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Obtaining natural-like flow releases in diverted river reaches from simple riparian benefit economic models

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ABSTRACT

We propose a theoretical river modeling framework for generating variable flow patterns in diverted-streams (i.e., no reservoir). Using a simple economic model and the principle of equal marginal utility in an inverse fashion we first quantify the benefit of the water that goes to the environment in relation to that of the anthropic activity. Then, we obtain exact expressions for optimal water allocation rules between the two competing uses, as well as the related statistical distributions. These rules are applied using both synthetic and observed streamflow data, to demonstrate that this approach may be useful in 1) generating more natural flow patterns in the river reach downstream of the diversion, thus reducing the ecodeficit; 2) obtaining a more enlightened economic interpretation of Minimum Flow Release (MFR) strategies, and; 3) comparing the long-term costs and benefits of variable versus MFR policies and showing the greater ecological sustainability of this new approach.

1. Introduction

The manner with which water from river courses is withdrawn from the mainstem for anthropic uses (e.g., hydropower, irrigation, drinking supply, etc.) can be by dams or simply by diversions, the latter requiring no significant storage at the node (Fig. 1). Flow diversion, has been increasing in Europe as a means of feeding small hydropower, agriculture, etc., acting as a viable alternative/complement to water uses based on traditional damming. Both practices, alter the magnitude, frequency, timing and duration of flows downstream of the dam or the diversion point (or node) (Graf, 1999; Molnar et al., 2008). Medium- and long-terms changes in the natural flow regime have been shown to affect ecomorphodynamic processes (Pizzuto, 1994; Friedman and Lee, 2002; Shafroth et al., 2002) at multiple temporal and spatial scales (Merritt and Cooper, 2002; Nilsson and Svedmark, 2002; Perona et al., 2009a,b).

The natural flow regime is one of the hydrologic and geomorphologic river attributes (Trush et al., 2000; Muneepeerakul et al., 2007; Rodriguez-Iturbe et al., 2009) which sustains the biodiversity of a riverine ecosystem (Poff et al., 1997; Azaele et al., 2009). Altering this regime can adversely impact sensitive ecosystems (Kupferberg et al., 2012), and making choices regarding the variability of flow releases in a regulated riverine system is a complex problem involving economic, political and social decisions (Dyson et al., 2003; Tharme, 2003). The challenges associated with addressing this complexity have been largely responsible for the decision to use simple release rules such as Minimum Flow Release (hereafter named MFR) as a means of ecosystem protection. While MFRs are convenient to implement, they are not terribly effective in mimicking natural flow patterns, and typically enhance the ecodeficit (Gao et al., 2009). The widespread application of MFR rules has produced a statistically significant geographical increase in ecological similarity (Poff et al., 2006) and a consequent homogenization of riverine flora (Arthington et al., 2009) and fauna (Moyle and Mount, 2007). Current evidence suggests that the MFR concept has been a very limited success in terms of maintaining the integrity of riverine ecosystems (Allen and Flecker, 1993; Petts, 1996; Rosenberg et al., 2000). Maintaining more natural flow regimes in regulated rivers is a high priority in many parts of the world, as it represents a basis for sustainable management and restoration strategies (Petts, 1996; Baron et al., 2002; Tockner and Stanford, 2002; Arthington et al., 2006; Petts et al., 2006). In

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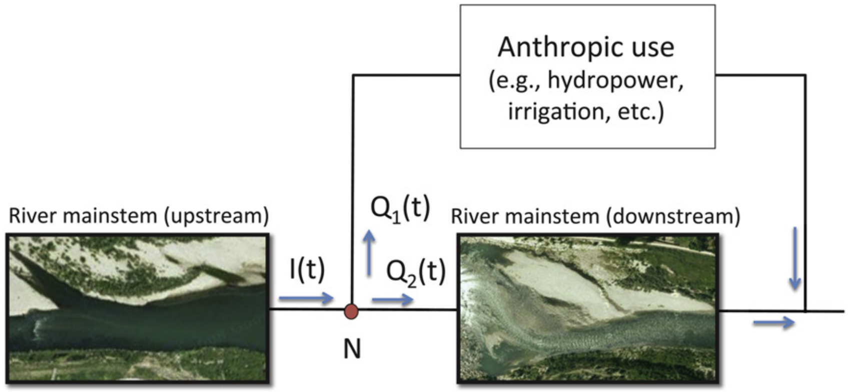

Fig. 1. Sketch of the river system, in which an upstream diversion node *N* diverts water from the river mainstem thus modifying the natural regime $I(t)$ downstream the node. Eventually, the flow Q_1 (or a percentage of it) after being used by the anthropic activity will re-join the residual flow Q_2 left to the environment somewhere downstream.

Switzerland, stakeholders from Canton Graubünden are considering the application of dynamic flow release policies to forthcoming small-hydropower plants. In neighboring countries (e.g., Italy, Austria, etc.) this problem is being addressed by designing weirs that proportionally redistribute the incoming flow (e.g., see (Gorla and Perona, in review)). Thus, there is increasing motivation to find a theoretical framework providing both ecological and economic arguments with which to promote such practical solutions.

In this work, we develop a theoretical economic modeling framework designed to obtain variable flow releases in diverted river reaches by considering the riparian environment as a non-traditional water use (Naiman et al., 2002) competing for water with a market-related, activity (e.g., hydropower, irrigation, etc.). This method provides a potentially useful alternative to the use of non-market valuation techniques (Champ et al., 2003). The first step is to define the utility of environmental water use. We make use of marginal analysis and evaluate the environmental water demand as a marginal benefit function (henceforth referred to as mbf). In contrast to a Willingness To Pay (WTP) approach (e.g., Hanemann, 1991; Amigues et al., 2002; Holmes et al., 2004) in which people value environmental amenities based on personal experience, we advance the idea that an alternative valuation can be done by relating the mbf of a particular flow regime to the benefits associated with the exploitation activity, but dependent on some assumptions regarding conditions. In this case, the assumption is that the allocation of water across both uses is optimal, that is, that the marginal benefits of water use at the optimum (ignoring costs or implicitly including them for the moment) in both activities are equal. The methodology developed here then allows for an indirect valuation of the water dedicated to creating a more natural flow regime. Essentially, this is solved by inverting the direct optimization problem, and by searching for the benefit function that leads to optimal allocation (i.e., that which maximizes benefits) of the resource across uses.

Our modeling approach makes use of economic theories to sustain ecological issues, and in this sense it attempts a first step in the direction discussed by Simpson (1998). More specifically, we aim to verify the following three hypotheses: i) More natural streamflow patterns in the river mainstem downstream of the diversion can be obtained from exact optimal water allocation rules, and represent an alternative approach to the use of MFRs; ii) from an economic viewpoint, the MFR policy is a special case of mbf, which corresponds to a perfectly inelastic demand function that leads to both economic and ecological paradoxes; iii) long-term benefits and costs of MFR versus release policies that lead to more natural flow patterns can be compared over the long term under the idea that reducing present financial profits in favor of environmental flows will balance future costs for restoration projects.

This work is organized as follows: Section 2 describes the development of an inverse technique to obtain the unknown parameters of a prototypical marginal benefit function representing the utility of environmental water use. Once that function is known we derive exact expressions for optimal water allocation rules and the related probability distribution functions. In Section 3 we apply the methodology using both synthetic and real streamflow data, and compare the flow release statistics in the regulated reach as obtained from our allocation model and from a MFR policy. Conclusions are included in Section 4.

2. Mathematical methodology

2.1. Inverse assessment of marginal benefits

For the sake of simplicity, we consider a scheme involving continuous diversion from a river to serve a market-related anthropic activity (e.g., small- or run-of-the-river hydropower, irrigation, etc.), as shown in Fig. 1. Because of the negligible upstream storage capacity, the optimization of water releases can be studied without invoking dynamic programming techniques (Hall et al., 1968). The scheme in Fig. 1 shows two water uses: the anthropic activity and the riverine environment, whose allocated flows are hereafter indicated using subscripts 1 and 2, respectively. The anthropic activity diverts water at a flowrate $Q_1(t)$ from the mainstem of the river whose natural flow regime is described as $I(t)$. The difference $Q_2(t) = I(t) - Q_1(t)$ is the residual flow that is left downstream of the node *N*, and eventually re-joins with the competitor return flow. From an operational viewpoint, such river regulation is often performed on a MFR basis, that is by keeping Q_2 as close as possible to a minimal residual flow Q_{MFR}. By considering the environment as an effective water use, we now show how to give Q_2 a natural-like variability.

Following the literature (e.g., Brown et al., 1990; Brown and Daniel, 1991; Diaz et al., 1997; Alfieri et al., 2006) we use marginal analysis to express the water demand of a specific user. We define as $b_1(Q; \mathbf{r}_1)$ the mbf of the anthropic activity, which we assume we can derive using market-based data (e.g., energy, crop, etc.), and with $\mathbf{r}_1$ being a vector of parameters. Next, we assume there exists a functional form for the mbf $b_2(Q; \mathbf{r}_2)$ describing the utility of the water being used in the regulated river reach. For the sake of simplicity we assume the functional form of this mbf to be time invariant, although time dependency could be introduced in later work. If both functions were defined, then their integrals could be directly summed (Laufer and Morel-Seytoux, 1979; Brown et al., 1990) to obtain the objective function expressing the Total Benefits, TB

$$\mathrm{TB} = \int_0^{Q_1} b_1(q_1; \mathbf{r}_1) dq_1 + \int_0^{Q_2} b_2(q_2; \mathbf{r}_2) dq_2, \quad (1)$$

where Q_1, Q_2 are the actual allocated quantities to the respective water use. Eventually, a classical optimization problem (Fig. 2a) could be solved by maximizing TB to find optimal water allocation to each user. However, given that environmental water use is a non-market good (Gatto and De Leo, 2000), the function $b_2(Q; \mathbf{r}_2)$ has generally non-monetary units and should first be defined by quantifying the parameters $\mathbf{r}_2$, for instance by means of the techniques described in Champ et al. (2003).

Here, we propose deriving the unknown parameters $\mathbf{r}_2$ of the mbf $b_2(Q; \mathbf{r}_2)$ by inverting the optimization problem (Fig. 2b) and considering the optimal allocation rule in the absence of operational constraints as known. That is, we ask for the global system (anthropic activity and environment) to work at the economical optimum which, for a flow diversion, can be demonstrated analytically (see Appendix A) to follow the Principle of Equal Marginal Utility (henceforth referred to as PEMU). The PEMU states that optimal water allocation between users occurs when

$$b_1(Q_1; \mathbf{r}_1) = b_2(Q_2; \mathbf{r}_2), \quad (2)$$

which means that the available resource, i.e., the incoming flow $I = Q_1 + Q_2$, must be allocated in such a way that each user assigns the same marginal value to the quantity they receive.

Consider for instance the simple linear and nonlinear mbfs shown in Fig. 3. In the linear case (Fig. 3a) users assign the following marginal benefits to the use of water

$$b_1 = a_{11} - a_{12} Q_1 \quad (3)$$

$$b_2 = a_{21} - a_{22} Q_2, \quad (4)$$

whereas for the nonlinear case considered here the mbfs are expressed by

$$b_1 = a_{11} - a_{12} Q_1 \quad (5)$$

$$b_2 = a_{21} (a_{22} + Q_2)^{-1}. \quad (6)$$

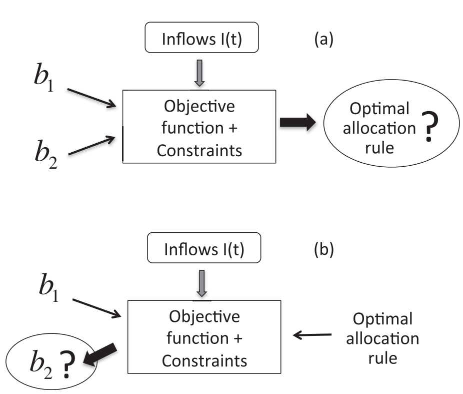

Fig. 2. Classic optimization problem and the inverse technique proposed in this work. (a) The result of direct optimization provides the optimal water allocation rules once marginal benefit functions and the inputs are known; (b) the inverse technique uses the optimal allocation rule to determine the unknown parameters of one of the marginal benefit functions.

Simple functional forms (3,4) and (5,6) describe economic scaling effects, non constant price elasticity (Loucks et al., 1981), and physiological plant marginal reaction to excess sediment and watering conditions (e.g., Friedman and Auble, 1999; Baird et al., 2005). Although at present we do not know which function might be considered more realistic, these functions are adequate considering our still limited knowledge about the actual economic value of the water used in the environment (Brown et al., 1990; Simpson, 1998). Moreover, these models allow us to proceed analytically, thus illustrating the sustainability of the method in an elegant way. Other functions to represent both environmental and anthropic uses can however be implemented and numerically solved at occurrence, as for instance shown by Gorla and Perona (in review).

Before continuing we follow engineering practice and rewrite the mbfs in a dimensionless form by scaling flowrates to some nominal flowrate Q_N expressing the designed water use capacity $Q_i = Q_N \tilde{Q}_i$, and the mbfs to the parameter a_{11}, $b_i = a_{11} \tilde{b}_i$, which represents the economic scale of the market-related anthropic activity. By assuming that the maximum benefit for the anthropic activity is reached at the nominal flowrate $Q_1 = Q_N$ (i.e., $\tilde{Q}_1 = 1$), then $a_{12} = a_{11}/Q_N$. Accordingly, the non dimensional parameters are $\tilde{a}_{21} = a_{21}/a_{11}$, and $\tilde{a}_{22} = a_{22} Q_N / a_{11}$. On dropping on the tilde superscript, the non dimensional form of Eqs. (3) and (4) is

$$b_1 = 1 - Q_1 \quad (7)$$

$$b_2 = a_{21} - a_{22} Q_2, \quad (8)$$

where a_{21}, and a_{22} are the only unknowns. Similarly, for the nonlinear case, the non dimensional parameters $\tilde{a}_{21} = a_{21}/(a_{11} Q_N)$ and $\tilde{a}_{22} = a_{22}/Q_N$, allow to rewrite Eqs. (5) and (6) as

$$b_1 = 1 - Q_1 \quad (9)$$

$$b_2 = a_{21} (a_{22} + Q_2)^{-1}, \quad (10)$$

where again the tilde has been dropped for the sake of clarity.

The PEMU is now used in the inverse manner shown in Fig. 2b in order to compute a_{21} and a_{22} in the absence of operational and physical constraints, which apply to the case being studied. Water redistribution between the users is economically optimal when it satisfies the condition (2) for which the users receive the quantities Q_1^* and Q_2^* for a given total incoming flow in the mainstem $I = Q_1^* + Q_2^*$ (see Fig. 3a). As river flow I decreases, so do Q_1^* and Q_2^*, until the competition stops when $Q_1^* = 0$ ($b_1 = b_2 = 1$) and $Q_2^* = I^*$. For discharges lower than such a value I^*, only user 2 (i.e., the environment) will receive water. At this point, the allocation is considered equal to the minimum flow requirement Q_{MFR}, beyond which more water cannot be withdrawn from the mainstem river reach. In terms of PEMUs, this condition is obtained by imposing $b_1(0; \mathbf{r}_1) = b_2(Q_{MFR}; \mathbf{r}_2)$, i.e., $a_{21} - a_{22} Q_{MFR} = 1$. Mathematically speaking, Q_{MFR} fixes the lower boundary for the competition between the water uses, and it imposes that for mainstem flows lower than Q_{MFR} all the water must remain in the mainstem. A second condition is now obtained by considering an uppermost limit for river discharges which allows water to be diverted to the anthropic activity until the point at which the resource is fully utilized and the corresponding benefit is maximized. This happens when both linear mbfs become zero, i.e., $b_1(1; \mathbf{r}_1) = b_2(Q_M; \mathbf{r}_2) = 0$ a condition that mathematically reads as $a_{21} - a_{22} Q_M = 0$. Here, Q_M has to be interpreted as a parameter that decides the importance of the environmental mbf with respect to that of the exploitation activity (Gorla and Perona, in review).

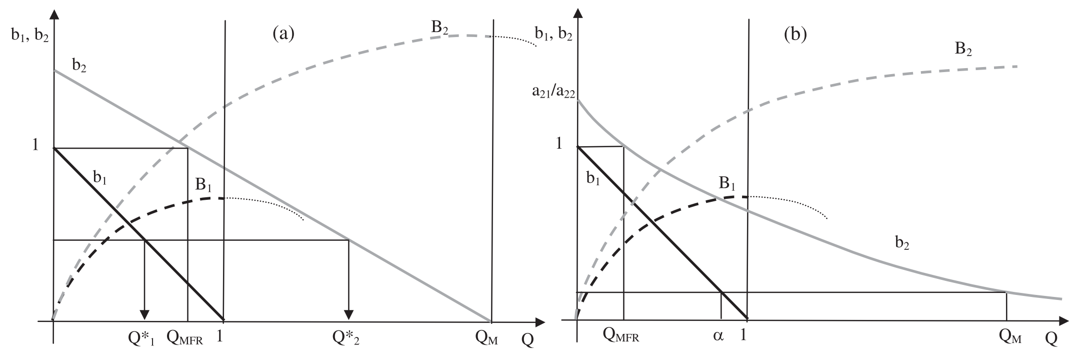

Fig. 3. Dimensionless marginal benefit functions b_i and related economical benefit B_i for both linear (panel a) and nonlinear (panel b) environmental mbfs. Both panels also show Q_{MFR} and the critical flow for the environment Q_M above which benefits are supposed to decrease for linear mbfs. An example of PEMU optimal allocation is given for the flow redistribution Q_1^* and Q_2^* such that $I^* = Q_1^* + Q_2^*$ and $b_1(Q_1^*) = b_2(Q_2^*)$. The limiting condition at which allocation stops is also shown in both cases for which $Q_1^* = 0$ and $Q_2^* = Q_{MFR}$.

The conditions above stated can now be solved algebraically, and used to find the unknown coefficients a_{21} and a_{22}. In the following, we show the linear case, and for the nonlinear case, we refer the reader to Appendix B. We obtain $a_{21} = Q_M/(Q_M - Q_{MFR})$ and $a_{22} = 1/(Q_M - Q_{MFR})$, which make the mbf b_2 of the environment

$$b_1 = 1 - Q_1 \tag{11}$$

$$b_2 = \frac{Q_M}{Q_M - Q_{MFR}} - \frac{Q_2}{Q_M - Q_{MFR}}, \tag{12}$$

such that it is linked to flow regime (i.e., environmental) metrics, but implicitly valued in economic terms through the comparison to water's value of the anthropic activity.

2.2. Optimal water allocation and related pdfs

Having determined the mbfs related to the optimal allocation rule, the optimal water allocation policy can now be explicitly calculated from the continuity equation at the node and the PEMU condition

$$I = Q_1^* + Q_2^* \tag{13}$$

$$b_1(Q_1^*) = b_2(Q_2^*), \tag{14}$$

where the decision variables Q_1^* and Q_2^* will be solved for in order to determine the optimal allocation of flows. Competition between the users occurs for $Q_{MFR} \le I \le 1 + Q_M$ and by solving algebraically for the decision variables Q_1^* and Q_2^* we obtain

$$Q_1^* = \begin{cases} 0 & 0 \le I < Q_{MFR} \\ \dfrac{I - Q_{MFR}}{Q_M + 1 - Q_{MFR}} & Q_{MFR} \le I \le 1 + Q_M \\ 1 & I > 1 + Q_M \end{cases} \tag{15}$$

$$Q_2^* = \begin{cases} I & 0 \le I < Q_{MFR} \\ \dfrac{I(Q_M - Q_{MFR}) + Q_{MFR}}{Q_M + 1 - Q_{MFR}} & Q_{MFR} \le I \le 1 + Q_M \\ I - 1 & I > 1 + Q_M \end{cases} \tag{16}$$

for the linear case. The nonlinear case again is shown in Appendix B.

Of practical interest is the determination of the probability distribution functions of the optimally allocated flows to both the anthropic activity $p_1(Q_1^*)$ and the environment $p_2(Q_2^*)$. This can be done by means of a derived distribution approach (Benjamin and Cornell, 1970), and by considering that given the discontinuous nature of the water allocation rules (15,16), such distributions will generally be discontinuous as well. For the sake of readability, the star superscript indicating the optimal allocated flow is now dropped. The term $p_i^c(Q_i)$ is used to indicate the continuous part of the pdf of user i and $p_i^{at}(Q_i^j)$ the atom of finite probability located at the discontinuity points (Q_i^j). Hence, the generic distribution function is $p_i(Q_i) = \sum_j p_i^{at}(Q_i^j) + p_i^c(Q_i)$. With respect to the continuous section, this can be obtained by transforming the distribution of the inflows $h(I)$ by using the optimal water allocation rules $Q_i = f_i(I)$, i.e., Eqs. (15), (16) or (B.2, B.3) for the linear and the nonlinear cases, respectively. Then, the derived distributions satisfy the normalization condition $\int_0^\infty p_i(Q_i)dQ_i = 1$ and read

$$p_1(Q_1) = \begin{cases} \displaystyle\int_0^{Q_{MFR}} h(I)\mathrm{d}I & Q_1 = 0 \\ h(I(Q_1))\left\|\dfrac{\mathrm{d}I(Q_1)}{dQ_1}\right\| & 0 < Q_1 < 1 \\ \displaystyle\int_{1+Q_M}^{\infty} h(I)\mathrm{d}I & Q_1 = 1 \end{cases} \tag{17}$$

$$p_2(Q_2) = \begin{cases} h(I(Q_2)) & 0 \le Q_2 < Q_{MFR} \\ h(I(Q_2))\left\|\dfrac{\mathrm{d}I(Q_2)}{\mathrm{d}Q_2}\right\|) & Q_{MFR} < Q_2 < Q_M \\ h(I(Q_2)) & Q_2 \ge Q_M. \end{cases} \tag{18}$$

Because of Eqs. (15) and (16), the distribution function of the anthropic activity $p_1(Q_1)$ shows two atoms of finite probability at $Q_1 = 0$ and $Q_1 = 1$ receiving no water when $I < Q_{MFR}$ and receiving no more than the dimensionless maximum capacity for $I \ge 1 + Q_M$. Consequently, the distribution representing the releases to the impounded reach $p_2(Q_2)$ is also discontinuous, and the presence of the MFR guarantees that all the water goes to maintaining flows in the mainstem of the river when $I < Q_{MFR}$. The described approach could be used to evaluate any river with given streamflow inputs and a defined Q_{MFR}.

3. Results and discussion

3.1. General solutions and application to synthetic data

The optimal water allocation policy resulting from the hypothetical marginal benefit functions shown in Fig. 4 is described. We approximate the probability distribution of the hydrograph of the natural flow regime by a simple density function such as $h(I) = bIe^{-aI}$ with $b = a^2$ representing a normalizing condition. This function was also theoretically investigated by Botter et al. (2008) for wet environments (i.e., $\lambda/k = 2$ and $\gamma = a$ using their paper terminology). Notice, that in the absence of storage capacity the density function alone is a sufficient descriptor, and the correlation of natural river discharges does not play a role in determining the optimal allocation policy obtained by the PEMU methodology. The distribution that is adopted has mean $\mu = 2/a$, mode $m = 1/a$ and variance $\sigma = 6/a^2$. An analytical expression for the flow duration curve $f(I) = P(I) = \int_I^\infty h(x)\mathrm{d}x$ is also available as described by Botter et al. (2008).

As far as the linear marginal benefit functions are concerned, the general form of the pdfs describing optimal flows is

$$p_1(Q_1) = \begin{cases} 1-(1+aQ_{\mathrm{MFR}})e^{-aQ_{\mathrm{MFR}}} & Q_1 = 0 \\ a^2a_0(a_0Q_1+Q_{\mathrm{MFR}})e^{(-a(a_0Q_1+Q_{\mathrm{MFR}})} & 0 < Q_1 < 1 \\ (1+a+aQ_{\mathrm{M}})e^{-a(1+Q_{\mathrm{M}})} & Q_1 = 1 \end{cases} \quad (19)$$

for the diversions to the anthropic activity, and

$$p_2(Q_2) = \begin{cases} a^2Q_2e^{-aQ_2} & 0 \le Q_2 < Q_{\mathrm{MFR}} \\ \dfrac{-a_0a^2(Q_{\mathrm{MFR}}-a_0Q_2)}{Q_{\mathrm{MFR}}-Q_{\mathrm{M}}}e^{-\frac{a(Q_{\mathrm{MFR}}-a_0Q_2)}{Q_{\mathrm{MFR}}-Q_{\mathrm{M}}}} & Q_{\mathrm{MFR}} < Q_2 < Q_{\mathrm{M}} \\ a^2(1+Q_2)e^{-a(1+Q_2)} & Q_2 \ge Q_{\mathrm{M}}. \end{cases} \quad (20)$$

for the mainstem river flows (i.e., environment), with $a_0 = 1 - Q_{\mathrm{MFR}} + Q_{\mathrm{M}}$.

Fig. 5 shows the optimal redistribution rules (15,16) corresponding to the marginal demand functions of Fig. 4. These cases are useful for illustrating the differences in the allocation strategy as dictated by the importance of the riparian environment relative to the market-related anthropic use.

Fig. 5a corresponds to imposing a condition in which $Q_{\mathrm{MFR}} < 1 < Q_{\mathrm{M}}$ ($Q_{\mathrm{MFR}} = 0.25$ and $Q_{\mathrm{M}} = 3$). The resulting redistribution is evident within three distinct regions. In region I all the incoming flow $I \le Q_{\mathrm{MFR}}$ goes to the environment, thus the slope of the redistribution functions is 45° with respect to environmental flows and zero for anthropic use (user 1), with $p_1^{at}(0) = 0.026$. Within region II the river carries enough water to allow for competition between the activities. Optimal flow allocation occurs according to Eqs. (15) and (16). In region III, saturation occurs for the anthropic use (which is producing at full capacity) and the excess flow is again released to the environment. In this case, the slope of the redistribution functions is zero for human activity and 45° for environmental flows, with $p_1^{at}(1) = 0.091$.

For the sake of better comparison, different policies are analyzed by maintaining the parameter Q_{MFR} constant, and letting only Q_{M} vary (Fig. 4). The corresponding results are shown in Fig. 5c,d, but the conclusions we draw are generally valid for any other combination of parameters. As the parameter Q_{M} decreases so does the relative importance of environment flows with respect to the anthropic activity until $Q_{\mathrm{M}} \ge 1$. Notice that by changing Q_{M} only, the linear mbf rotates around the point P in Fig. 4. For policies having $Q_{\mathrm{MFR}} < Q_{\mathrm{M}} < 1$ (see, Fig. 4) production from anthropic use will instead receive more water than does the environment if $2\hat{Q} \le I \le 1 + Q_{\mathrm{M}}$ (i.e., where $\hat{Q} = Q_{\mathrm{MFR}}/(1 - Q_{\mathrm{M}} + Q_{\mathrm{MFR}})$). However, this situation is inverted and environmental flows again dominate for mainstem flow levels less than $2\hat{Q}$. As $Q_{\mathrm{M}} \to Q_{\mathrm{MFR}}$, then $\hat{Q} \to Q_{\mathrm{MFR}}$ and the mbf becomes a vertical line with infinite slope. Accordingly, the reallocation relationship (16) for the environment flows becomes a horizontal function independent of I, such that

$$Q_1^* = \begin{cases} 0 & 0 \le I < Q_{\mathrm{MFR}} \\ I - Q_{\mathrm{MFR}} & Q_{\mathrm{MFR}} \le I \le 1 + Q_{\mathrm{M}} \\ 1 & I > 1 + Q_{\mathrm{M}} \end{cases} \quad (21)$$

$$Q_2^* = \begin{cases} I & 0 \le I < Q_{\mathrm{MFR}} \\ Q_{\mathrm{MFR}} & Q_{\mathrm{MFR}} \le I \le 1 + Q_{\mathrm{M}} \\ I - 1 & I > 1 + Q_{\mathrm{M}}, \end{cases} \quad (22)$$

indicating that for any streamflow level $Q_{\mathrm{MFR}} \le I \le 1 + Q_{\mathrm{MFR}}$, the environment will only receive Q_{MFR}. Under this policy, the pdf for environmental flows reduces to a point describing the atom finite probability of always receiving the same amount of water (Fig. 5b), equal to

$$\int_{Q_{\mathrm{MFR}}}^{1+Q_{\mathrm{MFR}}} h(I)\mathrm{d}I = e^{-aQ_{\mathrm{MFR}}}(1 + aQ_{\mathrm{MFR}}) - e^{-a(1+Q_{\mathrm{MFR}})}(1 + a + aQ_{\mathrm{MFR}}). \quad (23)$$

This situation corresponds to the Minimum Flow Release policy, as being interpreted by marginal analysis. That is, a vertical demand function at $Q = Q_{\mathrm{MFR}}$ implies perfect price inelasticity of water use for environmental flows, which is the willingness to pay any price for a fundamental good, with the demand immediately dropping to zero as soon as it is satisfied. Hence, if MFR were to be an optimal policy, environmental needs would be satisfied with an amount of water exactly equal to Q_{MFR}. This assumption clearly conflicts with the fact that ecosystem health depends on the variability of the natural flow regime (Poff et al., 1997). This conceptual paradox implies that price inelasticity does not describe environmental benefits and thus that the MFR can not be considered an optimal water allocation policy.

Fig. 5c,d also show optimal reallocation policies obtained by adopting the nonlinear marginal benefit function (6) for the environment ($Q_{\mathrm{MFR}} = 0.25$ and $Q_{\mathrm{M}} = 0.9$, $\alpha = 0.9$). Such a function (see Fig. 4) defines a competition for water over the whole range of possible mainstem flow levels, with windows where the relative importance of the two users depends on those flow levels. Thus,

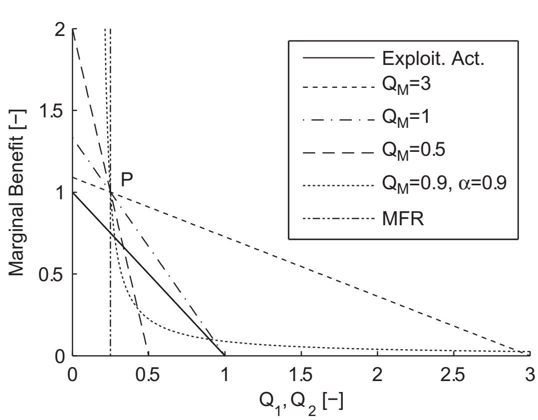

Fig. 4. Linear and nonlinear marginal benefit functions used for the example cases, for $Q_{\mathrm{MFR}} = 0.25$. The continuous line is the marginal benefit function of the anthropic activity. The vertical mbf corresponds to the MFR policy for which $Q_{\mathrm{M}} = Q_{\mathrm{MFR}}$.

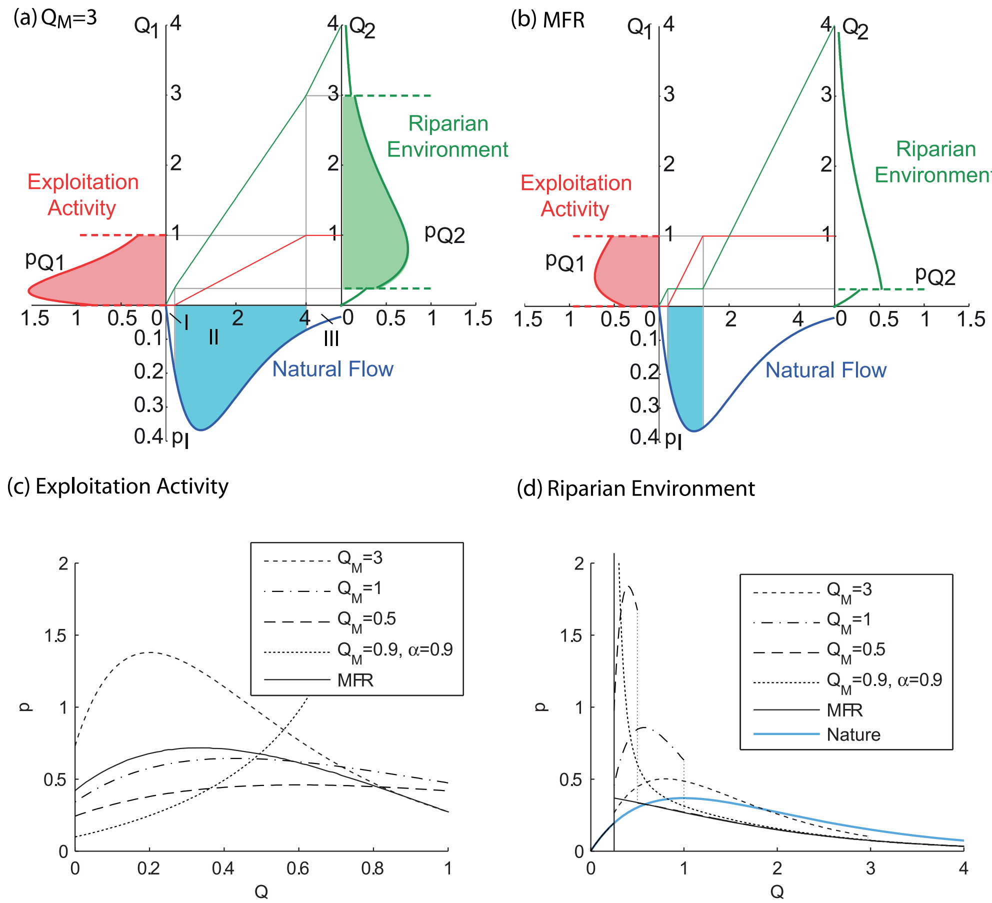

Fig. 5. Optimal water allocation and related pdfs for the linear mbf (a) and the MFR policies (b). The colored regions of the pdfs indicate the range of flows where competition for water occurs according to either one of the policies. The points of finite probability (atoms) are represented out of scale for the sake of visibility. Panels c) and d) show the pdfs, for anthropic use and environmental flows, respectively, resulting from the example mbfs shown in Fig. 4, including both the nonlinear case and the MFR policy.

a nonlinear function may be more realistic than linear ones beyond providing greater modeling flexibility.

3.2. Application to real data

We apply now our methodology to 30 years of observed streamflow data from a non-regulated European river,[1] and compare the simulated releases obtained by following either a MFR or a PEMU (our model) policy. Let us suppose there is interest in withdrawing water for an anthropic use with an associated flow design capacity Q_N. We compute the resulting flow releases for both our model and MFR (e.g., for $Q_{MFR} = 0.1$ and $Q_M = 0.7$) policies. In order to characterize the natural flow regime in terms of timing, seasonality, magnitude, duration and related frequency we computed the autocorrelation function $\rho_I(k) = \overline{I(t)I(t+k)}/\overline{I^2(t)}$ (k is the time delay), the pdfs of streamflow $I(t)$, $h(I)$(mean μ, mode m and standard deviation σ) and related flow duration.

Fig. 6a shows a 5 year sequence of normalized historical streamflow in the mainstem river which is then directly compared to flows resulting from the described water allocation strategy. This comparison is then juxtaposed with a similar comparison of flow regime using the MFR policy (Fig. 6b). As expected, the flow regime resulting from the allocation approach developed in this work shows much greater similarity to the natural flow regime than that derived from the MFR approach, as measured by the flow metrics typically considered fundamental to maintaining ecosystem health (i.e., seasonality, flood magnitude and frequency, flow duration and timing) (Petts, 1996; Petts et al., 2006).

The autocorrelation and related flow duration curves of the three flow patterns can be considered as a reasonable basis of comparison across the allocation strategies, without exceeding the scope of this work and using a larger, more difficult to evaluate, suite of hydrologic indicators (Richter et al., 1997; Gao et al., 2009). The autocorrelation structure (Fig. 6c) shows that the approach developed in this work represents an improvement over an MFR-based approach in terms of mimicking natural flow patterns (Fig. 6c). Similarly, the flow duration curve (Fig. 6d) suggests that our methodology reduces the ecodeficit, the latter intended as the ratio between the area below the flow duration curve of the natural streamflow and that of the released discharges (Botter et al., 2008; Gao et al., 2009). Notice, that the policy underlying this methodology is not intended to provide enough water to the river such as to maximize the development of one particular species (e.g., fishes). On the contrary, the method preserves the variability as a fundamental river hydrograph attribute that allows maximizing biodiversity.

The price to pay for applying the PEMU policy as compared to the more traditional MFR approach, is clearly reflected in the lost (dimensionless) benefits ΔB accruing to the anthropic use over time (Fig. 6e). This difference represents a cost that society pays in order to obtain a more natural flow regime that is likely enhancing the riverine system's future ability to recover from perturbations (e.g.,

[1] We prefer to omit the name in order to avoid misinterpretations surrounding the intention of this paper.

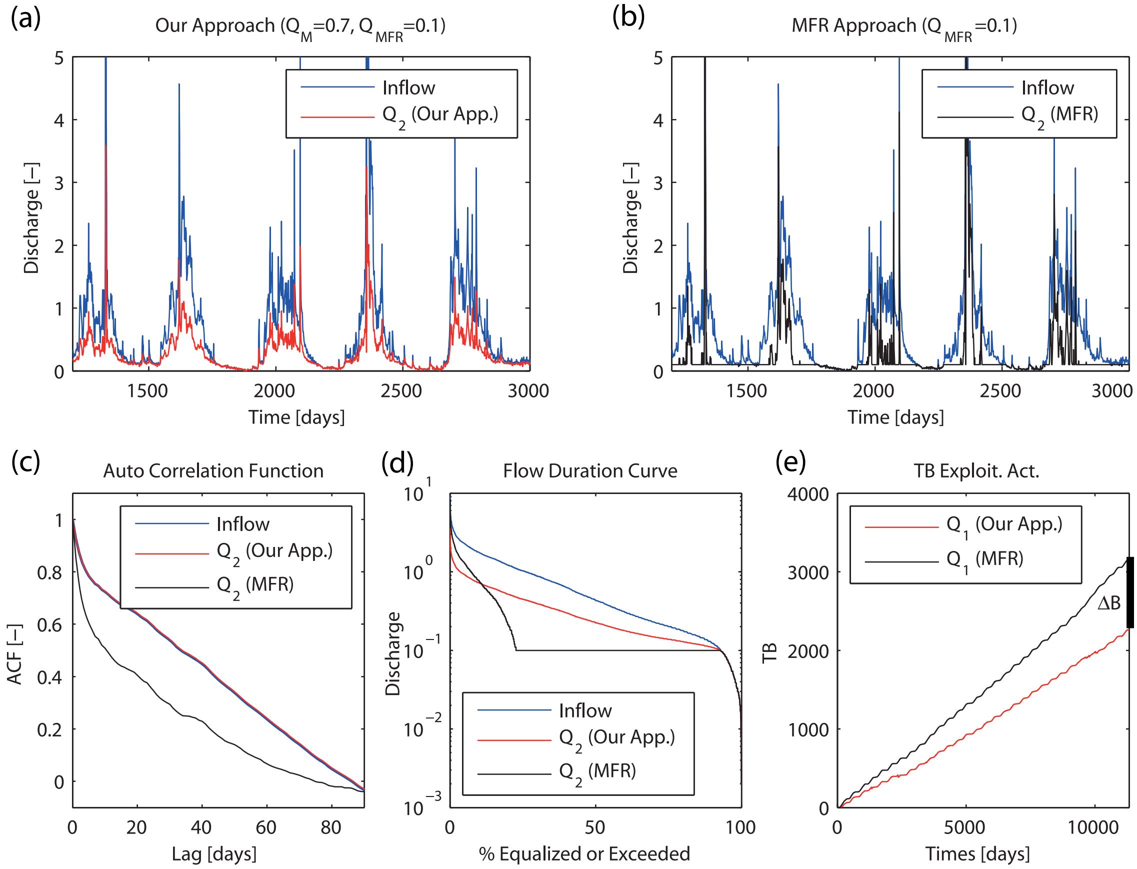

Fig. 6. Optimal water allocation resulting from (a) the developed approach (red),and: (b) the MFR approach (black) as compared to observed streamflow data (blue). The competition for water assures that the environment is the beneficiary of more natural flows with practically equal auto-correlation structure (c) and duration (d). In (e), the long-term comparison between the dimensionless total benefits (TB) of the anthropic activity under both this and the MFR approach is shown. The approach developed in this work clearly generates a reduction in benefits, which may be considered as the cost of maintaining a more natural flow regime.

see Folke, 2006). Eventually, should restoration of the regulated river reach become a long-term goal, then we recommend tuning such lost benefits ΔB to balance future restoration costs (Fig. 6e). In other words, following on the holistic viewpoint with which riverine ecosystem dynamics are understood (Arthington et al., 2006), we defend the idea that more natural flow patterns will inherently preserve or make the environment healthier thus reducing future costs for restoration. This has an intrinsic value considering the resilience (and nonlinear) response of environmental systems to perturbation, which may eventually lead to abrupt and irreversible changes (e.g., see Scheffer et al., 2001).

4. Conclusions

We developed a PEMU based methodology to generate variable flow releases in river reaches subject to diversions for anthropic water uses, and proposed it as a possible alternative to existing practices based on an MFR approach. The advantage of the proposed method is that it accounts for both environmental (instream flow Q_{MFR}) and economic (marginal benefit functions) conditions, and involves relatively few parameters, i.e., in the current simple form, a characteristic maximum flow Q_M, and the economic scale B_1 of the anthropic water use. The marginal benefit function associated with creating a more natural flow regime is determined in an inverse fashion, and the competition for water produces natural-like flows patterns in the river mainstem, as measured by several simple comparative metrics. This approach also facilitates direct comparison with MFR approach, which was demonstrated to treat ecosystem water demand as a perfectly inelastic good, i.e., clearly inconsistent with the variability of the natural flow regime.

This research is motivated by the need to provide stakeholders, river biogeomorphologists, ecologists and engineers with a sound theoretical framework for managing water withdrawal from diversion in a more sustainable way. Considering our still limited knowledge about environmental dynamics and the actual economic value of the water being used in it, we proposed an innovative and, more sustainable democratic approach. That is, by imposing the PEMU the global system (anthropic use plus environment) always works at the economical optimum. Then, environmental water demand (mbf) is indirectly priced by the competitor because for each water unit that the latter uses, it also indirectly values the water left to the environment. Accordingly, reduced profits for exploitation consequent to augmented and variable flow releases (as obtained from our approach) should be interpreted as a long-term benefit for the riparian ecosystem, i.e., under a preservation rather than a restoration viewpoint.

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Appendix A

The PEMU generally holds for unbounded problems, i.e., in the case there are no active constraints (e.g., physical, economic, political, social) affecting allocation among the activities. In this case, where there is no significant storage at the diversion node, and assuming that both mbf are positive monotonically decreasing functions, the objective function TB can be analytically maximized, i.e., by finding

$$Max|_{\mathbf{Q},T_h}\left[\sum_{i=1}^{2}\int_{T_h}\int_{0}^{Q_i} f_{\rm act}(\tau)b_i(q;\mathbf{r}_i(\tau))\mathrm{d}q\mathrm{d}\tau\right], \tag{A.1}$$

where $f_{\rm act}$ is a whatever function used to actualize the benefits to present time, Q_i is the actual quantity allocated to the $i-$ water use, and $T_{\rm h}$ the time horizon. By introducing the continuity at the node $I = q_1 + q_2$ into (A.1), and by equating to zero the derivative with respect to the variable Q_2 one obtains

$$\begin{aligned}&\frac{\mathrm{d}}{\mathrm{d}Q_2}\left(\int_{T_h}\int_{0}^{I-Q_2} f_{\rm act}(\tau)b_1(I-q_2;\mathbf{r}_1(\tau))\mathrm{d}(I-q_2)\mathrm{d}\tau\right)\\&+\frac{\mathrm{d}}{\mathrm{d}Q_2}\left(\int_{T_h}\int_{0}^{Q_2} f_{\rm act}(\tau)b_2(q_2;\mathbf{r}_2(\tau))\mathrm{d}q_2\mathrm{d}\tau\right) = 0.\end{aligned} \tag{A.2}$$

Because Q_2 does not depend explicitly on time t, the derivative can go under the first integral

$$\begin{aligned}&\int_{T_h}\frac{\mathrm{d}}{\mathrm{d}Q_2}\left(\int_{0}^{I-Q_2} f_{\rm act}(\tau)b_1(I-q_2;\mathbf{r}_1(\tau))\mathrm{d}(I-q_2)\right)\mathrm{d}\tau\\&+\int_{T_h}\frac{\mathrm{d}}{\mathrm{d}Q_2}\left(\int_{0}^{Q_2} f_{\rm act}(\tau)b_2(q_2;\mathbf{r}_2(\tau))\mathrm{d}q_2\right)\mathrm{d}\tau = 0.\end{aligned} \tag{A.3}$$

By gathering now the two domains of integration and making the derivative one obtains

$$\int_{T_h} f_{\rm act}(\tau)\left(b_1(I-Q_2;\mathbf{r}_1(\tau))\ \frac{\mathrm{d}(I-Q_2)}{\mathrm{d}Q_2}+b_2(Q_2;\mathbf{r}_2(\tau))\right)\mathrm{d}\tau = 0,$$

which finally reduces to the condition

$$\int_{T_h} f_{\rm act}(\tau)(-b_1(I-Q_2;\mathbf{r}_1(\tau))+b_2(Q_2;\mathbf{r}_2(\tau)))\mathrm{d}\tau = 0.$$

Given the generality of both the integration domain and the function $f_{\rm act}(\tau)$, then the bracket term within the integral must be zero. Therefore, by using again the continuity equation at the node one obtains

$$b_1(Q_1;\mathbf{r}_1(t)) = b_2(Q_2;\mathbf{r}_2(t)). \tag{A.4}$$

Appendix B

By choosing the mbfs (9) and (10), the competition for water will occur over the whole range of incoming river discharges (Fig. 3b). The two unknown parameters a_{21} and a_{22} can be determined by invoking again the existence of a MFR, i.e., $a_{21}(a_{22}+Q_{\rm MFR})^{-1} = 1$, and the fact that competition must now extend over the whole range of streamflows. In particular, since river discharge cannot be infinite, we may ask that a percentage α (e.g., $\alpha = 0.9$) of the nominal (dimensional) flow $\tilde{Q}_{\rm N}$ goes to the exploitation activity when the river carries for instance its historical maximum $I_{\rm max}$, and the environment receives $Q_{\rm M} = I_{\rm max} - \alpha$, i.e., $1-\alpha = a_{21}(a_{22}+Q_{\rm M})^{-1}$. Again, this condition is not limiting the present approach and can be adapted to the preferred case being studied on the base of historical flow statistics and the relative importance of one user respect to the other. Solving the algebraic system with the two conditions above leads to the unknown parameters,

$$a_{21} = \frac{(1-\alpha)(Q_{\rm M}-Q_{\rm MFR})}{\alpha};\quad a_{22} = \frac{(1-\alpha)Q_{\rm M}-Q_{\rm MFR}}{\alpha}, \tag{B.1}$$

together with $b_2 = 1$ for $I \le Q_{\rm MFR}$, which constraints the function when the competition for water stops.

The rule of optimal allocation for the nonlinear case is

$$Q_1^* = \begin{cases}0 & 0\le I<Q_{\rm MFR}\\ \frac{1}{2}\left(1+a_{22}+I-\sqrt{1+4a_{21}-2a_{22}+(a_{22}+I)^2-2I}\right) & I\ge Q_{\rm MFR}\end{cases} \tag{B.2}$$

$$Q_2^* = \begin{cases}I & 0\le I<Q_{\rm MFR}\\ \frac{1}{2}\left(-1-a_{22}+I+\sqrt{(1+a_{22}-I)^2-4(a_{22}(1-I)-a_{21})}\right) & I\ge Q_{\rm MFR}\end{cases} \tag{B.3}$$

where a_{21} and a_{22} are obviously given by Eq. (B.1).

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