The Potential for Water Market Efficiency when Instream Flows Have Value

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Most of the effort being expended to revise western water policy concerns the maintenance of instream waters to the exclusion of traditional diversionary interests. Absent from the economics literature is a theoretical treatment addressing the interface between diversionary and instream water uses. At issue is the potential for refining market operations to accomplish efficient allocation in the presence of both diversionary and instream uses. Optimization methods are employed to examine this issue in a highly generalized framework. If a specific structure is adopted, markets and other incentive-based policies are demonstrated to be capable of efficient water allocation.

Key words: instream flow, water allocation, water markets.

Water allocation problems are best perceived as an evolving set of interdependencies illuminated by growing scarcities. These scarcities pertain to each of the many different dimensions of water from which we derive value. Growing scarcity accentuates individual interdependencies (externalities) in a progressive fashion thereby motivating the search for institutions of ever-increasing scope. Transaction costs impede progress towards more comprehensive institutions, but evolving scarcity raises internalization benefits relative to transaction costs. Simultaneously, transaction costs can be lowered by technological advance and institutional investment. These ongoing processes motivate constant change as the adoption of untried institutions becomes justified.

It is in this context that the economics literature has gradually acknowledged the problems associated with property rights structures which focus on diversion quantities. The intricate water-related interdependencies imposed by physics and chemistry imply that institutions dealing solely through diversion quantities are inadequate. Fundamental, quantitative and qualitative aspects of water use cause diverse interrelation-

ships among users. Some of these relations are not accommodated when property rights are measured as diversions. As a result, our literature and our institutions have both evolved to embody more complicated visions of water interdependencies. Notable among the conditions of water use needing special attention are return flows, water quality, and instream flow maintenance.

The so-called "return flow externality" has been long acknowledged as a potential cause of water misallocation in a system of property rights based on allowed diversions (Milliman; Howe, Alexander, and Moses). Reallocations of diversion rights often involve third party impacts for other diverters. In response, the literature argues for a consideration of the consumptive use of each diversion although this is difficult information to obtain. Institutions have also responded to this problem. Water right transfers occurring in western states must obtain approval in established administrative or quasi-judicial processes designed to ferret out negative return flow externalities (Johnson and DuMars).

Though treated narrowly in this paper, water quality considerations have generated considerable debate in research and policy. This attention usually addresses quality issues in isolation from the allocation of water quantities. Quality issues have achieved a life of their own in that both literature and institutions have become quite specialized and do not integrate qualitative and quantitative externalities. Issues

of quantitative and qualitative water scarcity are interrelated, however and, as such, are in need of coordinated policy (Colby). As an obvious example, the assimilative capacity of every watercourse is linked to the quantity of its flows.

Instream flow protection has emerged recently as the major demand for refining research and allocative institutions. There is growing social concern about the maintenance of river, stream, and lake levels for habitat, environmental, and recreational purposes (MacDonnell, Rice, and Shupe). Even when return flow externalities are expunged and quality issues are ignored or are somehow irrelevant, market activity may not lead to economic efficiency when instream flows have value. Part of the problem is that particular nonrival and nonexclusive instream uses are inadequately represented. The other part, interfacing traditional diversionary water uses with new nondiversionary interests, presents a perplexing issue because the opposing parties care about different, though linked, dimensions of the resource. Some of the literature has argued for allowing market participation by instream users.[1] We will demonstrate that water marketing cannot efficiently allocate both diverted and instream water unless the market is administered in a particular fashion.

Alternative nonmarket policies for confronting the instream flow issue are being adopted and revised (Livingston and Miller). Most evident among these is the public trust doctrine which is being given new life through an extension to instream demands other than navigation. The public trust doctrine provides constitutional grounds for subjugating appropriative water rights to demands for increased stream flows. This represents more than the establishment of new initial endowments from which water marketing may proceed. Application of the public trust doctrine involves costly judicial actions as "vested" water right holders seek to protect their permits from uncompensated transferal to the public sector. Furthermore, uncertain tenure created by the threat of additional annexations by instream interests weighs heavily upon the value of water rights and the ability of the market to respond to future reallocative needs among diverters.

Our purpose here is to provide a more complete model of water use and human interrela-

tionships involving water than has previously been presented. The focus is on the development of a property rights system that can serve as an interface among water diverters and instream flow users. The intent is to more generally model the efficient allocation of water in a world *sans* transaction costs. Such a model is not argued to produce immediately commendable social actions. Rather, the model is construed as offering insights for the direction in which we can head.

Review of Literature

Early water resource economists recognized the intricate interdependencies of water users. Hirschleifer, De Haven, and Milliman provide an enlightening discussion in an appendix. They refer to the ordinary hydrologic depiction of "consumptive use" as a "crude approximation" (p. 66). "Water may contain a number of qualities of economic significance; among them are location in time and space, temperature, and purity in the chemical or bacteriological sense" (p. 68). Hartman and Seastone state that "physical interdependencies of water users preclude simple property-right systems such as exist for most productive assets." They initially emphasize third party impacts and nonmarket values as reasons for the inadequacy of ordinary property rights and proceed to examine third party relationships in a much simplified modeling framework. The Hartman and Seastone model identifies the importance of consumptive use but also highlights the importance of return flow impacts especially relating to the significance of the relative locations of users. Both of these works note the potential for a two-tiered system of water pricing involving charges for input (diverted) water and credits for output (return flow) water. Both are also consistent in indicating the dependence of allocative efficiency on temporal and spatial characteristics of uses even though their modeling abstractions prohibited detailed investigations. Finally, both note the importance of instream demands but provide no real inspection of the impact of this observation.

It is revealing to contrast this early literature with the approach of most contemporary research. Some recent literature focuses on stochastic characteristics of water flows and the relationship between this variability and institutional needs— particularly relating to the appropriations doctrine (Burness and Quirk). A second body of literature emphasizes institutional prop-

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[1] Water users who do not divert water have been treated as lesser interests, because they are typically not allowed to purchase or file for water rights (Colby). Even when ownership of water rights is permitted for nondiversionary uses, it is not on equal footing with diverters.

erties and needs in a more or less deterministic setting. Rather than neglecting it, this latter approach takes the importance of water flow stochastics as a separable issue. Here, typical writers maintain that the return flow issue can be readily accommodated within a simple market system if rights are defined by "consumptive use" rather than permitted diversion quantities (Anderson). This represents a subtle yet critical departure from the previous literature of Hirschleifer, Haven, and Milliman, and Hartman and Seastone, which attends to at least two quantitative dimensions of water use: diversion quantities (D) and return flow (R). The recent approach is to collapse these two metrics into a single dimension, consumptive use $(C = D - R)$, and argue for C rights.

The two approaches are only superficially equivalent. Some aspects of the earlier work seem lost on recent research. For example, the older work observed the dependency of return flow credits upon location along a river; this spatial dependency of optimal price is absent from most current work. The simplification employed by the more contemporary research may be at least partially responsible for its theoretical support of marketing. The simplification is appropriate if the utility/profit of all users is dependent solely upon C and if interdependencies among users occur only in the form of C impacts. It is intuitively clear, however, that this is not the case.[2]

The legal profession is making a concerted effort to shore up western water law with concepts such as the public trust doctrine, which may supplant recent advances in water market development (Blumm; Johnson and DuMars). Although economists possess tools with which to address such nonrival and "nonconsumptive" use issues, we have failed to integrate this knowledge within our conceptual models of competing water uses. Accomplishing this requires more than transferal of public good theory to a new setting. The joint interrelationships of diversion, consumption, and instream water levels must be simultaneously modeled in order to obtain a workable paradigm with promise for prescription. Thus far, the extent of progress largely rests in claims that individuals demanding instream flow could adequately provide their needs through the purchase and retirement of consumptive rights (Anderson; Anderson and Leal; Huffman; Tre-

garthen). The difficulties with these claims are not due solely to the public good character of instream flows. Account must be taken of the third party effects of such retirements, just as for exchanges of water rights among diverters (Livingston and Miller). By not addressing these effects explicitly, the promarketing literature may have cavalierly treated instream water levels as a factor influencing the value of water. A more rigorous examination is needed.

The Model

To deal adequately with the instream flow issue requires a new economic depiction of water interrelationships. A model of these interrelationships should recognize that the withdrawal of water resources from a stream impacts those people who derive value from instream flow even if the entire diversion is returned downstream. The issues of return flow interdependencies and instream flow demands are inseparable.

Elements of the needed model are as follows. Water is a multidimensioned good in that people derive value from multiple properties of water; each water use has substitution opportunities implying that diversion, consumption, and return flow quantities can be controlled; the withdrawal of water for use and the subsequent return flow alters the availability of water at downstream locations; each water use can have a unique character with respect to when and where its return flow will reenter the stream; and the flow characteristics of the stream, especially natural inflows/outflows and speed, can be important.

These fundamentals suggest an optimization problem which should incorporate spatial details. The relative locations of water users and return flows is relevant to any theory attempting to integrate diversionary and instream water demands.

The "bare bones" framework employed here holds that people care about the amount of water they divert, d; the amount of water they consume, c, from this diversion; and the amount of water residing in the stream/river, w. Different users weigh these metrics differently, but all three are potentially important. Furthermore, they likely have a nonseparable influence in many, if not most, uses. Other water properties such as quality or velocity are not considered in the present model. The decision variables are d and c; w is influenced by the decision variables. We begin with a general river basin containing many water

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[2] In the same vein, some models assume that across all users consumptive use (or return flow) is an immutable percentage of the quantity of water diverted. If this were true, then consumptive use could serve as an adequate basis for defining property rights.

Table 1.   Variable Definitions

Variable	Definition
a_j^i	proportion of diverter s_i's return flow returning at s_j
$c(s_i),\ d(s_i)$	amounts of water consumption and diversion by diverter s_i
$\hat{c}_{si},\ \hat{d}_{si}.$	diverter s_i's endowment of consumption and diversion rights
$c_{ij},\ d_{ij}$	amounts of rights transferred from diverter s_i to diverter s_j
$F_{s_i}(\ )$	diverter s_i's utility function
$G_{s_i}(\ )$	aggregate instream use utility function for the segment $(s_i,\ s_{i+1})$
$p_i,\ q_i$	prices for consumption and diversion rights
$p^{li},\ q^{li}$	instream water district i's unit payments for c and d transfers
s_i	a location along the river beginning at s_0 and ending at s_N
$w(s_i)$	amount of instream water at location s_i after s_i's diversion
$\bar{w}(s_i)$	natural amount of instream water at location s_i (no human use)
$\tilde{w}(s_i)$	amount of instream water at location s_i after existing use patterns and prior to market participation by instream users
λ_i	Lagrange multiplier indicating the marginal value of instream water across the segment $(s_i,\ s_{i+1}]$

users with various desires. All notation defined below is also summarized in table 1.

Let there be two classes of water users to consider, diverters and instream users. Diverters (e.g., farms, families, factories) are located at a finite number of points along a river basin that extends from the most upstream location, $s = s_0$, down to the end of the river, $s = s_N$ (figure 1). Diverters at places $s_1, s_2, \ldots, s_N$ have utility functions

Figure 1.   Model structure and return flow coefficients

$$(1)\quad U_{s_i} = F_{s_i}(w(s_{i-1}), d(s_i),\ c(s_i)),\ i = 1, \ldots, N,$$

where $w(s_{i-1})$ is the amount of instream water before diverter s_i removes any water from the stream, $d(s_i)$ is the diversion by user s_i from the river, and $c(s_i)$ is the amount of consumptively used water from the diversion. If more than one diverter is present at s_i, then F_{s_i} represents aggregate welfare. At the river's end, $s = s_N$, the user or user group need not be a true diverter. F_{s_N} is similar to salvage value in a temporal context. If s_N is the terminal point of a tributary or stream segment, then F_{s_N} is the value of water downstream. If s_N is the place where a river system empties into the sea, then F_{s_N} could include bay and estuary values.

Instream users are continuously located on the intervals separating neighboring diverters. At each point within these intervals, instream water value is given by a location-specific function of water quantity, $g_s(w(s))$. Instream values can be aggregated across each segment of the basin to form segment-specific welfare functions for the nonrival uses undertaken by instream users. This aggregation produces N utility functions specified by

$$(2)\quad V_{s_i} = G_{s_i}(w(s_i)) = \int_{s_i}^{s_{i+1}} g_s(w(s_i))ds,$$

$$i = 0, \ldots, N - 1,$$

where $w(s_i)$ is again the amount of instream water after diversions at s_i.

The model is structured so that diversion, consumption, and return flow occur only at locations $s_1, s_2, \ldots, s_N$. Nothing prevents F_{s_i} from being zero at some locations, so it is possible to model return flow locations or special stream
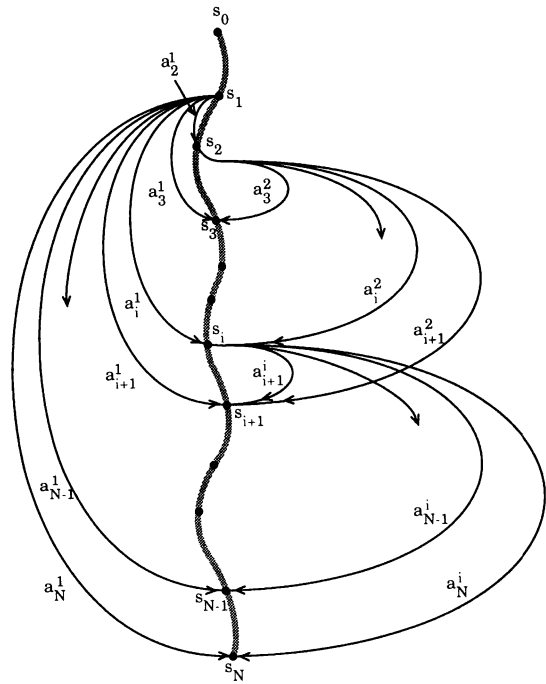
segments not demarcated by diverters. All variables are parameterized by location*s*. Conventional regularity conditions, e.g., the concavity of the utility functions G_{s_i} and F_{s_i} with respect to all arguments, are assumed.

The inclusion of several water-related variables in the preceding utility functions permits a more accurate depiction of actual water uses. For example, irrigators generally benefit from larger stream flow (w) because pumping lifts are reduced, inlet pipes are submerged, and diversion gates are functional. Diversion quantities (d) are useful to the irrigator because more uniform application rates can be achieved with greater diversions and soil salinity can be better controlled. Greater consumptive use (c) permits more irrigated acreage, higher yields, and/or more valuable crops. In urban uses, larger w typically assists water withdrawal by municipal utilities. Urban waste treatment authorities value w for its ability to receive pollutants. Many household uses are primarily dependent upon d (most aspects of sanitation) although a portion of such diversions are inevitably consumed during conveyance or in waste treatment processes. Some household uses are more dependent upon c—lawn irrigation, for example. These examples show that a single water use can simultaneously derive its value from multiple water parameters.

Typical diversions of water for any purpose will have positive derivatives of F with respect to all the identified water variables in the ranges of interest. For instream uses, however, we generally expect

$$\frac{\partial G}{\partial w} \neq 0, \frac{\partial G}{\partial d} = 0, \text{ and } \frac{\partial G}{\partial c} \cong 0$$

so d and c are omitted as arguments of G.

The amount of water flow at the initial point, s_i, of each segment is determined by the condition

$$(3) \quad w(s_i) = \bar{w}(s_i) + \sum_{k=2}^{i} \sum_{j=1}^{k-1} a_k^j (d(s_j)$$

$$- c(s_j)) - \sum_{j=1}^{i} d(s_j)$$

where $\bar{w}(s_i)$ is the stream flow without any diversion by or return flow from previous users.[3]

The convention adopted here is that $w(s_i)$ excludes water withdrawn by diverter s_i, so that $w(s_i)$ is available throughout the segment $(s_i, s_{i+1}]$. The coefficient as a_i^j characterizes the proportion of return flow of user s_j, i.e., that amount of $(d(s_j) - c(s_j))$ that comes back into the river at location i where user s_i is located (see figure 1). (Water flows down from the superscript to the subscript). Return flow can only occur downstream of the diversion point. Return flow coefficients are viewed as fixed constants representing the distribution of each user's return flow across downstream locations. We clearly must have

$$\sum_{i=j+1}^{N} a_i^j = 1, \text{ and } 0 \leq a_i^j \leq 1.$$

Equation (3) describes the influence of diversions and subsequent return flows upon instream flow for $s \in (s_i, s_{i+1})$. Recognition that a diverter's return flow can be distributed across multiple locations is a desirable model feature. This contributes to analyses concerning instream flows, for the location of return flow can matter greatly when instream flows are valuable.

The optimal consumption of water in the presence of return flows can be elucidated through the maximization of a regional welfare function.[4] The regional objective is assumed to be to choose $c(s_i)$ and $d(s_i)$, $i = 1, \ldots, N$, so as to maximize

$$(4) \quad J = \sum_{i=0}^{N-1} \{G_{s_i}(w(s_i)) + F_{s_{i+1}}(w(s_i), c(s_{i+1}), d(s_{i+1}))\}$$

subject to the N equations (3). Two obvious constraints, $d \leq w$ and $c \leq d$, at every diversion point are not included in the present model. Analytical incorporation of these constraints was not found to contribute substantially to the nature of the results, so they are omitted from the model presented here. The concept of economic efficiency embodied in this particular model is clearly one of potential Pareto optimality.[5]

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[3] Naturally occurring water inflows and losses along the watercourse can be handled within this formation as long as they are fully exogenous. Tributary inflows can normally be treated in this way. Water movement to and from a hydrologically connected groundwater body is often not exogenous, however, as these exchanges are commonly dependent upon $w(s)$.

[5] This efficiency criterion is commonly employed in models investigating optimal resource use, yet we should be mindful that it is a more restrictive criterion than Pareto optimality. The selected allocation will be Pareto optimal, but there are an infinite number of Pareto optima. Like the numerous other economic models of this type, our model will select the allocation where the net benefits of reallocation are the highest without regard to the distribution of losses or gains.

Combining the system equality constraints with the objective function, we obtain the Lagrangian expression

$$(5) \quad L = \sum_{i=0}^{N-1} G_{s_i}(w(s_i)) + \sum_{i=0}^{N-1} F_{s_{i+1}}(w(s_i),$$

$$c(s_{i+1}), d(s_{i+1})) - \sum_{i=0}^{N-1} \lambda_i \Bigg\{ w(s_i) - \bar{w}(s_i)$$

$$- \sum_{k=2}^{i} \sum_{j=1}^{k-1} a_k^j \left(d(s_j) - c(s_j) \right) + \sum_{j=1}^{i} d(s_j) \Bigg\}$$

Grouping terms differently to facilitate the derivation of necessary conditions, equation (5) becomes

$$L = \sum_{i=0}^{N-1} G_{s_i}(w(s_i)) + \sum_{i=0}^{N-1} F_{s_{i+1}}(w(s_i), c(s_{i+1}),$$

$$d(s_{i+1})) - \sum_{i=0}^{N-1} \lambda_i \{w(s_i) - \bar{w}(s_i)\}$$

$$- \sum_{i=1}^{N-1} d(s_i) \Bigg\{ \sum_{k=1}^{N-1} \lambda_k - \sum_{j=i+1}^{N-1} a_j^i \left(\sum_{k=j}^{N-1} \lambda_k \right) \Bigg\}$$

$$- \sum_{i=1}^{N-1} (c(s_i) \Bigg\{ \sum_{j=i+1}^{N-1} a_j^i \left(\sum_{k=j}^{N-1} \lambda_k \right) \Bigg\}.$$

Taking derivatives with respect to w, d, and c, the following set of necessary conditions are obtained:

$$(6a) \quad \lambda_i = \frac{\partial G_{s_i}}{\partial w} + \frac{\partial F_{s_{i+1}}}{\partial w}, \quad i = 0, \ldots, N-1;$$

$$(6b) \quad \frac{\partial F_{s_i}}{\partial d} = \sum_{k=i}^{N-1} \lambda_k - \sum_{j=i+1}^{N-1} \left(a_j^i \sum_{k=j}^{N-1} \lambda_k \right),$$

$$i = 1, \ldots, N-1; \text{ and}$$

$$(6c) \quad \frac{\partial F_{s_i}}{\partial c} = \sum_{j=i+1}^{N-1} \left(a_j^i \sum_{k=j}^{N-1} \lambda_k \right),$$

$$i = 1, \ldots, N-1.$$

Interpretations

The Lagrangian multiplier λ_i is the opportunity cost or shadow price of small changes in the variable $w(s)$ on the stream segment $(s_i, s_{i+1}]$. Thus, if diverter s_i were to forego a small unit of diversion and thereby enhance w across the entire segment $(s_i, s_{i+1}]$, the social value of this change across the immediately following stream segment is given by λ_i.

With this understanding of the economic meaning of λ_i, equation (6c) can be readily interpreted. With maximized regional welfare, user s_i's marginal benefit from consuming water that has been diverted (left hand side of (6c)) must be equal to the foregone total benefits from location s_{i+1} down to the end of the river. That is, user s_is decision not to consume a unit of diverted water bestows benefits upon all downstream users through increased return flows.

To further inspect the effect of return flow externalities upon efficient water allocation, consider any two diverters at different locations, e.g., $s_i < s_{i+h}$. A reformulation of equation (6c) implies

$$(7) \quad \frac{\partial F_s}{\partial c}\bigg|_{s=s_i} = \sum_{j=i+1}^{i+h} a_j^i \Bigg\{ \sum_{k=j}^{N-1} \lambda_k \Bigg\}$$

$$+ \sum_{j=i+h+1}^{N-1} (a_j^i - a_j^{i+h}) \Bigg\{ \sum_{k=j}^{N-1} \lambda_k \Bigg\} + \frac{\partial F_s}{\partial c}\bigg|_{s=s_{i+h}}.$$

According to (7), the marginal benefit from consuming water at location s_i must equal the sum of the foregone instream benefits from s_{i+1} down to s_{i+h+1} plus the difference between user s_i and s_{i+h} in foregone return flow benefits from location s_{i+h+1} down to the end of the river plus the foregone marginal consumptive benefit accruing to user s_{i+h}. Clearly, the return flow externalities are affected by both types of marginal instream benefits, $\partial G/\partial w$ and $\partial F/\partial w$, embodied in the λ_k's and the return flow coefficients a_j^i. In general, unless public good values such as instream flow values are insignificant, the marginal benefit from consuming water should not be identical along the river basin. Optimally, $\partial F/\partial c$ should decline from s_0 to s_N. Upstream users would otherwise tend to consume more water than their socially optimal level, and insufficient water would be allocated to instream and downstream users. If diverters' utility functions are equivalent along the basin, the concavity of F with respect to c implies that the water manager should allocate progressively more consumptive use to each diverter as we proceed downstream.

Furthermore, the pattern of return flow is important. If most of s_i's return flow would come back to the river at locations above s_{i+h+1}, then the weighted sum of the foregone instream benefits could be considerably large. Unusual hydrological circumstances can lessen or reverse some of the conclusions just drawn. For in-

stance, if none of s_i's return flow comes back to the river above location s_{i+h+1} and $a_j^i = a_j^{i+h}$ for $j \geq i + h + 1$, then the sum of the forgone instream benefits would be zero and the efficient allocation among consumptive uses would require equal marginal consumptive benefits of water for users s_i and s_{i+h}. In more extreme settings, s_i's return flow might primarily occur after the return flow of the downstream diverter s_{i+h}. In this unusual case, economic efficiency dictates lower marginal benefits of consumption at the upstream location.

Analyzing optimal diversions in a similar way, the first sum in the right hand side of (6b) is the direct opportunity cost of user s_i's decision to remove one unit of water from the stream. The second sum captures return flow benefits to all downstream users. Analogous to equation (7), equation (6b) can be rewritten as follows:

$$(8) \quad \left.\frac{\partial F_s}{\partial d}\right|_{s=s_i} = \sum_{k=i}^{i+h-1} \lambda_k - \sum_{j=i+1}^{i+h} a_j^i \left[\sum_{k=j}^{N-1} \lambda_k\right]$$
$$- \sum_{j=i+h+1}^{N-1} (a_j^i - a_j^{i+h}) \left[\sum_{k=j}^{N-1} \lambda_k\right] + \left.\frac{\partial F_s}{\partial d}\right|_{s=s_{i+h}},$$

where $s_i < s_{i+1}$. Thus, diversions should be allocated so that the marginal opportunity cost of diverting water at the upstream location s_i is equal to a rather complex set of instream water values weighted by return flow coefficients plus the marginal opportunity cost of diverting water at the downstream location s_{i+h}. A more intuitive interpretation of (8) is difficult to obtain immediately, but further clarification is forthcoming.

Water Markets with Instream Demand

Equations (6) set forth a desired norm for all allocative institutions addressing water scarcities. In this section we investigate the ability of an idealized water market to obtain these first order equations simultaneously. Intuitively, the dimensionality of policy instruments (price and quantity guides) must at least equal the dimensionality of water attributes (d, c, w) if social optimality is to be achieved. Therefore, we presume that by establishing three distinct, but coordinated, water right structures economic efficiency can be obtained. But because instream water levels can always be enhanced by reallocating diversion and consumption to points farther downstream, it may be possible to achieve optimality with only two instruments. This approach is also consistent with Johnson, Gisser, and Werner's observations concerning marketable water rights in situations where upstream transfers might harm intervening diverters.

Current legal doctrines are undergoing rapid change, varying from state to state, and these doctrines do not clearly rely on d, c, and/or w rights. Diversion and consumption rights do appear to have some emphasis, however, so it is interesting to investigate whether d and c rights systems can be managed to achieve efficient results. The objective here is to assess the feasibility of such a notion as well as to examine salient features of efficient water markets when instream flows possess value.

A Simplified Scenario

The exchange of consumption or diversion rights between any two water users produces complex effects upon others. These effects are importantly related to return flow patterns. To render the analysis more understandable and presentable, we introduce the following temporary assumption: all return flows from a diversion at s_i reenter the stream at s_{i+1}. That is, $a_{i+1}^i = 1$ and $a_j^i = 0$ for all $j > i + 1$. Equations (6) now become (9).

$$(9a) \quad \lambda_i = \frac{\partial G_{s_i}}{\partial w} + \frac{\partial F_{s_{i+1}}}{\partial w}, \quad i = 0, \ldots, N - 1;$$

$$(9b) \quad \frac{\partial F_{s_i}}{\partial d} = \lambda_i, \quad i = 1, \ldots, N - 1; \text{ and}$$

$$(9c) \quad \frac{\partial F_{s_i}}{\partial c} = \sum_{k=i+1}^{N-1} \lambda_k, \quad i = 1, \ldots, N - 1.$$

Interestingly, (7) and (8) now become

$$(10) \quad \left.\frac{\partial F_s}{\partial c}\right|_{s=s_i} = \sum_{j=i+1}^{i+h} \lambda_j + \left.\frac{\partial F_s}{\partial c}\right|_{s=s_{i+h}} \text{ and}$$

$$(11) \quad \left.\frac{\partial F_s}{\partial d}\right|_{s=s_i} = \lambda_i - \lambda_{i+h} + \left.\frac{\partial F_s}{\partial d}\right|_{s=s_{i+h}}.$$

These latter equations are intuitively lucid. In (10) we can clearly see that water consumption reallocated from s_i to a downstream diverter at s_{i+h} also produces an aggregate instream value summed across all stream segments intermediate to return flow locations s_{i+1} and s_{i+h+1}. In (11), we likewise see that the downstream reallocation of diversion water from s_i to s_{i+h} con-

tributes instream value along $(s_i, s_{i+1}]$ while losing instream value along $(s_{i+h}, s_{i+h+1}]$.

Idealized d and c Markets

A market system using d and c rights (two distinct instruments) and capable of achieving (10) and (11) is sought. Instream users who value w can conceivably participate in the c market so as to purchase and "retire" c rights—thereby increasing w. Retiring some of s_i's consumptive use does not actually increase stream flow until the point where s_i's return flow occurs (at s_{i+1} under the current simplified scenario). Stream flow is then increased for the remaining length of the river. Diversion rights can be likewise retired, but in this case stream flow is immediately but temporarily enhanced. For example, retiring one acre-foot of s_i's diversions increases w by one acre-foot across the segment (s_i, s_{i+1}) but has no impact on stream flow from s_{i+1} to s_N under the simplified scenario because the diverted water is returned at s_{i+1} (unless consumption rights are also retired). Actually, there is no need to retire either c or d rights, for it suffices to reallocate consumption and/or diversion to the farthest diverter, s_N. Such a reallocation increases w as much as retirement, and it is also available for full use by s_N. Aside from the limiting case of reallocation to s_N, there are more moderate, and more interesting, alternatives to reallocate diversion and consumption to downstream points above s_N.

Suppose water rights are initially granted only to diverters as is the prevailing custom in the west.[6] Although water availability may limit upstream transfers in true settings, let each diverter purchase rights from any other diverter. Each diverter is granted two types of rights: consumption rights, $\hat{c}_{s_i}$, and diversion rights, $\hat{d}_{s_i}$. Economic efficiency requires that prices be allowed to vary spatially, as will be demonstrated shortly. The market-clearing price for consumption rights at s_i is p_i, and q_i is the price of diversion rights at s_i.

Consider all possible transfers of consumption and/or diversion rights from diverter s_i to and from all other diverters. Let c_{ij} and d_{ij} designate transfers from diverter s_i to diverter s_j. Negative values of c_{ij} or d_{ij} represent transfers from s_j to s_i. Therefore, $c_{ij} = -c_{ij}$ and $d_{ij} = -d_{ij}$. Essential details of diverter s_i's participation in these two water markets are captured within the following individual optimization problem:

$$\max F_{s_i}(w(s_{i-1}), c(s_i), d(s_i)) + \sum_{\substack{j=1 \\ j\neq i}}^{N-1} c_{ij} p_i + \sum_{\substack{j=1 \\ j\neq i}}^{N-1} d_{ij} q_i$$

subject to $c(s_i) = \hat{c}_{s_i} - \sum_{\substack{j=1 \\ j\neq i}}^{N-1} c_{ij}$

$$\text{and } d(s_i) = \hat{d}_{s_i} - \sum_{\substack{j=1 \\ j\neq i}}^{N-1} d_{ij}.$$

Buying and/or selling is allowed within this structure. Absent from this formulation is any recognition of the impact of the diverter's market activities upon the stream flows experienced by the diverter.[7] For analytical convenience, it is presumed that these indirect impacts are small relative to the direct effects of c and d transfers. In any case, the stream flow effects upon diverters are soon addressed in combination with the more important stream flow concerns of nondiverters. Necessary conditions generated for this problem are given by (12) and (13).

(12) $\dfrac{\partial F_{s_i}}{\partial c}\dfrac{\partial c}{\partial c_{ij}} + p_i = 0 \Rightarrow \dfrac{\partial F_{s_i}}{\partial c} = p_i \quad \text{for all } s_i;$

(13) $\dfrac{\partial F_{s_i}}{\partial d}\dfrac{\partial d}{\partial d_{ij}} + q_i = 0 \Rightarrow \dfrac{\partial F_{s_i}}{\partial d} = q_i \quad \text{for all } s_i.$

Thus, if $\partial F_{si}/\partial c < p_i$, diverter s_i should sell consumption rights. If prices were constant along the basin, then these two sets of necessary conditions would imply

$$\frac{\partial F_{s_i}}{\partial c} = p = \frac{\partial F_{s_j}}{\partial c} \quad \text{for all } i, j, \text{ and}$$

$$\frac{\partial F_{s_i}}{\partial d} = q = \frac{\partial F_{s_j}}{\partial d} \quad \text{for all } i, j$$

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[6] By this assumption we intend no sanction of this custom nor does this assumption bias the results of the investigation in any meaningful way. The allocation of diversion and consumption rights among diverters has the side effect of declaring a status quo arrangement regarding sanctioned instream flow levels. It is from these initial endowments that the analysis of this section proceeds. Alternative endowments are equally addressed by this analysis in that the same first order conditions apply to all starting points.

[7] Under the simplified scenario, if diverter s_i exchanges c rights with a diverter downstream or d rights with any other diverter, then $w(s_i)$ is unaltered. If, however, the exchange involves c rights with an upstream diverter, then $w(s_i)$ is changed, and the diverter would wish to account for this benefit or harm in considering the prospective exchange.

which are inconsistent with efficiency conditions (10) and (11). Therefore, market design requires spatial pricing of consumption and diversion rights. Moreover, instream water users must participate in this market in a particular manner if the efficiency conditions are to be achieved.

The modeling of water markets requires careful attention to the externalities associated with these transactions. Within the simplified scenario, transfers of diversion quantities have no third party impacts on other diverters and will not usually affect nondiverters. Only the stream segment immediately beneath each transacting diverter will be affected by a transfer of d. Transfers of d from s_i to s_j will increase w along the stream segment (s_i, s_{i+1}) and reduce w along (s_j, s_{j+1}). This is true regardless of whether it is upstream or downstream transfer.

Transfers of consumption rights influence all intermediate diverters and nondiverters. The implications of these observations for the design of efficient markets are as follows. First, all intermediate water users should participate in transfers of consumption rights. Second, two stream segments should be involved in transfers of diversion rights.

To further develop this market setting into one capable of supporting maximum regional water value, let us introduce N "Instream Water Districts," each representing collective desires relating to instream flows along portions of the river. Instream Water District i, hereafter I_i, is an organization of all water users along $(s_i, s_{i+1}]$. Organization I_i is constructed so as to include diverter s_{i+1}'s instream interests, although these interests will generally be small in relation to the nondiverting membership of the district.

Transfers of consumption rights influence all intermediate diverters and nondiverters. If $j < i < k$, then downstream transfers of c_{jk} (>0) are beneficial to I_i. As discussed above, only stream segments (s_j, s_{j+1}) and (s_k, s_{k+1}) are affected by a transfer of d_{jk}. In order to support the efficient provision of stream flows, suppose that I_i participates in water marketing by subsidizing consumption transfers benefiting the district and accepting compensation for diversion transfers harming the district. The unit price paid by the district for c_{jk} is p^{I_i}, and the unit price paid for d_{jk} is q^{I_i}. The district's optimization problem is then to maximize

$$G_{s_i}(w(s_i)) + F_{s_{i+1}}(w(s_i), c(s_{i+1}), d(s_{i+1}))$$

$$- \sum_{j=1}^{i} \sum_{k=i+1}^{N} p^{I_i} \cdot c_{jk} - \sum_{j=i+1}^{N} q^{I_i} \cdot d_{ij}$$

with respect to the selection of $w(s_i)$, c_{jk}, and d_{jk} subject to

$$w(s_i) = \bar{w}(s_i) + \sum_{j=1}^{i} \sum_{k=i+1}^{N} c_{jk} + \sum_{j=i+1}^{N} d_{ij}$$

where $\bar{w}(s_i)$ identifies preexchange water levels. Forming the appropriate Lagrangian and using the same multipliers as before for convenience,

$$L_{I_i} = G_{s_i}(w(s_i)) + F_{s_{i+1}}(w(s_i), c(s_{i+1}), d(s_{i+1}))$$

$$- \sum_{j=1}^{i} \sum_{k=i+1}^{N} p^{I_i} \cdot c_{jk} - \sum_{j=i+1}^{N} q^{I_i} \cdot d_{ij}$$

$$- \lambda_i \left\{ w(s_i) - \bar{w}(s_i) - \sum_{j=1}^{i} \sum_{k=i+1}^{N} c_{jk} - \sum_{j=i+1}^{N} d_{ij} \right\}$$

District responses to this price system are embodied in the resulting first order conditions which presume $j \le i < k$:

$$(14a) \quad \lambda_i = \frac{\partial G_{s_i}}{\partial w} + \frac{\partial F_{s_{i+1}}}{\partial w}, \quad i = 0, \ldots, N - 1$$

$$(14b) \quad p^{I_i} = \lambda_i, \quad i = 1, \ldots, N - 1;$$
$$1 \le j \le i < k \le N;$$

$$(14c) \quad q^{I_i} = \lambda_i, \quad i = 1, \ldots, N - 1;$$
$$1 \le j \le i < k \le N.$$

These conditions are valid for all c_{jk} and d_{ij} regardless of sign, that is, both upstream and downstream transfers. By (14b) and (14c), $p^{I_i} = q^{I_i}$. One of these price variables is superfluous, because the district is indifferent to the type of transfer impacting it—a unit of water of increase/decrease in stream flow possesses the same value regardless of whether it results from a c or d exchange. Dropping q^{I_i} and comparing economic efficiency conditions (10) and (11) with market equilibrium conditions (12), (13), (14b), and (14c), optimal market pricing is feasible if

$$(15) \quad p_i = \sum_{j=i+1}^{i+h} p^{I_j} + p_{i+h} \quad \text{and}$$

$$(16) \quad q_i = p^{I_i} - p^{I_{i+h}} + q_{i+h}.$$

For either downstream or upstream reallocations, an idealized market appears to require two special features. First, a spatially dependent price is needed. Second, collaborative market participation by instream users is needed. Each of N distinct "Instream Water Districts" representing

the aggregate interests of each stream segment $(s_i, s_{i+1}]$ should receive compensation in the amount of λ_i for unit transfers of c or d rights harming the district and pay a like amount for beneficial transfers. As w is a nonrival and nonexclusive good, there are obvious problems associated with the functionality of Instream Water Districts, but the need is clear and the device is illustrative for another incentive-based policy to be identified later.

Spatial price differentiation and participation by Instream Water Districts are interrelated, and district participation takes on different forms for these two markets. Overall, an efficient price system for consumption and diversion rights is captured by (15) and (16). Within the simplified scenario, all instream water districts lying between the return flow locations of transacting diverters should participate in transfers of c rights. Other districts are irrelevant to this type of exchange. When d rights are exchanged, only two districts need be involved. A transfer of d_{ij} (>0) should be accompanied by compensation for district I_j and copayment by district I_i. In equilibrium, it is optimal for a district to employ the same marginal valuation of c and d rights in both markets for all transfers affecting the district.[8] These conclusions are specific to the simplified scenario.

Spatial differentiation of optimal prices is only required when instream flows possess value at the margin. Where preferences do not extend to instream flow quantities or when instream flows are at high levels where $\partial G/\partial w$ and $\partial F/\partial w$ are everywhere zero (implying zero λ_i's), there is no need for differentiated prices or Instream Water Districts. In general though, uniform prices across a basin are incompatible with economic efficiency. Price differences between locations should reflect instream values of affected third parties. When prices are appropriately established, economic efficiency can be achieved with two instruments, c and d property rights, and a third instrument pertaining to instream flow rights would be redundant. If prices are spatially invariant, however, the market system will promote an allocation pattern where water is consumed farther upstream than is optimal. In general, it cannot always be said that diversion prices should increase systematically as one proceeds upstream (equation (16)). Similarly, a uniform diversion price, while inconsistent with

efficiency, does not necessarily cause water to be diverted farther upstream than is optimal.[9]

Marketing beyond the Simplified Scenario

Whether the general or simplified scenario is best suited to a given basin depends upon the distributions of both diverters and return flows which serve to partition the river into segments. In the simplified case where $a_{i+1}^i = 1$ and $a_j^i = 0$ for all $j > i + 1$, the original social optimality conditions become greatly clarified, and the potential for water marketing is lucid. This optimal marketing contrasts with the current conduct of water marketing in the west. Current marketing procedures typically provide for the administrative or quasi-judicial hearing of objections by potentially harmed diverters, and if a claim of potential harm is substantiated the proposed transfer is denied. Positively affected diverters have no apparent roles, however, and nondiverters have little standing regardless of whether they are positively or negatively impacted (Colby).

Where return flow is distributed across multiple downstream locations, the required institutions are somewhat more complex. In the generalized situation, water markets or other institutions must pursue equations (7) and (8) rather than the simplified (10) and (11). In the more general case, it remains clear that consumption and diversion prices require spatial definition. Furthermore, under an efficient market system c prices will typically decrease in a particular manner as one moves downstream. Again, use of a single diversion price and a single consumption price implies that consumption of water will occur farther upstream than is optimal (i.e. instream levels will be too small). These conclusions are substantively unaltered from the simplified case.

The potential for constructive participation by Instream Water Districts is clouded in the most general case however. Required district participation is now complex, for the return flow coefficients now serve as weights upon the marginal benefits/costs of all districts receiving direct or secondary return flows from either con-

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[8] Admitting transaction costs would alter this conclusion and justify compensation prices that are larger than copayment prices (Foley).

[9] If all diverters have equivalent utility functions and all instream users do too, and if $w(s_i)$ increases as $i \mapsto N$ as is commonly true, the concavity of utility functions with respect to w can be employed to argue that λ_i decreases as $i \mapsto N$(equation (14a)). Under these conditions p^{l_i} also decreases as $i \mapsto N$, and equation (16) implies that diversion prices should be lower as $i \mapsto N$. Concavity of diverters' utility functions with respect to d then implies that uniform diversion prices would allocate water diversions farther upstream than is optimal.

tracting party. District participation is no longer constrained to those districts lying between the buyer and seller. Every district downstream of the uppermost transactor is potentially relevant to the transaction. This conclusion becomes more apparent when (7) and (8) are revised so as to collect terms for each district's λ_i. First, define a new variable,

$$A_k^i = \sum_{j=i+1}^{k} a_j^i$$

representing s_i's accumulated return flow coefficients down to $s_k \cdot A_k^i$ is the proportion of s_i's return flow having returned to the stream anywhere from s_{i+1} to s_k, inclusive. After careful manipulation, equations (7) and (8) can be rewritten as

$$(17) \quad \left.\frac{\partial F_s}{\partial c}\right|_{s=s_i} = \sum_{k=i+1}^{i+h} A_k^i \lambda_k + \sum_{k=i+h+1}^{N-1}$$

$$\{A_k^i - A_k^{i+h}\}\lambda_k + \left.\frac{\partial F_s}{\partial c}\right|_{s=s_{i+h}}, \text{ and}$$

$$(18) \quad \left.\frac{\partial F_s}{\partial d}\right|_{s=s_i} = \lambda_i + \sum_{k=i+1}^{i+h-1} \{1 - A_k^i\} \lambda_k$$

$$- A_{i+h}^i \lambda_{i+h} - \sum_{k=i+h+1}^{N-1} \{A_k^i - A_k^{i+h}\} \lambda_k + \left.\frac{\partial F_s}{\partial d}\right|_{s=s_{i+h}}$$

The λ_k are ordered from λ_i to λ_{N-1} in both of these equations to facilitate examination. Here, it is observed that all instream districts downstream of the uppermost transactor are potential parties to a c or d transaction and that optimal participation by districts requires prices which are weighted λ_i's. Weights applied to the λ_i's are potentially different in the two markets, particularly for districts lying between the transactors. Also, districts downstream from both transactors do not become irrelevant until that point on the river where all of both transactors' return flow has reentered the river ($A_k^i = A_k^{i+h} = 1$). Depending on the hydrological features of the basin, market operations capable of producing efficient results can be complex.

Administratively Established Incentives

The formation of Instream Water Districts is problematic in light of the information costs for elliciting accurate and funded valuation state-

ments from member individuals. It may also be worrisome that each district possesses the market power to prevent upstream transfers by establishing a suitably high asking price.[10] Fortunately, while the preceding analysis has been presented in the context of direct water market participation by instream users, clear implications for the design of related institutions are also present.

In lieu of Instream Water Districts, a state or regional agency can erect and manage a system of economic incentives based upon hydrological information regarding return flow coefficients and economic research concerning marginal instream values for each river segment. Agency-promulgated incentives, the λ_i, would likely vary along the river. Diverters who are considering market-based exchanges with other diverters would have to carry out their bargains with the knowledge that agency incentives represent subsidies for downstream transfers and charges for upstream transfers in accordance with equations (17) and (18). This type of policy mechanism is advantageous in that it still relies upon the decentralized market for managing water allocation responsive to consumption and diversion values. That is, the agency need not concern itself with any valuations other than for instream flows. Because it sidesteps the demand relevation problem to be experienced by Instream Water Districts, the economic incentives approach may be a superior policy.

Conclusions

The model developed here employs a highly generalized framework capturing essential details of hydrologic interdependencies among water users. The results are intuitively supported and offer an insightful perspective concerning policy opportunities for achieving economic efficiency when some user groups benefit from instream flow levels. To summarize the most policy-relevant results, water marketing is capable of promoting potential Pareto optimality if the fol-

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[10] It is noteworthy, however, that these districts are envisioned as participants in upstream and downstream transfers of rights. Such two-way activity creates a more practical policy. Market involvement by districts is predicated on the districts' statements of λ_i— an amount indicating willingness to pay for downstream transfers and willingness to accept for upstream transfers. Misstatement of λ_i is potentially harmful to the district: overstatement may serve districts' interests by limiting upstream transfers, but to do so would constrain district income—income employed to subsidize downstream exchanges.

lowing elements are included in market design

(*i*) Transferable diversion andconsumption rights must be established. These rights can be exchanged independently or together. (Because of inseparabilities in most uses, market transactions would likely involve both *d* and *c* rights simultaneously.)

(*ii*) Return flow coefficients must be established to identify where each diverter's return flow reenters the water body. This information is required for every diverter engaged in water marketing.

(*iii*) An institutional mechanism such as Instream Water Districts or administratively established economic incentives is needed to establish market presence for those individuals with preferences concerning instream flows. In the case of either districts or incentives, equations (17) and (18) dictate how unrestricted market exchanges between diverters need to be corrected in *c* and *d* markets, respectively.

These are the three fundamental components of an efficient system of water marketing. When instream flows do not have value, a system of *c* and *d* rights with trade only involving diverters is capable of managing return flow externalities—much like the early literature's reference to two-tiered pricing of diversion rights and return flow quantities.

The optimality results identified here demonstrate the complexity of achieving economic efficiency when instream flow is valuable. To simply allow instream users or user groups to purchase water rights is not a complete solution for the issue of allocating water to instream flows. The problem is substantially more complicated. Even when the implications of nonrivalness and nonexclusiveness are set aside, optimal market participation by instream users is a complex affair (recall equations (17) and (18)). Current trends to permit water right ownership by instream users can serve to improve resource allocation, but the consequences appear inadequate. The primary reason is that market transfers among diverters will continue to neglect instream water values in the absence of the third fundamental component above. It is noteworthy that both the public good character of instream water use and the absence of a proper interface between instream users and diverters result in the underallocation of water for instream purposes.

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