." *Sci. Total Environ.* 579: 1035–1049. https://doi.org/10.1016/j.scitotenv.2016.11.049.

Chávez-Jiménez, A., and D. González-Zeas. 2015. "El impacto de los caudales medioambientales en la satisfacción de la demanda de agua bajo escenarios de cambio climático." *RIBAGUA-Revista Iberoamericana del Agua* 2 (1): 3–13. https://doi.org/10.1016/j.riba.2015.04.001.

Cohon, J. L. 2004. *Multiobjective programming and planning*. Mineola, NY: Dover Publications.

Colby, B. G. 1990. "Enhancing instream flow benefits in an era of water marketing." *Water Resour. Res.* 26 (6): 1113–1120. https://doi.org/10.1029/WR026i006p01113.

Daubert, J. T., and R. A. Young. 1981. "Recreational demands for maintaining instream flows: A contingent valuation approach." *Am. J. Agric. Econ.* 63 (4): 666–676. https://doi.org/10.2307/1241209.

De Vincenzo, A., and B. Molino. 2013. "The rehabilitation of a reservoir: A new methodological approach for calculating the sustainable useful storage capacity." *Agric. Sci.* 4 (08): 46. https://doi.org/10.4236/as.2013.48A007.

Draper, A. J., M. W. Jenkins, K. W. Kirby, J. R. Lund, and R. E. Howitt. 2003. "Economic-engineering optimization for California water management." *J. Water Resour. Plann. Manage.* 129 (3): 155–164. https://doi.org/10.1061/(ASCE)0733-9496(2003)129:3(155).

Gobierno de Chile. 2016. "Guia metodológica para determinar el caudal ambiental para centrales hidroeléctricas en el Seia." Accessed March 5, 2018. http://www.sea.gob.cl/sites/default/files/imce/archivos/2016/08/guia_caudal_ambiental_0.pdf.

Haas, J., M. Olivares, R. Palma, and A. Quintero. 2013. "Efectos económicos de la modelación de los estanques de regulación de hidroeléctricas de pasada en el predespacho del SIC (Economic effects of modeling regulation tanks of run-of-river hydropower plants in Chile's unit commitment)." In *Chilean Congress of Hydraulic Engineering*. Santiago, Chile: Chilean Society of Hydraulic Engineering.

Harou, J. J., M. Pulido-Velazquez, D. E. Rosenberg, J. Medellín-Azuara, J. R. Lund, and R. E. Howitt. 2009. "Hydro-economic models: Concepts, design, applications, and future prospects." *J. Hydrol.* 375 (3–4): 627–643. https://doi.org/10.1016/j.jhydrol.2009.06.037.

Homa, E. S., R. M. Vogel, M. P. Smith, C. D. Apse, A. Huber-Lee, and J. Sieber. 2005. "An optimization approach for balancing human and ecological flow needs." In *Proc., World Water and Environmental Resources Congress 2005*, 1–12. Anchorage, AK: Environmental and Water Resources Institute of ASCE.

Hyra, R. 1978. *Methods of assessing instream flows for recreation*. Rep. No. 6. Fort Collins, CO: United States Fish and Wildlife Service.

International Rafting Federation. 2015. "Top 10 most threatened rivers." Accessed November 5, 2018. http://www.internationalrafting.com/conservation/top-10-most-threathened-rivers/.

Jager, H. I., and B. T. Smith. 2008. "Sustainable reservoir operation: Can we generate hydropower and preserve ecosystem values?" *River Res. Appl.* 24 (3): 340–352. https://doi.org/10.1002/rra.1069.

Jenkins, M. W., J. R. Lund, and R. E. Howitt. 2003. "Using economic loss functions to value urban water scarcity in California." *J. Am. Water Works Assoc.* 95 (2): 58–70. https://doi.org/10.1002/j.1551-8833.2003.tb10292.x.

Jorda-Capdevila, D., and B. Rodríguez-Labajos. 2017. "Socioeconomic value(s) of restoring environmental flows: Systematic review and guidance for assessment." *River Res. Appl.* 33 (3): 305–320. https://doi.org/10.1002/rra.3074.

Jowett, I. G. 1997. "Instream flow methods: A comparison of approaches." *Regulated Rivers Res. Manage.* 13 (2): 115–127. https://doi.org/10.1002/(SICI)1099-1646(199703)13:2<115::AID-RRR440>3.0.CO;2-6.

Kayak River Stewards of Chile. 2018. "Rio Maipo." Accessed March 3, 2018. http://www.kayakstewards.org/maipo.html.

King, J. M., R. E. Tharme, and M. S. De Villiers. 2000. *Environmental flow assessments for rivers: Manual for the building block methodology*, 340. Pretoria, South Africa: Water Research Commission.

Kraft, M., D. E. Rosenberg, S. E. Null. Forthcoming "Optimizing barrier removal to prioritize connected aquatic habitat and water reliability." *J. Am. Water Resour. Assoc*.

Ligare, S. T., J. H. Viers, S. E. Null, D. E. Rheinheimer, and J. F. Mount. 2012. "Non-uniform changes to whitewater recreation in California's Sierra Nevada from regional climate warming." *River Res. Appl.* 28 (8): 1299–1311. https://doi.org/10.1002/rra.1522.

Loomis, J., P. Kent, L. Strange, K. Fausch, and A. Covich. 2000. "Measuring the total economic value of restoring ecosystem services in an impaired river basin: Results from a contingent valuation survey." *Ecol. Econ.* 33 (1): 103–117. https://doi.org/10.1016/S0921-8009(99)00131-7.

Loomis, J. B. 1998. "Estimating the public's values for instream flow: Economic techniques and dollar values." *J. Am. Water Resour. Assoc.* 34 (5): 1007–1014. https://doi.org/10.1111/j.1752-1688.1998.tb04149.x.

Martin, D. M., J. W. Labadie, and N. L. Poff. 2015. "Incorporating social preferences into the ecological limits of hydrologic alteration (ELOHA): A case study in the Yampa-White River basin, Colorado." *Freshwater Boil.* 60 (9): 1890–1900. https://doi.org/10.1111/fwb.12619.

McCluney, K. E., N. L. Poff, M. A. Palmer, J. H. Thorp, G. C. Poole, B. S. Williams, M. R. Williams, and J. S. Baron. 2014. "Riverine macrosystems ecology: Sensitivity, resistance, and resilience of whole river basins with human alterations." *Front. Ecol. Environ.* 12 (1): 48–58. https://doi.org/10.1890/120367.

Medellín-Azuara, J., J. R. Lund, and R. E. Howitt. 2007. "Water supply analysis for restoring the Colorado River Delta, Mexico." *J. Water Resour. Plann. Manage.* 133 (5): 462–471. https://doi.org/10.1061/(ASCE)0733-9496(2007)133:5(462).

Mims, M. C., and J. D. Olden. 2013. "Fish assemblages respond to altered flow regimes via ecological filtering of life history strategies." *Freshwater Biol.* 58 (1): 50–62. https://doi.org/10.1111/fwb.12037.

Mosley, M. P. 1983. "Flow requirements for recreation and wildlife in New Zealand rivers—A review." *J. Hydrol.* 22 (2): 152–174.

Null, S. E., and J. R. Lund. 2012. "Fish habitat optimization to prioritize river restoration decisions." *River Res. Appl.* 28 (9): 1378–1393. https://doi.org/10.1002/rra.1521.

Null, S. E., and L. Prudencio. 2016. "Climate change effects on water allocations with season dependent water rights." *Sci. Total Environ.* 571: 943–954. https://doi.org/10.1016/j.scitotenv.2016.07.081.

Null, S. E., and J. H. Viers. 2013. "In bad waters: Water year classification in nonstationary climates." *Water Resour. Res.* 49 (2): 1137–1148. https://doi.org/10.1002/wrcr.20097.

Ocampo-Melgar, A., S. Vicuña, J. Gironás, R. G. Varady, and C. A. Scott. 2016. "Scientists, policymakers, and stakeholders plan for climate change: A promising approach in Chile's Maipo Basin." *Environ. Sci. Policy Sustainable Dev.* 58 (5): 24–37. https://doi.org/10.1080/00139157.2016.1209004.

Olivares, M. A., and J. R. Lund. 2012. "Representing energy price variability in long- and medium-term hydropower optimization." *J. Water

Resour. Plann. Manage. 138 (6): 606–613. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000214.

Pareto, V. 1896. *Manual of Political Economy: A critical and variorum edition*, edited by A. Montesano, A. Zanni, L. Bruni, J. S. Chipman, and M. McLue. Oxford, UK: Oxford University Press.

Poff, N. L., et al. 2010. "The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards." *Freshwater Biol.* 55 (1): 147–170. https://doi.org/10.1111/j.1365-2427.2009.02204.x.

Rheinheimer, D. E., S. E. Null, and J. H. Viers. 2016. "Climate-adaptive water year typing for instream flow requirements in California's Sierra Nevada." *J. Water Resour. Plann. Manage.* 142 (11): 04016049. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000693.

Richter, B. D., J. V. Baumgartner, J. Powell, and D. P. Braun. 1996. "A method for assessing hydrologic alteration within ecosystems." *Conserv. Biol.* 10 (4): 1163–1174. https://doi.org/10.1046/j.1523-1739.1996.10041163.x.

Rosegrant, M. W., C. Ringler, D. C. McKinney, X. Cai, A. Keller, and G. Donoso. 2000. "Integrated economic-hydrologic water modeling at the basin scale: The Maipo River basin." *Agric. Econ.* 24 (1): 33–46. https://doi.org/10.1111/j.1574-0862.2000.tb00091.x.

Sale, M. J., E. D. Brill, and E. E. Herricks. 1982. "An approach to optimizing reservoir operation for downstream aquatic resources." *Water Resour. Res.* 18 (4): 705–712. https://doi.org/10.1029/WR018i004p00705.

SEIA (Sistema de Evaluación de Impacto Ambiental). 2008. *Estudio de Impacto Ambiental Proyecto Hidroeléctrico Alto Maipo. Anexo 10 Caudal Ecológico y Análisis de los Requerimientos Ambientales*. Accessed March 30, 2016. http://seia.sea.gob.cl/archivos/20080528.195355.pdf.

Shelby, B., T. C. Brown, and J. G. Taylor. 1992. *Streamflow and recreation*. Washington, DC: US Dept. of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Stafford, E., N. Fey, and J. J. Vaske. 2017. "Quantifying whitewater recreation opportunities in Cataract Canyon of the Colorado River, Utah: Aggregating acceptable flows and hydrologic data to identify boatable days." *River Res. Appl.* 33 (1): 162–169. https://doi.org/10.1002/rra.3049.

Steinschneider, S., A. Bernstein, R. Palmer, and A. Polebitski. 2014. "Reservoir management optimization for basin-wide ecological restoration in the Connecticut River." *J. Water Resour. Plann. Manage.* 140 (9): 04014023. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000399.

USACH (Universidad de Santiago de Chile). 2016. *Manual de curvas de preferencia para la realización de actividades recreativas*. Technical Rep. Proyecto Incorporación de la variabilidad hidrológica en la determinación del caudal ecológico (12BPC2-13421), CORFO. Santiago, Chile: USACH.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. "The river continuum concept." *Can. J. Fish. Aquat. Sci.* 37 (1): 130–137. https://doi.org/10.1139/f80-017.

Vicuña, S., M. Gil, O. Melo, G. Donoso, and P. Merino. 2018. "Water option contracts for climate change adaptation in Santiago, Chile." *Water Int.* 43 (2): 237–256. https://doi.org/10.1080/02508060.2017.1416444.

Ward, F. A. 1987. "Economics of water allocation to instream uses in a fully appropriated river basin: Evidence from a New Mexico wild river." *Water Resour. Res.* 23 (3): 381–392. https://doi.org/10.1029/WR023i003p00381.

Whittaker, D., and B. Shelby. 2002. "Evaluating instream flows for recreation: Applying the structural norm approach to biophysical conditions." *Leisure Sci.* 24 (3–4): 363–374. https://doi.org/10.1080/01490400290050808.

Yin, X. A., and Z. F. Yang. 2011. "Development of a coupled reservoir operation and water diversion model: Balancing human and environmental flow requirements." *Ecol. Modell.* 222 (2): 224–231. https://doi.org/10.1016/j.ecolmodel.2010.06.025.

Young, R. A. 2005. *Determining the economic value of water: Concepts and methods*. Washington, DC: Resources for the Future.

Young, R. A., and J. B. Loomis. 2014. *Determining the economic value of water: Concepts and methods*. Abingdon, UK: Routledge.