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The allocative efficiency and conservation potential of water laws encouraging investments in on-farm irrigation technology

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Abstract

Agricultural water conservation statutes are emerging in the West encouraging private irrigators to improve on-farm irrigation efficiency as a basinwide conservation measure. We investigate whether private improvements promote the economic efficiency and conservation of water use basinwide under a wide variety of hydroeconomic circumstances. The standard of efficiency is how an irrigation district manager should optimally invest in improving the irrigation efficiencies of individual farms located along a stream while internalizing intrabasin allocative externalities of these investments. The results indicate that the popular Oregon legislative model may be the least effective in conserving water and promoting economically efficient water allocation. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Basinwide conservation measure; On-farm irrigation technology; Investments

1. Introduction

Farmers have long been shifting to more technically efficient irrigation methods to capture private benefits from increased crop yield and quality, increased efficiency in the use of nutrients and chemicals, and reduced irrigation labor costs (Hydrosphere Resource Consultants, 1991). On-farm irrigation efficiency is defined as the ratio of the water stored in the crop root zone for consumptive use to the total water diverted for irrigation (Whittlesey et al., 1986). Increased irrigation efficiency allows farmers to apply water more uniformly across fields, thereby enabling crops to sustain or increase their consumptive use of water from smaller diversions. For example, improv-

ing irrigation efficiency from 25 to 80% reduces the diversion needed to meet a prior crop demand for 2 units of consumptive use from 8 to 2.5 units.

Irrigators, policy makers, environmentalists, and journal commentators generally contend that the reduction in diversion due to increased on-farm irrigation efficiency (5.5 units in the above example) constitutes water savings that can be used to increase the reliability of water supplies for both instream uses and irrigation (Columbia and Snake River Irrigators Association (CSRIA, 1994); Honhart, 1995; Moon, 1993; Oregon Environmental Council, 1994; Oregon Trout, 1994; Pagel, 1993). Consistent with this contention, the federal government and several western states have passed (or are contemplating passing) agricultural water conservation laws encouraging farmers to further invest in improved on-farm irrigation technology. For example, Oregon's *equitable division* policy [Or. Rev. Stat. §537.455 (Supp. 1994)], appor-

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tions the reduced diversions between the efficiency improving irrigator (to spread over additional acreage) and the public (to apply to instream uses), and thus is recommended to other western states as a *win-win* policy (Honhart, 1995). Washington [SB5527 (1997 and 1998 Regular Sessions)] and Colorado (Honhart, 1995) have considered similar policies over multiple legislative sessions. In another example, the federal Yakima River Basin Water Enhancement Project Act [Pub. L. No. 103–434 §1201] provides public financing for improvements in on-farm irrigation efficiency and earmarks the reduction in diversions to increase the reliability of the water supply for both instream flows and irrigation.

We analyze whether increases in on-farm irrigation efficiency can succeed in meeting the water conservation objectives of the above statutes/bills for a wide range of western hydrologic circumstances, and the consequences of a failure to do so on the economic efficiency of water allocation in an irrigated river basin. Our analysis proceeds in two stages. We initially formulate a continuous version of an interspatial optimal water allocation model and use the necessary conditions to qualitatively explain how an irrigation district manager, interested in maximizing the net economic benefits of water allocation across all agricultural users within a river basin, should invest in improving the on-farm irrigation efficiencies of individual farms. Net economic benefits include the farm specific benefits of increasing irrigation efficiency and any external costs inflicted on other water rights holders. This qualitative standard of basinwide efficiency represents how private irrigators should invest in improving irrigation efficiency if their legal rights to water hold them accountable for the external costs of their decisions.

We next solve the optimal water allocation model by reformulating it as a discrete problem whose solution as an empirical nonlinear programming problem facilitates the introduction of important policy and hydrologic restrictions (i.e. statutory instream flow constraints). The optimal solution provides a numerical standard of basinwide efficiency against which the simulated operation of a representative agricultural water conservation statute is compared for its allocative efficiency and effectiveness in conserving irrigation water. We conclude by recommending how effective and efficient agricultural water conservation policy should be crafted.

2. A qualitative standard of basinwide economic efficiency

Our focus on the basinwide economic efficiency of increasing on-farm irrigation efficiencies requires the formulation of an optimization-based water allocation model falling within the gaps left by previous modeling efforts. The only previous economic model determining optimal basinwide investment in improving on-farm irrigation efficiency investigated the case in which diverted water unconsumed by crops is irretrievably lost to the basin (i.e. irrigation return flows are zero) (Chakravorty et al., 1995). Because irrigation return flows constitute a significant portion of stream flows in the West (Hydrosphere Resource Consultants, 1991), we extend the analysis to a hydrologic system including irrigation return flows. Our model differs from past optimization-based return flow models (Hsu and Griffin, 1992) by focusing on investment in on-farm irrigation efficiency as the mechanism controlling consumptive water use in agriculture.

Following Chakravorty, Hochman and Zilberman (CHZ), we consider a single irrigation district delivering water over a single irrigation season to equally productive farms located along a river of constant depth and within an irrigated basin of constant width measured in miles (m). Let x represent the distance (m) from the origin of basin inflows ($x = 0$) to the point at which the irrigation district delivers water to a given farm. The amount of water delivered to, and diverted by, the farm at location x is $q(x)$ and the level of consumptive water use by crops is $e(x)$. Each quantity is in acre feet per square mile (AF/m²). On-farm irrigation efficiency at x is defined as

$$h[I(x)] = \frac{e(x)}{q(x)} \quad (1)$$

where $0 \leq h \leq 1$ is assumed to be an increasing and concave function of an investment undertaken to improve it, $I(x)$ (\$/m²), i.e. $h'(I) > 0$; $h''(I) < 0$, where $h'(\cdot)$ and $h''(\cdot)$ represent first and second partial derivatives, respectively. Each farm produces one crop whose yield per square mile, $f[e(x)]$, is assumed to be an increasing and concave function of consumptive water use, i.e. $f'(e) > 0$, and $f''(e) < 0$. The constant unit output price of the crop is denoted by p .

Departing from CHZ, we assume that some portion $0 \leq \delta_1 \leq 1$ of the difference between the water

diverted from the stream and consumed by crops on the farm (i.e. the unconsumed diversion) eventually returns to the stream. A value $\delta_1 = 0$ represents an “open” hydrologic basin where unconsumed diversions are irretrievably lost to the basin. Alternatively, $\delta_1 = 1$ represents a “closed” hydrologic basin where unconsumed diversions return to the river as irrigation return flows. Finally, a value $0 < \delta_1 < 1$ represents a range of intermediate cases in which unconsumed diversions are split between irretrievable losses (i.e. evaporative losses) and irrigation return flows. For the purposes of this paper (i.e. deriving a qualitative standard of basinwide efficiency for investing in improved irrigation efficiency), we simplify matters by assuming that irrigation return flow reenters the river at the point of initial diversion.

Let $z(x)$ (AF) denote the volume of instream flow at x for a fixed irrigation season. Also, let $z'(x)$ (AF/m) represent the spatial rate of change of instream flow at x , which is given by

$$z'(x) = -q(x)\alpha + \delta_1 q(x)\{1 - h[I(x)]\}\alpha - \delta_2 z(x) \quad (2)$$

Instream flow adjusts at each location x according to the volume of water diverted and applied over the width of the river basin, $q(x)\alpha$, the portion of the unconsumed diversion that reenters the river as irrigation return flow, $\delta_1 q(x)\{1 - h[I(x)]\}\alpha$, and the portion of instream flow lost in seepage to an underlying aquifer, $\delta_2 z(x)$, where $0 \leq \delta_2 \leq 1$ is the proportional seepage rate. For example, a 1980 water budget demonstrates that the Eastern Snake Plain Aquifer System was recharged in the amount of 0.4 MAF with seepage from the Snake River (Hydrosphere Resource Consultants, 1991, p. 2.6). For simplicity, we assume that aquifer recharge of the river occurs outside the basin.

The irrigation district manager’s assumed objective is to select diversions, $q(x)$, and levels of investment in irrigation efficiency, $I(x)$, to maximize the total net benefits (\$) accruing along the river in a single cropping season, i.e.

$$\max_{q, I} \int_0^X \{pf[e(x)] - I(x)\}\alpha dx \quad (3)$$

subject to equation of motion (2) and where X represents the fixed length of the river within the basin. We introduce nonnegativity conditions on $q(x)$ and

$I(x)$ because corner solutions on the controls turn out to be pivotal in analyzing the basinwide economic efficiency of improving on-farm irrigation efficiency.

Following Takayama (Theorem 8.C.1), (Takayama, 1985) the Lagrangian function (\$/m) for this problem is

$$L = [pf(e) - I]\alpha + \lambda\{-q\alpha + \delta_1 q[1 - h(I)]\alpha - \delta_2 z\} + \mu_q q + \mu_I I \quad (4)$$

where $\lambda = \lambda(x)$ (\$/AF) is the marginal value of instream flows at x , and μ_q and μ_I are multipliers associated with the non-negativity restrictions on $q(x)$ and $I(x)$. The spatial designation of each variable is dropped for notational brevity, i.e. $z = z(x)$, $q = q(x)$, $I = I(x)$, and $e = e(x)$.

The necessary conditions for optimization are

$$L'(q) = pf'(e)h(I) - \{1 - [1 - h(I)]\delta_1\}\lambda(x) + \frac{\mu_q}{\alpha} = 0 \quad (5a)$$

$$L'(I) = [pf'(e) - \delta_1 \lambda(x)]qh'(I) - 1 + \frac{\mu_I}{\alpha} = 0 \quad (5b)$$

$$L'(z) = -\lambda'(x) = \delta_2 \lambda(x) \quad (5c)$$

$$\mu_q q = \mu_I I = 0 \quad (5d)$$

Assuming that the manager can optimally divert some quantity of water at x , i.e. $q(x)^* > 0$, implies that $\mu_q = 0$ in Eq. (5a) by complementary slackness conditions (5d). Then, optimality condition (5a) requires that the diversion at each location x be set at the level balancing the marginal value product of diversion, $pf'(e)h(I)$ (i.e. the marginal value product of consumptive water use weighted by the increase in consumptive use due to an incremental increase in diversion), against the marginal value of instream flow, $\lambda(x)$, weighted by a term accounting for the extent to which unconsumed diversion reenters the river as irrigation return flow. In short, incrementally increasing diversion at x redistributes water application to that point, which is optimal only when the marginal benefits at x balance the opportunity costs of any foregone production at other locations measured by $\lambda(x)$.

When diversions are set optimally along the river, $\lambda(x)$ defines the price that the manager assesses for diverted water at each location. It is measured as follows

for the polar hydrologic cases (Eq. (5a)):

$$\lambda(x) = pf'(e)h(I), \quad (\delta_1 = 0) \quad (6a)$$

$$\lambda(x) = pf'(e), \quad (\delta_1 = 1) \quad (6b)$$

In the presence of irrigation return flows ($\delta_1 = 1$), optimal water prices are equated with the marginal value product of consumptive water use, $pf'(e)$. Alternatively, in the absence of return flows ($\delta_1 = 0$), and when farms are less than 100% efficient in irrigation ($h < 1$), optimal water prices are equated with the marginal value product of diverted water, $pf'(e)h(I)$, and thus are set lower at all locations than those in the return flow case. Optimal prices are identical in the two polar cases only when on-farm irrigation efficiency is 100% so that there is no unconsumed diverted water available to reenter the river as irrigation return flow.

Eq. (5b) dictates that the manager invest in improving irrigation efficiency at x , i.e. $I(x)^* > 0$, when the marginal net benefits of a positive level of investment offset the unitary marginal cost of investment, in which case $\mu_1 = 0$ by complementary slackness conditions (5d). The marginal net benefits of investment are measured as the weighted difference between the marginal benefits of increased consumptive water use at x , $pf'(e)$, and the foregone marginal value of any resulting decreased irrigation return flows that would have supplied downstream farms, $\delta_1\lambda(x)$, where the weight is given by the marginal increase in consumptive water use by crops due to an increase in on-farm irrigation efficiency, $qh'(I)$. In short, a positive level of investment in increasing on-farm irrigation efficiency is optimal at location x when the net economic impact of trading off downstream for upstream benefits is positive at the margin of consumptive water use, and is greater than the unitary investment cost.

The extent to which such a spatial tradeoff is expected to generate positive marginal benefits depends on underlying hydroeconomic circumstances. In the absence of irrigation return flow ($\delta_1 = 0$), improved irrigation efficiency does not effect a spatial tradeoff. To see this, substitute $\delta_1 = 0$ into necessary condition (5b):

$$pf'(e)qh'(I) - 1 = 0 \quad (7)$$

The manager is required only to select an investment level equating the marginal agricultural benefits of increasing irrigation efficiency with the site specific

unitary marginal cost of the investment. The absence of return flows removes the linkage between upstream and downstream water use, so that downstream opportunity costs are zero. Consequently, an investment in irrigation efficiency that is cost effective at an individual farm promotes basinwide economic efficiency because the associated increase in consumptive water use decreases the portion of the diversion that is irretrievably lost to the basin. A diversion creates agricultural benefits at only one location, so the location should be as efficient in consumptive water use as is cost effective.

Consider next the polar case in which all unconsumed diverted water reenters the river as an irrigation return flow ($\delta = 1$). Substituting λ from Eq. (6b) into necessary condition (5b) yields a positive value for the slack variable $\mu_1 = \alpha > 0$. This signifies that the marginality condition for investing optimally in irrigation efficiency does not hold anywhere along the river, and thus the optimal investment is held constant at zero at all locations, i.e. $I(x)^* = 0$, by the complementary slackness conditions (5d). The basinwide optimal solution is for all farms to continue operating with the status quo irrigation technology at efficiency $h(I = 0)$. In sum, the marginal benefits accruing to the efficiency improving farm are exactly offset by the external costs imposed on a downstream farm which has had its water supply cut short due to decreased irrigation return flow. In intermediate cases ($0 < \delta_1 < 1$), these external costs gain greater weight in devaluing the basinwide net benefits of investing in on-farm irrigation efficiency as the fraction of unconsumed diversion reentering the river as irrigation return flow increases (i.e. δ_1 , increases toward 1).

The above standards of basinwide efficiency also govern how private irrigators should invest in improving on-farm irrigation efficiency when they are liable for the external costs of such investment. In the absence of irrigation return flows, public policy promotes basinwide efficiency by encouraging individual farms to increase their irrigation efficiencies. Alternatively, as return flows become more prominent in basin hydrology, such policy becomes increasingly inefficient. In the limiting case (i.e. all unconsumed diverted water returns to the river), private investments effect a zero sum redistribution of economic benefits along the river which cannot recoup the positive private costs of investment.

In the Section 3, we formulate a more hydrologically complex discrete version of the continuous basinwide optimal water allocation model. The solution of the discrete formulation as an empirical nonlinear programming problem establishes a baseline against which the economic efficiency and conservation potential of a representative agricultural water conservation statute can be illustrated for a range of hydrologic circumstances.

3. Empirical formulation

The discrete formulation of the optimal water allocation model is given by

$$\max_{q, I} \sum_{x=1}^X \{pf[e(x)] - I(x)\} \alpha \quad (8a)$$

$$z(x) = z(x-1) - q(x)\alpha + \delta_1 q(x-1) \times \{1 - h[I(x-1)]\} \alpha - \delta_2 z(x-1) \quad (8b)$$

$$z(x) \geq z_c, \quad \text{for } x \geq 1 \quad (8c)$$

$$z(0) = z_0 \quad (8d)$$

Eq. (8a) is the discrete objective function which is interpreted the same as its continuous counterpart in Eq. (3). All units of measurement remain the same as in the continuous model except for α which represents the basin's constant cross sectional areal width (m^2) in the discrete formulation. Eq. (8b) calculates the instream flow at a given location x as the flow at adjacent upstream location $x-1$ plus the net change in flow between the two locations. Flow decreases between the two points due to diversion at x , i.e. $q(x)\alpha$, and seepage at $x-1$, i.e. $\delta_2 z(x-1)$. Flow increases by the portion of unconsumed diversion at $x-1$ reentering the river at x , i.e. $\delta_1 q(x-1)\{1-h[I(x-1)]\}\alpha$. The nonlinear programming solution solves for the optimal instream flows satisfying this recursive relationship simultaneously (Howitt, 1996). Eq. (8c) imposes an instream flow constraint requiring that stream flow at each location be at least as large as some publicly determined level z_c . Western states generally rely on such constraints to protect public instream uses such as hydropower generation, recreation, fish and wildlife habitat. Finally, Eq. (8d) fixes basin inflow (i.e. flow at $x=0$) at an exogenously determined level z_0 .

3.1. Policy simulation model

The discrete optimal water allocation model (8a)–(8d) can be modified to simulate the general operation of a representative agricultural water conservation policy. Our representative policy is drawn from the Oregon agricultural water conservation statute [Or. Rev. Stat. §537.455 (Supp. 1994)], and the federal Yakima River Basin Water Enhancement Project Act (Yakima Project Act) [Pub. L. No. 103–434 §1201, 108 Stat. 4526 (1994)]. Both policies encourage individual farmers to increase on-farm irrigation efficiency with the expectation that water will be conserved. Oregon offers efficiency improving irrigators a portion of the conserved water to spread over additional acreage [§537.470(3) (Supp. 1994)]. The Yakima Project Act authorizes the Secretary of the Interior to provide funding assistance to the efficiency improving irrigators [§1203(j)(3)]. Both policies measure water savings in terms of reduced diversions [Or. Rev. Stat. §537.455(1) (Supp., 1994); Yakima Project Act §1205(a)(1)]. Finally, to satisfy their statutory purposes of increasing water for public instream uses, basin irrigators must be restricted from appropriating conserved water to firm up unfulfilled appropriative rights or to expand those rights.

The above shared characteristics constitute the representative agricultural water conservation policy that we simulate by adding two sets of restrictions to the discrete model specified in Eqs. (8a)–(8d). First, an equality constraint fixes investment in on-farm irrigation efficiency at an arbitrary level, I_f , exceeding the baseline optimal value at a given diversion point x_f :

$$I(x_f) = I_f \quad (9)$$

Second, to protect any conserved water from further appropriation, a set of inequality constraints restricts all farms along the river to appropriate at most baseline levels, $q_b(x)$, i.e.

$$q(x) \leq q_b(x), \quad \text{for } x = 1, \dots, X \quad (10)$$

3.2. Empirical information

Empirical solution of the discrete specification as a nonlinear programming problem requires that functional forms be specified for production, $f[e(x)]$, and

on-farm irrigation efficiency, $h[I(x)]$, and that the associated parameters be calculated. Consistent with the restrictions imposed in the last section, $f[\cdot]$ and $h[\cdot]$ are specified as the following quadratic functions:

$$f[e(x)] = a_0 + a_1 e(x) - a_2 e(x)^2 \quad (11a)$$

$$h[I(x)] = b_0 + b_1 I(x) - b_2 I(x)^2 \quad (11b)$$

where parameters a_0 , a_1 , a_2 , b_0 , b_1 , and b_2 are non-negative.

The parameters for production function (11a) are calculated from data representing a *Russet Burbank* commercial potato operation in southern Idaho. The 1997 crop budget formulated by the University of Idaho Cooperative Extension System shows that a square mile of land requires a water application of 1382.4 AF to produce 272,000 cwt of potatoes. This translates into a consumptive water use of $e(x) = q(x)h = (1382.4)(0.8) = 1105.92$ AF/m², given the budget's irrigation efficiency of 80%. For the purposes of this illustration, we presume that: (1) there is no yield when consumptive water use is zero, i.e. $f(0) = a_0 = 0$; (2) the consumptive water use derived from the crop budget generates the maximum yield, i.e. $f'(1105.92) = 0$; and (3) the yield curve is a symmetric negative quadratic function so that production is zero at twice the maximum yield consumptive use level, i.e. $f(2211.84) = 0$. Under these circumstances, Cramer's Rule can be applied to solve for the two parameters of the production function from the following system:

$$\begin{aligned} 425 &= a_1(1105.92) - a_2(1223059.05)^2, \\ 0 &= a_1(2211.84) - a_2(4892236.19)^2 \end{aligned} \quad (12)$$

The parameters are calculated to be $a_1 = 491.898$ and $a_2 = 0.222393$.

The parameters for the irrigation efficiency investment function (11b) are estimated from data reported in a study linking irrigation application systems of various efficiencies to their total annualized costs in dollars per acre (Roberts et al., 1986, Table 3.2). The OLS estimated irrigation efficiency function is

$$h(I) = 0.5947 + 0.0000047I - 0.00000000023I^2 \quad (13)$$

We calculate the seepage rate parameter δ_2 (in units of m⁻¹) from information available in a recent study

of the Eastern Snake River Basin in southern Idaho (Hydrosphere Resource Consultants, 1991, p. 2–4). The Snake River stretches approximately 300 miles across the basin and has an average flow of 4.3 million acre feet (MAF) in the upper reaches, and 2 MAF in the lower reaches, giving an overall average of 3.15 MAF. Of this 3.15 MAF, approximately 0.4 MAF were lost as seepage to the Eastern Snake Plain Aquifer as reported in a 1980 water budget (Hydrosphere Resource Consultants, 1991, Table 2–1). Thus, the fractional seepage loss is 0.127 (=0.4/3.15), or $\delta_2 = 0.0004$ (=0.127/300) per mile of river.

4. Comparison of the basinwide optimal policy with the representative conservation policy

4.1. Presence of irrigation return flow

Fig. 1 compares the operation of the basinwide optimal water allocation policy with the representative agricultural water conservation policy in the presence of irrigation return flow ($\delta_1 = 1$). Without loss of generality, we work with the following scaled down hypothetical river basin. The basin's cross sectional areal width is one square mile (i.e. 640 acres or a *section* of land), and there are 10 diversion points within the basin. The volume of basin inflow is $z_0 = 10,000$ AF in a given irrigation season. The seniority of water rights runs upstream so that, for example, the farm at $x = 1$ has the most senior right and that at $x = 10$ the least senior right. The instream flow constraint protecting environmental uses is assumed to require that stream flow at each location be at least $z_c = 1000$ AF. Recall that $x = 0$ represents the location of basin inflow and that diversions do not commence until $x = 1$.

Consistent with the standard of basinwide efficiency derived in the last section, the optimal policy is to not invest in improved on-farm irrigation efficiency at any diversion point except for that at the bottom of the basin, $x = 10$. The rationale for the investment at $x = 10$ is discussed below. Thus, the optimal policy holds on-farm irrigation efficiency at the status quo level of approximately 60% at each interior diversion point ($0 < x < 10$) (Fig. 1(a)). We define the representative water conservation policy to call for an investment of $I_f = \$61,737.70/\text{m}^2$ at diversion point

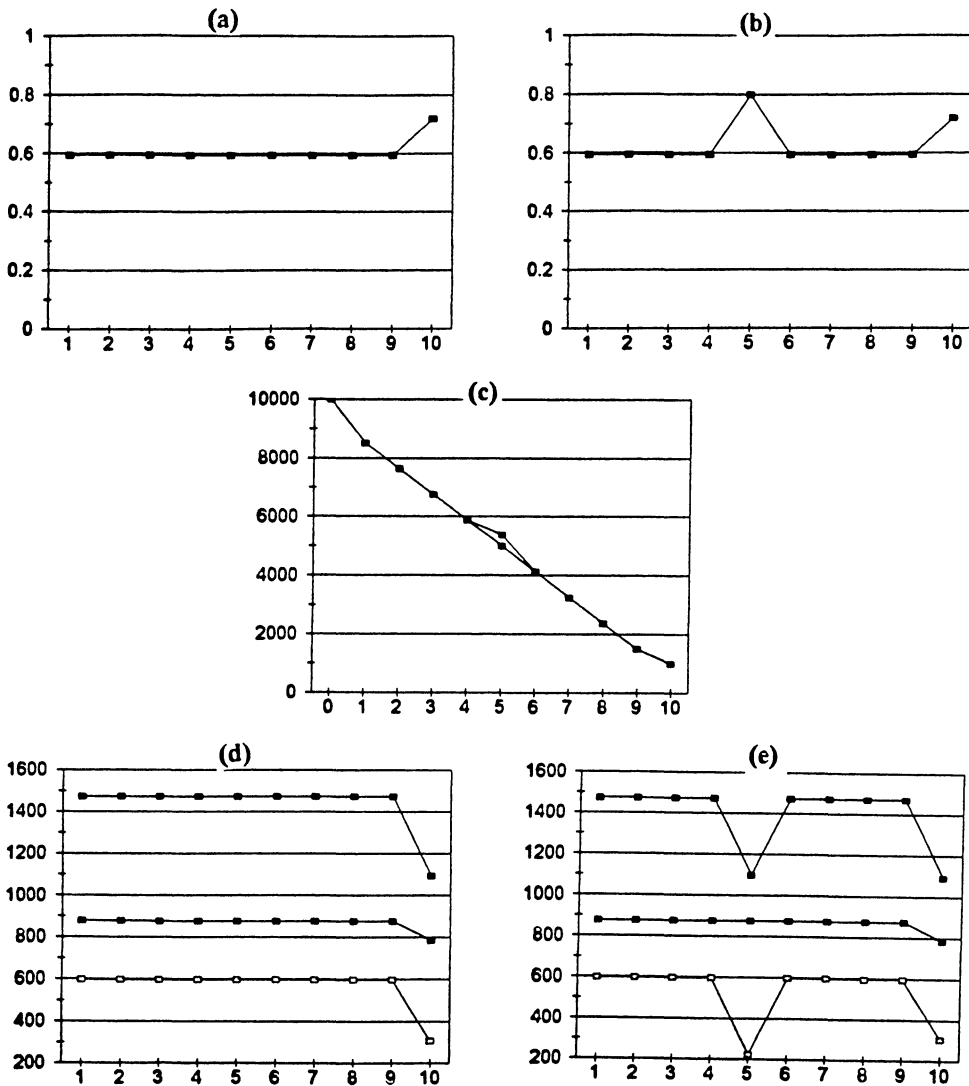


Fig. 1. Comparison of basinwide optimal water allocation policy with the representative agricultural water conservation policy in the presence of return flow: (a) irrigation efficiency under the optimal policy; (b) irrigation efficiency under the representative policy; (c) instream flows under the optimal policy (lower curve) and the representative policy (upper curve); (d) diversion (upper curve), consumptive use (middle curve), and return flow (lower curve) under the optimal policy; (e) diversion (upper curve), consumptive use (middle curve), and return flow (lower curve) under the representative policy.

$x_f = 5$, which increases its irrigation efficiency to 80% (Fig. 1(b)).

Fig. 1(c) plots instream flow under the optimal and conservation policies at each diversion point in the basin. The plots are coincident except at $x = 5$, where instream flow increases by 375 AF under the conser-

vation policy. Fig. 1(d) and (e) shed some light on the hydrologic significance of this augmented flow at $x = 5$, and the reason that it disappears by the next diversion point $x = 6$. These figures plot diversion (upper curves), consumptive water use (middle curves), and unconsumed diverted water (lower curves) over the 1

square mile cross sectional width of the basin for the basinwide optimal policy (Fig. 1(d)) and the representative water conservation policy (Fig. 1(e)).

Under the optimal policy, farms at interior diversion points ($0 < x < 10$) each divert approximately 1473 AF, and given identical irrigation efficiencies of 60%, consume approximately 876 AF (Fig. 1(d), top curve). Diversion and consumptive use decreases a little as one moves downriver due to the impact of seepage losses to the aquifer. The basin inflow $z_0 = 10,000$ AF is sufficiently large that the instream flow constraint $z_c = 1000$ AF is nonbinding at all diversion points within the basin except for the last at $x = 10$. The farm at this point has the least senior water right, and thus meets the instream flow constraint by diverting less water than upstream farms (i.e. 1091.98 AF). However, the optimal policy allows this farm to achieve the same consumptive water use as upstream farms by calling for an investment in on-farm irrigation efficiency which increases it to 72%.

Consistent with the design of the representative conservation policy, each farm is restricted to diverting at most the basinwide optimal levels. Fig. 1(e) shows that: (1) diversions (upper curve) remain at basinwide optimal levels at all points except for $x = 5$ where demanded diversion is reduced by 375 AF ($=1473-1098$) in response to the increased irrigation efficiency at that point; (2) consumptive water use (middle curve) remains constant at baseline optimal levels at all points; and thus (3) unconsumed diverted water (lower curve) decreases at $x = 5$ by 375 AF ($=597-222$), which represents a reduction in the irrigation return flow from $x = 5$ that replenishes instream flow at downstream reentry point $x = 6$. In sum, the incremental increase in instream flow due to decreased diversion at the point of increased irrigation efficiency is exactly offset by the decrease in instream flow due to decreased irrigation return flow at the downstream reentry point.

Consequently, when an irrigator increases irrigation efficiency in the presence of irrigation return flow, the reduction in demanded diversion signals the intrabasin redistribution of water between instream flow and irrigation return flow rather than the creation of additional water. Reduced diversion gives the illusion of water conservation because instream flow increases between the point at which on-farm irrigation efficiency in-

creases and the point at which unconsumed diversion reenters the river. Conservation policy encouraging irrigators to invest in increased on-farm irrigation efficiency is economically inefficient because illusory water savings cannot generate the additional basinwide economic benefits needed to offset the cost of investment.

Such policy may become increasingly economically inefficient when it permits the efficiency improving farm to mistakenly claim reduced diversion as conserved water to be spread over additional irrigated acreage (e.g. as per Oregon's *equitable division* policy discussed in the introduction). The efficiency improving farm's use of illusory water savings to irrigate additional acreage means that, in reality, water is being taken from other farms in the basin. Such redistribution of water might enhance basinwide economic efficiency if the water were redistributed away from less productive farms, but existing statutory water conservation policies contain no restrictions that would generate this result consistently.

4.2. Absence of irrigation return flow

Fig. 2 compares the operation of the basinwide optimal water allocation policy with the representative agricultural water conservation policy in the absence of irrigation return flows ($\delta_1 = 0$). Recall that, in the absence of return flows, an investment in improving irrigation efficiency that is cost effective at an individual farm also promotes basinwide economic efficiency. Similarly, the conservation potential of the representative agricultural water conservation policy turns out to also depend on whether investment is cost effective. Cost effectiveness depends, in turn, on the availability of water relative to the level of consumptive use needed to maximize crop yield. We illustrate these results by comparing the optimal with the representative policy during "normal" and "low" flow irrigation seasons.

In a "normal" flow irrigation season, basin inflow is assumed to be sufficiently large that each of the 10 farms in the basin can feasibly divert the water needed to meet the level of consumptive water use maximizing yield per square mile (i.e. 1105.92 AF by Eq. (11a)) at the status quo irrigation efficiency of 60%, while satisfying the public instream flow restriction $z_c =$

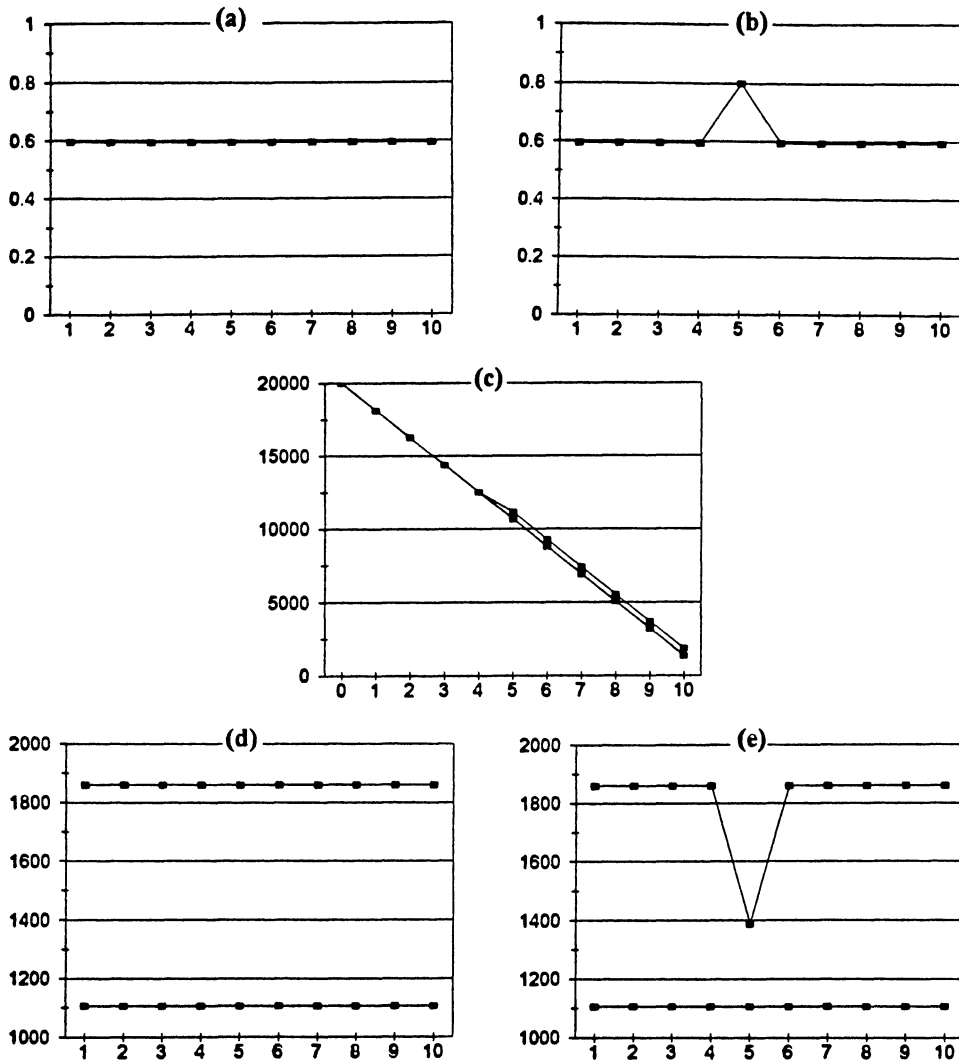


Fig. 2. Comparison of basinwide optimal water allocation policy with the representative agricultural water conservation in the absence of return flow (normal flow year): (a) irrigation efficiency under the optimal policy; (b) irrigation efficiency under the representative policy; (c) instream flows under the optimal policy (lower curve) and the representative policy (upper curve); (d) diversion (upper curve) and consumptive use (lower curve) under the optimal policy; (e) diversion (upper curve) and consumptive use (lower curve) under the representative policy.

1000 AF. A level of basin inflow meeting these conditions for this illustration is $z_0 = 20,000$ AF, and this value underlies Fig. 2(a)–(e).

The basinwide optimal policy is to maintain on-farm irrigation efficiency at the status quo level of 60% (Fig. 2(a)). The reason is that, at the status quo irrigation efficiency, the optimal diversion (≈ 1859.53

AF/farm in Fig. 2(d)) leads to an optimal consumptive use of water (1105.92 AF/farm in Fig. 2(d)) that is identical to the yield maximizing level. Under these circumstances, there is no economic incentive to invest in improving irrigation efficiency to further increase consumptive water use, i.e. investment is cost ineffective.

By design, the representative conservation policy increases irrigation efficiency to 80% at $x = 5$ and holds it at basinwide optimal levels everywhere else (Fig. 2(b)). Also by design, each farm is restricted to diverting at most basinwide optimal levels. Fig. 2(e) shows that diversions (upper curve) remain at basinwide optimal levels for all points except for $x = 5$ where diversion decreases by 472.33 AF (=1859.53–1387.20). Despite the reduced diversion, increasing irrigation efficiency to 80% maintains consumptive water use (lower curve) at the yield maximizing level (i.e. 1105.92 AF in Fig. 2(e)). Instream flow increases at $x = 5$ by the 472.33 AF of reduced diversion (=1142.14–10669.81, Fig. 2(c)), and this increment is sustained at all downstream diversion points because, in the absence of return flow, the associated decline in unconsumed diversion is irretrievably lost and thus has no offsetting impact on instream flow.

In summary, when unconsumed diversion does not return to the river, and when investment in improved irrigation efficiency is cost ineffective because consumptive water use is near the yield maximizing level for the status quo irrigation efficiency, then the representative water conservation policy truly creates additional water in the basin equal to the reduction in demanded diversion at the point of increased irrigation efficiency.

Finally, consider the impact of a “low” flow irrigation season in which basin inflow is insufficient for each farm to divert enough water to meet the yield maximizing consumptive water use level at the status quo irrigation efficiency of 60% while satisfying the public instream flow constraint $z_c = 1000$ AF. A basin inflow meeting these conditions for this illustration is $z_0 = 10,000$ AF, and this value underlies Fig. 3(a)–(e).

The basinwide optimal program roughly divides the difference between basin inflow and the instream flow constraint, i.e. $z_0 - z_c = 10000 - 1000 = 9000$ AF, equally among the identically productive 10 farms in the basin, so that each farm receives approximately 898 AF to divert while satisfying the instream flow constraint (Fig. 3(d), top curve). Upstream farms receive a bit more water than average, and downstream farms a bit less, due to the accumulation of seepage losses from the river. The average diversion of 898 AF would translate into an average consumptive water use of 538.8 AF per farm if each remained

at the status quo irrigation efficiency of 60%, i.e. $(898)(0.6) = 538.8$. However, this level of consumptive use is well below the yield maximizing yield, 1105.92 AF. Hence, the optimal policy calls for each farm to increase consumptive use to approximately 668 AF (Fig. 3(d), lower curve) by increasing irrigation efficiency to about 74% (Fig. 3(a)).

As before, the representative conservation policy increases on-farm irrigation efficiency at $x = 5$ –80% while holding efficiency at all other points constant (Fig. 3(b)). Also as before, diversions are restricted to be no greater than basinwide optimal levels. In contrast to the “normal” flow case, the demanded diversion under the conservation policy is not adjusted downward at the efficiency improving farm ($x = 5$), but, similar to the other farms in the basin, remains at the optimal baseline level (Fig. 3(d) and (e), top curves). By diverting at the maximum allowable level, the efficiency improving farm increases consumptive use to 715.71 AF (Fig. 3(e), bottom curve), and thus makes the greatest possible stride toward the yield maximizing level. However, also in contrast to the “normal” flow case, instream flow is not increased under the conservation policy (i.e. the instream flow curves for the optimal and representative policies are coincident in Fig. 3(c)), and thus water is not conserved. In summary, when unconsumed diversion does not return to the river, and when investment in improved irrigation efficiency is cost ineffective because consumptive water use is far below the yield maximizing level for the status quo irrigation efficiency, then the representative water conservation policy fails to create additional water in the basin.

The overall performance of the representative agricultural water conservation policy in the absence of return flow is troublesome because it may be ineffectual in conserving water when conservation is needed the most (i.e. during low flow years), and effectual when conservation is less important (i.e. during normal flow years).

5. Discussion

Given that agricultural water conservation policy focusing on diversion may be economically inefficient and ineffectual in conserving water in wide ranging hydroeconomic circumstances, what are some other policy options? One option is to allow unrestricted

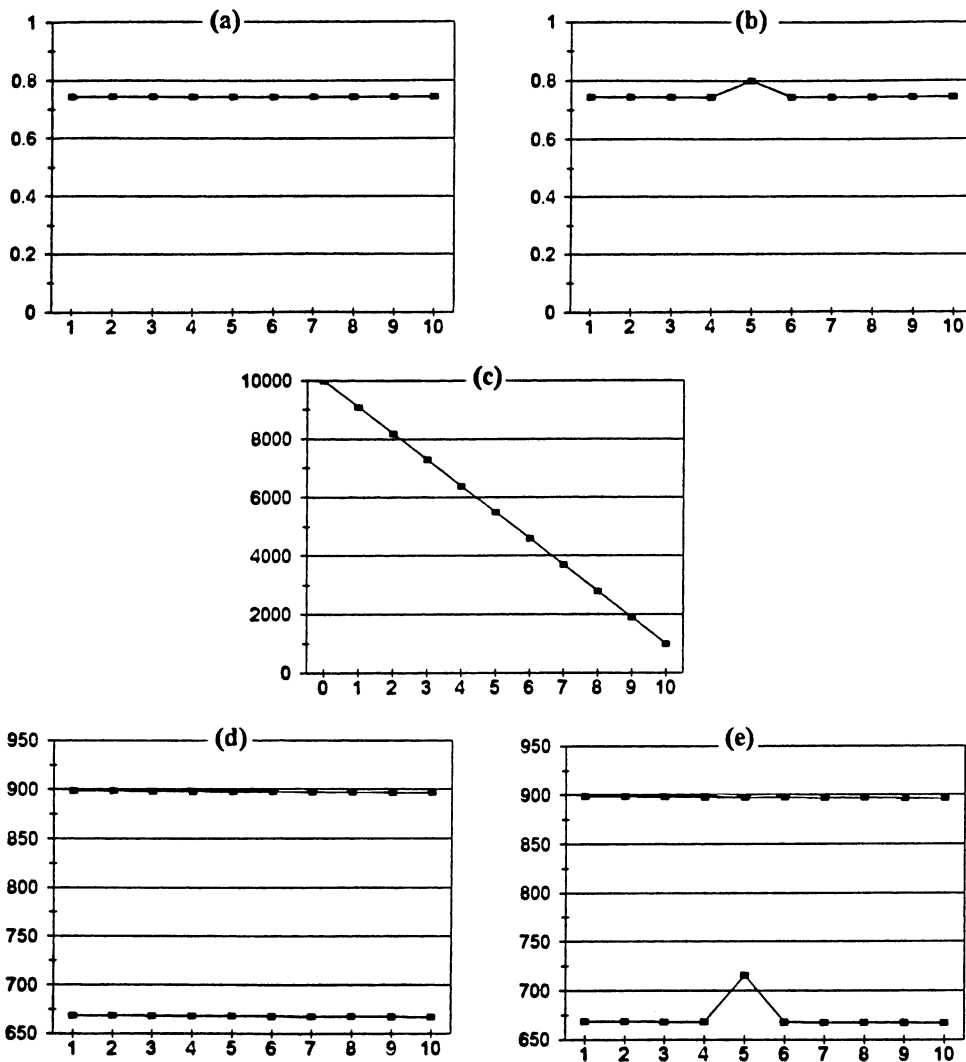


Fig. 3. Comparison of basinwide optimal water allocation policy with the representative agricultural water conservation policy in the absence of return flow (low flow year): (a) irrigation efficiency under the optimal policy; (b) irrigation efficiency under the representative policy; (c) instream flows under the optimal policy (lower curve) and the representative policy (upper curve); (d) diversion (upper curve) and consumptive use (lower curve) under the optimal policy; (e) diversion (upper curve) and consumptive use (lower curve) under the representative policy.

private investment in improving on-farm irrigation efficiency, but somehow facilitate bargaining between the efficiency-improving irrigator and negatively impacted water users downstream to voluntarily internalize return flow externalities. Unfortunately, the potentially large transaction costs associated with such bargaining are a major reason that water markets have

failed to proliferate within the framework of the prior appropriation system (Gould, 1988; Parala and Benson, 1995). Hence, several economists recommend avoiding the return flow impacts of water marketing as much as possible by limiting trading to the seller's consumptive water use (Gardner, 1980; Milliman, 1959).

Following this logic, another policy option is to encourage only those private investments in on-farm irrigation efficiency that do not decrease the return flows relied upon by downstream appropriators and instream uses. Return flows are not reduced if investment leads to reductions in the water consumed or irretrievably lost to the basin, or if the reduction in irretrievable water loss is at least as large as the increase in consumptive use. Such policy neutralizes the return flow externality, and does not discourage private investments in the absence of irrigation return flows when it leads to net water savings in satisfaction of the above requirements.

The California agricultural water conservation statute is an example of such a policy designed to operate effectively and efficiently under either the presence or absence of irrigation return flow. It grants efficiency improving irrigators a portion of conserved water measured as

the reduction of **the amount of water consumed or irretrievably lost** in the process of satisfying beneficial uses which can be achieved either by improving the technology of the method for diverting, transporting, applying, reusing, salvaging, or recovering water, or by implementing other conservation methods.

[Cal. Water Code §10521(a) (West Supp. 1992), *boldface added*].

Since this definition is consistent with the way in which water is truly conserved in both non-return-flow and return-flow systems, the California statute encourages private investments in on-farm irrigation efficiency only when such investments lead to actual, and not illusory, water savings. This ensures that such investments enlarge the basinwide economic benefits of water use, and not simply redistribute them inefficiently among irrigators along the river.

Although the California agricultural water conservation statute appears better suited to the general hydrologic conditions of the West, the Oregon statute measuring conservation in terms of diversionary quantities seems to be preferred by other western states designing their own programs (see, e.g. State of Washington House Bill 1113 (1997 Regular Session)), and water-policy commentators (see, e.g. Honhart, 1995; Rawson, 1994). The legislative history of the Oregon statute sheds some light on possible reasons.

Interestingly, Oregon's current statute amended an earlier version that, identical to California, measured conserved water as "...the reduction of the amount of water consumed or irretrievably lost..." (Or. Rev. Stat. §537.455 (1)(1987)). However, some agricultural interests in the state viewed this definition as overly restrictive, and argued that a more liberal definition in terms of reduced diversions would join the *equitable-division* policy in providing adequate incentives for voluntary water conservation (Moon, 1993). Environmental groups supported the revised statute, apparently under the mistaken perception that reduced diversion could be equated generally with reduced use [see, e.g. Oregon Environmental Council, 1994; Trout Unlimited of Oregon, 1994; Oregon Trout, 1994]. The state Water Resources Commission agreed that "...the concept of 'irretrievably lost' often leaves little water defined as 'conserved' even though the reduced diversion may be large" (Pagel, 1993). Evidently, Oregon shifted to a less restrictive, but generally inappropriate, standard of water conservation in a misguided attempt to provide stronger private incentives for voluntary water conservation and increase the quantity of water savings.

Alternatively, California has maintained a definition of water conservation that is more restrictive of private conservation efforts, but more consistent with hydrologic reality. Two years before the agricultural water conservation statute passed; the California Water Commission, the California Department of Water Resources, and the San Joaquin Valley Agricultural Water Committee cosponsored a statewide workshop on agricultural water conservation (California Water Commission, 1982). The widely representative participants recognized a number of the principles guiding the economic efficiency of water use and conservation basinwide derived in this paper. They agreed that "...the benefits of 'conservation' must be real rather than simply perceived," and that "[a] State-sponsored... water conservation program... will become a meaningful, workable, significant, acceptable and practiced part of our water policy only if the water is truly conserved..." They also agreed that guaranteeing real conservation made it essential to distinguish "...between the 'efficiency of use' for... an individual farm... and... an entire hydrologic basin," and "...between recoverable and irrecoverable losses." Consistent with these principles,

they recognized that "...reduction of... irrigation return flow may indicate a higher farm efficiency but may at the same time produce negligible net savings and adversely impact other owners... downstream on the canal or river system" (pp. 6–7). In short, California adopted a relatively restrictive, and generally appropriate, standard of water conservation that is consistent with its emphasis on determining whether a conservation investment will yield true water savings.

6. Concluding comments

The current decade has witnessed the emergence of legislation in the irrigated West encouraging private investment in on-farm irrigation efficiency to promote agricultural water conservation. The bulk of this legislation focuses on the impact that a farm's increased irrigation efficiency has on the level of its irrigation diversions and ignores the impact on other components of the hydrologic system. It measures agricultural water conservation as the reduction in a farm's diversions before and after the increase in irrigation efficiency. The focus on irrigation diversions may not present a problem when water users along the river are not linked by irrigation return flows. Under these circumstances, reduced diversions truly represent water conservation and improved on-farm irrigation efficiency promotes basinwide economic efficiency since the water allocations of all water users can be increased with the water savings.

However, focusing on a farm's diversions creates problems when irrigation return flows are an important component of hydrologic systems, as in many areas of the West. The reduction in diversions no longer measures water conservation. Such a measure conceals the true impact of increasing an individual farm's irrigation efficiency in a return-flow system, which is to increase the consumptive water use of the efficiency improving farm without creating any new water, and to reduce irrigation return flows supplying water to downstream users. In effect, the efficiency improving farm's additional consumptive use is funded by an involuntary water transfer and tradeoff of agricultural benefits from a downstream irrigator. Agricultural water conservation legislation defining water conservation in terms of diversions in return flows systems will trigger these types of trade-

offs unexpectedly, and thus fail to optimally manage them to ensure basinwide economic efficiency.

We recommend that states avoid these tradeoffs altogether by following California's lead in approving only those private conservation investments that produce true water savings. True conservation in return flows systems occurs when crops consume less water (e.g. by irrigating fewer acres, growing crops requiring less water, or deficit irrigation), or water is recovered that is otherwise irretrievably lost.

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