The Implications of Surface–Ground Water Hydrology for Optimal Conjunctive Management

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Introduction

Broadly interpreted, conjunctive management is concerned with the joint regulation of surface and ground water resources. In the Eastern Snake Plain of Idaho, conjunctive management has developed largely as a tool to regulate surface and ground water diversion by agricultural irrigators. The practical upshot of Idaho's conjunctive management rules is that the state may reduce ground water pumping in order to ensure adequate flows for owners of senior surface water rights. This approach is consistent with established water rights institutions, but was developed without detailed knowledge of the hydrologic relationship between surface and ground water (Cosgrove and Johnson 2004; 2005). Questions remain about the most economically efficient means of allocating surface and ground water across irrigators given the characteristics of the region's water system (Cosgrove and Johnson 2005; Slaughter 2004).

This article addresses the question: How does the hydraulic relationship between surface and ground water affect the economically optimal allocation of water across surface and ground water irrigators? We present an economic model of optimal conjunctive water management that incorporates different hydraulic relationships between surface and ground water.[2] We then use that model to simulate observed conditions on the Eastern Snake Plain. The results of the simulation analysis demonstrate that optimal conjunctive management differs significantly with the form of the hydraulic relationship between surface and ground water. More generally, the analysis shows that incorporating the characteristics of natural systems into an economic analysis can inform more efficient policy decisions.

Surface and Ground Water Relationships

Whenever a surface water body overlies an aquifer, the two water stocks may be classified, at any point in space and time, as hydraulically disconnected or connected.[3] The key difference between the two regimes is that ground water pumping does not affect the quantity of surface water available in a disconnected system, but reduces surface water availability in a connected system.

In a hydraulically disconnected system, the surface water stock is separated from the aquifer by an unsaturated zone (figure 1a). In this case, water flows from the surface water stock into the

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[2] By "optimal management," we mean the amount of surface and ground water diverted that maximizes aggregate irrigator surplus. We do not consider other management objectives, such as maintenance of minimum flows for hydropower production or environmental services.

[3] Whether the surface body is disconnected, connected–losing, or connected–gaining may vary significantly over space and time, shifting across reaches of a river or with precipitation events (Winter 1998).

aquifer. A hydraulically connected system, in contrast, is one in which the water table is sufficiently high in elevation that the surface water body and the aquifer are not separated by an unsaturated zone. In a connected system, the surface water stock may be losing to or gaining from the aquifer. In a losing regime (figure 1b), water flows from the surface water stock into the aquifer; in a gaining regime (figures 1c), water flows from the aquifer into the surface water stock.

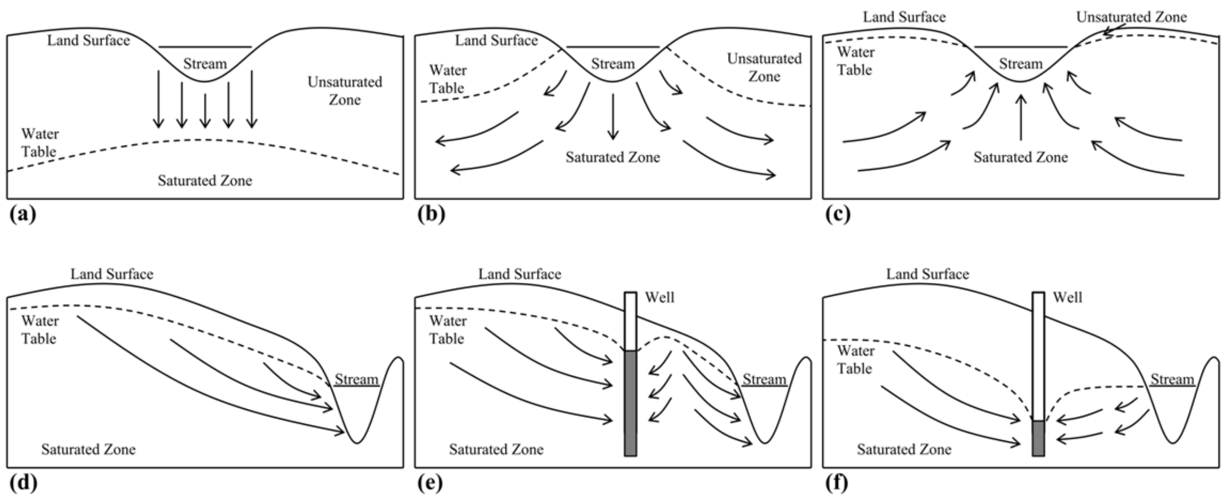

Figure 1. Hydraulic Connectivity and the Effect of Groundwater Pumping
Notes: Panels (a)-(c) depict types of hydraulic regimes: (a) disconnected stream-aquifer system; (b) hydraulically connected–losing system; (c) hydraulically connected–gaining system. Panels (d)-(f) depict the potential impact of pumping on a hydraulically connected system with a gaining stream: (d) an undeveloped system; (e) pumping reduces discharge; (f) pumping eliminates discharge, system switches to losing stream. Figures reproduced based on Winter (1998).

In a connected–losing regime, ground water pumping plays a key role in determining the rate at which water moves from the surface water stock into the aquifer: As pumping increases and the water table falls, the rate of recharge increases, drawing more water out of the surface stock and into the aquifer. In a connected–gaining system, an increase in ground water pumping reduces the water table, reducing the rate at which water flows from the aquifer back into the surface water stock (figure 1e).[4] Regardless of whether the system is losing or gaining, hydraulic connectivity implies that ground water pumping reduces surface water supplies, though the mechanism by which that process occurs differs between the two regimes.

Hydraulic Connectivity in the Economic Literature

Though connectivity between surface and ground water stocks is recognized in the scientific literature (Miller et al. 2003), the economic literature predominantly considers water management in the context of disconnected systems. The bulk of the economic literature on

[4] In the extreme, pumping may cause a gaining regime to shift to a losing regime, thereby eliminating discharge from the aquifer into the surface water stock and increasing the rate at which the surface water stock loses water to the aquifer (figure 1f). This situation is not considered in the analysis. We assume that the losing and gaining reaches are perennially losing and gaining, respectively, as is the case in the study region.

optimal water management follows a seminal analysis by Gisser and Sanchez (1980), who examine ground water pumping from an unconfined, renewable aquifer. The basic premise of their analysis is that ground water exhibits some characteristics of a common property resource. Thus, individual ground water pumpers, when left to their own devices (i.e. when operating in a perfectly competitive environment), choose a rate of diversion that does not account for the effect of their pumping on the height of the water table and on their neighbors' pumping costs. Optimal regulation of ground water pumping addresses these externalities and should, in theory, increase aggregate irrigator welfare. They find that this is not the case, particularly for large aquifers. A number of subsequent studies examine the extent to which this result is driven by the behavioral and hydrologic assumptions of the original analysis.[5]

A subset of this literature focuses specifically on the returns to optimal management in systems that rely on both surface and ground water. These studies vary substantially in their approach and results. For example, Knapp and Olson (1995) and Tsur and Graham-Tomasi (1991) consider the implications of stochasticity in the surface water supply. The former find little difference in the returns to ground water management when including uncertainty, while the latter present evidence that ground water possesses significant value as a buffer against surface water variability. Despite their differences, analyses in this literature generally share the assumption that surface and ground water resources are hydraulically disconnected.

An exception is a study by Burness and Martin (1988), which explicitly considers a connected–losing hydraulic regime. In this situation, ground water pumping generates an externality for surface water users by decreasing surface water flows (in addition to increasing pumping costs for other ground water users). They demonstrate qualitatively that economic optimality requires that surface water be diverted prior to any ground water pumping and that ground water pumping decreases over time before reaching a steady state. However, they do not compare their result with what would occur in a hydraulically disconnected system, nor do they quantify the difference between the optimal management plan and that in which water users operate in a perfectly competitive environment.

A Model of Optimal Water Management

The analysis herein extends the economic literature on optimal water management. We develop a model to quantify the surface and ground water diversions that maximize economic welfare across agricultural irrigators.[6] Our analysis differs from the bulk of the literature in two key respects. First, we quantitatively compare the allocation of water across surface and ground water users when the stocks are managed independently and when they are managed conjunctively. Second, we explicitly consider the different types of hydraulic relationships that characterize surface–ground water interaction.

We develop six model variants that differ economically and hydraulically. We present two economic scenarios—one in which surface and ground water are managed independently and one in which they are managed conjunctively—and three hydraulic scenarios. The hydraulic scenarios include a system in which surface and ground water are disconnected, one in which

[5] Koundouri (2004) provides a comprehensive summary of the literature. More recent extensions include Saak and Peterson (2007) and Brozovic et al. (2010).
[6] The basic structure of the model can be adapted to accommodate other users and other management objectives.

they are connected and the surface water body is losing to the aquifer, and one in which they are connected and the surface water body is gaining from the aquifer.

In specifying the model, we consider the simplest functional forms that capture the basic characteristics of the problem. We assume separate linear demand curves for surface and ground water, of the form $W = a + bP_S$ and $M = c + dP_G$, respectively.[7] W denotes surface water diversions, M denotes ground water pumping, P_S and P_G are the per-unit prices of surface and ground water, and a, b, c, and d are parameters. In each period, the gross benefits associated with surface and ground water use are given by the area below the demand curve. The net benefits of water use are given by the area below the demand curve and above the marginal cost curve for water. We assume that the marginal cost of diverting surface water is effectively zero (Contor et al. 2008). The marginal cost of pumping ground water depends on the elevation of the water table, H. The marginal cost of pumping a unit of ground water is given by $MC_G = m + nH$ (Gisser and Sanchez 1980). The per-period net benefits of water diversions are

$$\frac{1}{2b}W^2 - \frac{a}{b}W$$

for surface water, and

$$\frac{1}{2d}M^2 - \frac{c}{d}M - (m + nH)M$$

for ground water.

The first economic scenario considered is that in which the surface and ground water stocks are managed optimally but independently. Optimal management of ground and surface water implies that any externalities between users within a group are internalized, as are any temporal externalities associated with water use. The only remaining externalities are those that arise between ground and surface water users. Specifically, ground water users do not take into account the impact of pumping on the surface water stock and surface water users do not take into account the impact of their diversion decisions on ground water levels. In the second economic scenario, ground and surface water are managed conjunctively to maximize the sum of irrigator surplus across surface and ground water users. Under conjunctive management, any externalities between surface and ground water irrigators are internalized. The objective functions by economic scenario are listed in table 1.

[7] There is little conjunctive use of surface and ground water at the individual level in the study region. Overlap of surface and ground water rights boundaries is on the order of 0.72 percent of all permitted acreage (IDWR 2011). Even if an individual producer owns both ground and surface water rights, by-and-large that water is not being applied to the same fields. Under these circumstances, it is appropriate to model the demand curves for surface and ground water as separate because there is limited opportunity for substitution between water sources.

Table 1. Objective Functions and Constraints by Scenario

Objective Function by Economic Scenario

Scenario (1): Independent Management

Surface Water

$$\max_{W_t} \int_0^\infty e^{-rt} \left(\frac{1}{2b} W_t^{\,2} - \frac{a}{b} W_t \right) dt$$

Ground Water

$$\max_{M_t} \int_0^\infty e^{-rt} \left[\frac{1}{2d} M_t^{\,2} - \frac{c}{d} M_t - (m + nH_t) M_t \right] dt$$

Scenario (2): Conjunctive Management

$$\max_{W_t, M_t} \int_0^\infty e^{-rt} \left[\frac{1}{2b} W_t^2 - \frac{a}{b} W_t + \frac{1}{2d} M_t^{\,2} - \frac{c}{d} M_t - (m + nH_t) M_t \right] dt$$

Constraints by Hydraulic Scenario

Scenario (a): Hydraulically Disconnected System

$$\dot{S} = R_S - \alpha(S - W) + (\gamma - 1)W$$

$$\dot{V} = R_V + \alpha(S - W) + \varphi W + (\delta - 1)M$$

Scenario (b): Hydraulically Connected–Losing System

$$\dot{S} = R_S - \alpha(H)(S - W) + (\gamma - 1)W$$

$$\dot{V} = R_V + \alpha(H)(S - W) + \varphi W + (\delta - 1)M$$

Scenario (c): Hydraulically Connected–Gaining System

$$\dot{S} = R_S + \beta(H)V + (\gamma - 1)W$$

$$\dot{V} = R_V - \beta(H)V + \varphi W + (\delta - 1)M$$

Notes: $\dot{S} = dS/dt$, $\dot{V} = dV/dt$, and $\dot{V} = A \cdot S \cdot \dot{H}$, where *A* and *S* are time-invariant parameters.

In addition to the objective functions, we need to specify how irrigator diversions affect the dynamic behavior of the surface water stock, denoted *S*, and the ground water stock. The ground water stock is denoted *V*, where $V = A \cdot S \cdot H$. This is the simple "bathtub" aquifer model in which the total volume of water available for pumping equals the area of the aquifer (*A*) times its storativity (*S*) times the height of the water table above the base of the aquifer (*H*). We assume, as is common in these models, that *A* and *S* are fixed and that changes in the volume of ground water are due solely to changes in the height of the water table.

We consider ground and surface water dynamics in the context of three hydraulic scenarios. Hydraulic scenario (a) represents a hydraulically disconnected system, scenario (b) represents a connected–losing system, and scenario (c) represents a connected–gaining system. Table 1 specifies the dynamic constraints (equations of motion) for each water stock by hydraulic scenario.

There are several commonalities across hydraulic scenarios. R_S and R_V denote exogenous net recharge to the system. In all scenarios, a fixed proportion of water diverted from either source is consumed by plants. For surface water diversions (*W*), a fixed proportion of excess water applied, given by γ, flows back into the surface water stock as return flows. The remaining proportion, given by φ, percolates directly into the aquifer. This latter proportion is known as incidental recharge, which has historically accounted for on the order of 60 percent of total recharge to the Eastern Snake Plain Aquifer (DAI 2012). Of water pumped from the aquifer (*M*), the proportion of applied water that is not consumed, given by δ, percolates back into the aquifer.[8]

The three hydraulic scenarios differ in how water moves between the surface and the ground water stock. In a disconnected system, some proportion of water in the surface water stock, given by α, percolates directly into the aquifer. In a connected–losing system, water seeps from the surface stock into the ground water stock, but the rate at which it does so depends on the height of the water table: The rate of recharge is a function of H and is denoted $\alpha(H)$. In a connected–gaining system, water does not move from the surface water stock directly into the aquifer. Rather, water seeps from the aquifer into the surface water stock. The rate at which is does so depends on the height of the water table and is given by $\beta(H)$. In a connected–gaining system, water moves into the aquifer only via exogenous natural recharge and incidental recharge from surface water applications.

Numerical Simulation Analysis

For the simulation analysis, we consider three reaches of the Snake River that represent hydraulic scenarios (a)-(c). Based on Kjelstrom (1995) and Johnson et al. (1998), we model the disconnected system after the Lewisville-to-Shelley reach, the connected–losing system after the Heise-to-Lorenzo reach, and the connected–gaining system after the Hagerman-to-King Hill reach (Figure 2). For each scenario, we numerically solve for the optimal steady-state values of surface and ground water diversions. To parameterize the simulations, we draw on Kjelstrom (1995), and derive other parameters based on the state of the system at the time of Kjelstrom's study. The parameters are reported in table 2 and described briefly here.

[8] No excess ground water applied runs off into surface water bodies. We have not found any evidence that return flows from ground water irrigation contribute significantly to surface water flows. This may be the case if fields irrigated with ground water tend to be distant from surface waterways or lack return flow conveyance infrastructure.

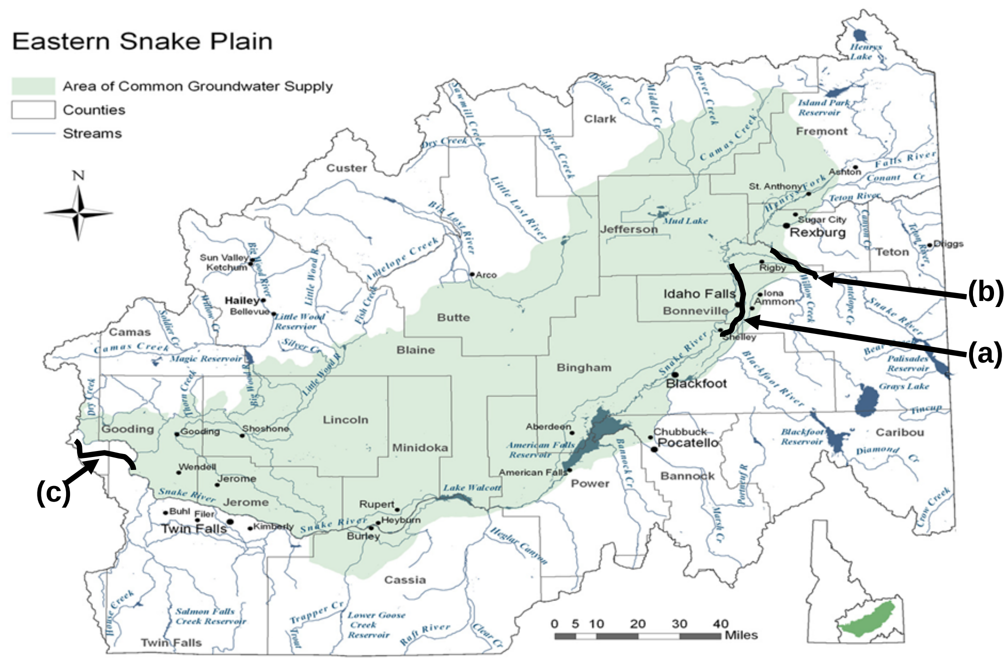

Figure 2. Simulated Reaches of the Snake River

Notes: Reach (a) is the Lewisville-to-Shelley reach and represents a disconnected system; reach (b) is the Heise-to-Lorenzo reach and represents a connected–losing system; reach (c) is the Hagerman-to-King Hill reach and represents a connected–gaining system. Sources: Eastern Snake Plain map (Cosgrove et al. 2006); Snake River reaches (Kjelstrom 1995).

It is generally accepted that the most productive ground water in the ESPA is in the upper 500 feet. The aquifer is spread over an area of 10,800 square miles, or 6.912 million acres, and stores a total of 200-300 million acre-feet of water (DAI 2012). Assuming a maximum storage capacity of 300 million acre feet (maf) and a maximum water table height of 500 feet, the implied aquifer storativity coefficient is 0.087.[9] This is within previously estimated bounds for the ESPA (Cosgrove et al. 2006).

[9] We define the height of the water table, *H*, relative to the base of the aquifer, which we assume is 500 feet below the land surface. For example, an *H* of 200 indicates that the water table is 300 feet below the land surface and 200 feet above the bottom of the aquifer.

Table 2. Economic and Hydrologic Assumptions Used in the Simulation Analysis

Symbol	Description	(a)	(b)	(c)
Economic Assumptions				
a	Demand Intercept, SW (acre-feet/year)	300,315	1,791,864	50,521
b	Demand Slope, SW	–1663.96	–9,928.22	–277.32
c	Demand Intercept, GW (acre-feet/year)	150,158	895,932	25,026
d	Demand Slope, GW	–831.98	–4,964.11	–138.66
m	Marginal Cost Intercept, GW ($/acre-foot)	34.51	34.51	34.51
n	Marginal Cost Slope, GW	–0.051	–0.051	–0.051
r	Annual discount rate	0.05	0.05	0.05
Hydrologic Parameters				
R_S	Net SW Inflows (acre-feet/year)	523,836	1,638,740	–56,318
R_V	Net GW Inflows (acre-feet/year)	–198,734	302,251	111,570
A	Aquifer Area (acres)	262,483	1,566,138	43,747
S	Aquifer Storativity Coefficient	0.087	0.087	0.087
γ	SW Return Flows (proportion)	0.125	0.125	0.125
φ	Incidental Recharge (proportion)	0.125	0.125	0.125
δ	GW Return Flows (proportion)	0.250	0.250	0.250
α	Recharge, Disconnected System (proportion)	0.061	–	–
h	Recharge Intercept, Connected-Losing System	–	0.093	–
j	Recharge Slope, Connected-Losing System	–	–0.00019	–
k	Discharge Intercept, Connected-Gaining System	–	–	0
l	Discharge Slope, Connected-Gaining System	–	–	0.00020

Notes: (a) indicates the hydraulically disconnected reach (Lewisville-to-Shelley); (b) indicates the hydraulically connected–losing scenario (Heise-to-Lorenzo); (c) indicates the hydraulically connected–gaining scenario (Hagerman-to-King Hill). The symbol – indicates that the parameter is not applicable to that particular model variant. R_S and R_V are interpreted as net inflows into stock in each reach. A net negative value indicates that more water flows out of the reach than in. These two parameters are free calibration parameters that we adjust such that surface water flows, surface diversions, and the ground water table reflect observed values from Kjelstrom (1995) under the independent management scenario.

Approximately 2.5 million acres in the Eastern Snake Plain are irrigated. The bulk of the agricultural land base is in forage crops, wheat, and barley (NASS 2007). Roughly half of the total is in forage, and the remainder is split between wheat and barley. Assuming this crop mix and using the IDEP (Irrigation Water Demand from Evapotranspiration Production Functions) tool, an aggregate water demand curve is estimated for the entire Eastern Snake Plain (Contor 2008). Total water demand is split such that 2/3 of is for surface water and 1/3 is for ground water (Kjelstrom 1995).[10] The IDEP produces non-linear demand curves, to which we take a linear approximation over the range of prices for which the quantity of water demanded is positive (0 to $190 per acre-foot). Given zero marginal cost, the quantity of surface water diverted is the intercept of the surface water demand curve, or 7.9 maf for the region.

We generate a scaling factor for each reach based on reach-level surface water diversions reported by Kjelstrom and a total of 7.9 maf for the region. We use this scaling factor to generate reach-level demand curves for surface and ground water. We also scale the size of the aquifer underneath the river reach. In so doing, we impose the assumption that the manager is considering only surface and ground water diversions in a neighborhood of each reach (where the size of that neighborhood depends on the relative weight of that reach in total surface water use). Of course, water management decisions anywhere on the Eastern Snake Plain will affect water availability throughout the Plain, not just in a neighborhood of a reach. However, the externalities between surface and ground water users are arguably greatest within a neighborhood of a reach, both in quantity and immediacy.[11] Moreover, defining a neighborhood around a reach is consistent with the way in which conjunctive management has been practically implemented to date.[12] Finally, in a region that exhibits heterogeneous hydraulic relationships between surface and ground water, optimal management will likely differ by sub-region. The appropriate boundaries or shape of the neighborhood around each reach are an empirical question (Cosgrove and Johnson 2005).

The proportion of applied irrigation water that is consumed via evapotranspiration depends on the efficiency of irrigation technology. We assume widespread use of sprinkler application systems across the region, with average consumption on the order of 75 percent of total applied water. For surface water diversions, the remaining 25 percent is divided equally between return flows (γ = .125) and incidental aquifer recharge (φ = .125). For ground water pumping, the unconsumed 25 percent percolates back into the aquifer (δ = 0.25).

We use water budget figures from 1980, as presented by Kjelstrom (1995), to characterize surface water flows, irrigator diversions, recharge, and discharge by reach. The Lewisville-to-Shelley reach has 4.58 million acre feet (maf) of inflows and 4 maf of outflows. Of the difference, 0.30 maf are diverted for irrigation and 0.28 maf recharges the aquifer. The scaling factor for the reach is 0.0380 (0.3 of 7.9). In the Heise-to-Lorenzo reach, inflows are 4.75 maf and outflows are 2.84 maf. Of the difference, 1.79 maf is diverted for surface water irrigation, and 0.12 maf recharges the aquifer. The scaling factor for this reach is 0.2266 (1.79 of 7.9). In the Hagerman-to-King Hill reach, inflows total 5.81 maf and outflows total 6.78 maf. Surface water diversions total 0.05 maf and the aquifer replenishes the river in the amount of 1.02 maf. The scaling factor is 0.0063 (0.05 of 7.9).

Based on Kjelstrom's estimates, recharge in the Lewisville-to-Shelley reach is 6.1 percent of total surface water inflows. Observed recharge in the Heise-to-Lorenzo reach is 2.53 percent of inflows, and discharge in the Hagerman-to-King Hill reach is 17.6 percent of inflows. In the latter

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[10] This derivation implies that the crop mix is identical across land irrigated from the two different water sources. This is likely not the case, but the objective is simply to derive an approximate demand curve for the simulation.

[11] Specifically, as the distance between a ground water well and the surface water stock increase, the effect of pumping on surface water is attenuated and *vice versa* (Cosgrove and Johnson 2004; 2005).

[12] Several states, such as Oregon, have implemented conjunctive management policies that regulate pumping only within a specific distance from the aquifer (OWRB 2010).

two reaches, the rate of recharge or discharge depends on the height of the water table. With an average depth to water of 136.6 feet in 1980 (based on USGS monitoring well observations across the Plain), the water table height is 363.4 feet above the base of the aquifer. We use this information to estimate linear recharge and discharge functions of the form $\alpha(H) = h + j \cdot H$ and $\beta(H) = k + l \cdot H$. To parameterize these functions, we assume that in a connected–losing reach recharge equals zero when the water table is at its highest, and in a connected–gaining reach discharge equals zero when the water table is at its lowest.

Results and Discussion

Table 3 presents the results of the numerical simulation by economic and hydraulic scenario. Hydraulic scenario (a) represents a disconnected system. When surface and ground water are managed independently in a disconnected system, surface water users do not consider the impact of their diversion decisions on aquifer recharge. When water is left in the surface water stock, it recharges the aquifer at a rate of 6.1 percent. Any water that is diverted for surface water irrigation does not contribute to direct recharge, but contributes to incidental recharge at a rate of 12.5 percent of the water diverted. Recharge of either type benefits ground water users by increasing the height of the water table. Under conjunctive management, whether it is more beneficial to provide incidental or direct recharge depends on the quantity of surface water diversions demanded relative to the quantity of water moving through the river reach. For this particular reach, it is beneficial to reduce surface water diversions, leaving more surface water in the river. Doing so reduces incidental recharge by 488 acre-feet but increases direct recharge by 3,172 acre-feet. With an increase in net recharge, the ground water table rises as does the optimal amount of ground water pumping.

Table 3. Results of the Simulation Analysis, by Reach and Economic Scenario

	Surface Water			Ground Water		
Reach and Scenario	*W* (af)	*S* (af)	λ_S	*M* (af)	*H* (af)	λ_H
Lewisville to Shelley Reach (a)						
Independent Management (1)	300,315	4.580m	0	133,154	363.4	135,817
Conjunctive Management (2)	296,410	4.632m	3.4	137,059	458.0	139,800
Heise to Lorenzo Reach (b)						
Independent Management (1)	1.792m	4.750m	0	796,124	363.4	750,160
Conjunctive Management (2)	1.785m	5.915m	1.5	803,067	391.4	755,717
Buhl to Hagerman Reach (c)						
Independent Management (1)	50,521	5.866m	0	23,149	363.4	–12,380
Conjunctive Management (2)	50,575	5.867m	0	22,654	364.1	5,906

Notes: (a) indicates the hydraulically disconnected scenario; (b) indicates the hydraulically connected–losing scenario; (c) indicates the hydraulically connected–gaining scenario. λ_S and λ_H are the shadow values for surface and ground water, respectively. af denotes acre-feet per year. All quantities are steady-state values. Those for the independent management scenario are calibrated to reflect conditions in each reach in 1980, based on Kjelstrom (1995) and USGS (2011[a]; 2011[b]). The conjunctive management scenario reflects a departure from the observed baseline.

Hydraulic scenario (b) represents a connected–losing reach. The only difference from scenario (a) is that the height of the water table affects the rate of direct recharge. As in scenario (a), surface water use generates an externality for ground water users by influencing the amount of aquifer recharge. However, ground water pumpers now produce an externality for surface water users: When the water table falls, the rate of recharge from the surface water stock increases, reducing the amount of water available for surface diversions. The simulation results are qualitatively similar to those of scenario (a): It is optimal to reduce surface water diversions, which increases net recharge and the height of the water table, and increase ground water pumping.

Hydraulic scenario (c) represents a connected–gaining reach. The externalities generated by one group for another differ substantially in this scenario, relative to the other two. Surface water diversions affect ground water users via their effect on incidental recharge, but there is no direct recharge from the surface water stock. Ground water pumping generates a negative externality for surface water users: As the ground water table falls, discharge decreases, reducing the amount of water in the surface stock. In this reach, it is economically optimal to reduce ground water pumping. There is a slight increase in the size of the surface water stock and in the height of the ground water table. The change in surface water diversions increases total surface water use over the maximum quantity demanded. This is driven by the assumption that the only way to increase aquifer recharge is by augmenting incidental recharge. It is more appropriate to think of this excess as representing artificial recharge, instead of additional crop applications.

Table 3 also reports shadow values for the surface and ground water stock, λ_S and λ_H, under each management scenario. These values represent the increase in irrigator profit associated with a one-unit increase in the relevant water stock (an acre-foot for surface water and a foot of elevation for ground water). The shadow value for surface water is zero under independent management because surface water users already divert the maximum quantity demanded (the constraint on surface water availability is non-binding). Under conjunctive management, the shadow value represents the change in profit across all water users from an increase in one of the water stocks. In all but one case, the shadow values increase under conjunctive management. The increase in λ_H reflects a decrease in the marginal cost of ground water pumping in all scenarios, but also captures the value of a unit of ground water in influencing the surface water stock in scenarios (b) and (c).

The results reported for the independent management scenario in Table 3 replicate observations by reach, as reported by Kjelstrom (1995). The change in water use and stock levels under the conjunctive management scenario represent the optimal direction of change when the two resources are jointly managed. As a basis of comparison for our results, we consider the change in water rights allocations across the Eastern Snake Plain between 1980 and 2008. Based on total permitted diversion limits for all irrigation water rights in the region, surface water diversion limits were relatively constant (they increased by 0.07 percent), while ground water rights allocations increased by 10.7 percent. For ground water, the results differ across the Plain: In the Magic Valley, where reach (c) is located, ground water rights increased by 6.5 percent; in the eastern portion of the Plain where reaches (a) and (b) are located, ground water rights increased by 11.4 percent. The simulation results suggest that a decrease in ground water pumping is optimal in reach (c), while the optimal increase in pumping in reaches (a) and (b) is on the order of 0.87 to 2.9 percent. While the relative magnitude of permit changes reflects these differences to some degree (i.e. the increase in the Magic Valley is lower than that in other areas), this comparison suggests that the growth in institutional constraints has exceeded the optimal change in diversions under conjunctive management.

Conclusion

This article addresses the design of a conjunctive management system that maximizes the combined welfare of surface and ground water irrigators. The analysis considers different hydraulic relationships between surface and ground water, highlighting a number of externalities that may arise in any system that relies on surface and ground water resources. Considering these externalities is essential in determining the economically efficient allocation of water across users. We show that under some circumstances it may be optimal to reduce surface water diversions and increase ground water pumping. It is therefore possible that the optimal allocation of water across irrigators may conflict with the rules established under existing water management institutions.

However, there are a couple of caveats to this conclusion. First, we do not explore the degree to which these results are sensitive to the parameters used in the analysis. Second, examining each river reach in isolation does not capture the full spectrum of externalities between surface and ground water users. Each reach is tied to other reaches and to pumping in other areas of the Plain. However, looking at individual reaches, as we do here, allows us to isolate the externalities produced by ground and surface water users in each type of hydraulic system. If we were to examine a system that exhibits all three of these scenarios, whether optimal conjunctive management involves reducing surface diversions or ground water pumping depends on the relative strength of each of the externalities discussed.

Perhaps a stronger argument to be made on the basis of the results presented is simply that optimal management differs with the form of the relationship between surface and ground water. Any management system that does not consider the characteristics of the natural system may introduce economic inefficiencies. Such a management system may negatively impact those users who depend on the resources in question. A logical question that arises from this analysis is whether institutions are flexible enough to accommodate different hydrologic conditions. The answer to that question will differ state-to-state across the West. Given recent attention to conjunctive management in Idaho, Oregon, Kansas, Nebraska, and Colorado, for example, the concerns raised in this analysis are likely to become increasingly important for policymakers.

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