Dynamic Feedback between Surface and Groundwater Systems: Implications for Conjunctive Management

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Abstract

A key feature of hydrologically connected surface and groundwater stocks is the two-way exchange of water between the systems. Increasing water scarcity, particularly in arid environments, has spurred debate on how to coordinate management of the two resources. In this paper, I present a model that describes the dynamic feedback loop between surface and groundwater systems when economic agents withdraw water from both for use in production. I use the model to describe optimal water extraction from both stocks and to evaluate how a conjunctive management policy shifts welfare between surface and groundwater user groups. Finally, I explore the importance of accounting for two-way feedback between the two stocks, when it exists, in estimating the benefits to a conjunctive management system. I estimate that the returns to conjunctive management in a closed system are greater than 6.5 times that in a system with an open feedback loop between water stocks.

Historically, property rights for surface and groundwater on the Snake Plain in Idaho have been allocated and administered independently. Dwindling water supplies and the adoption of increasingly efficient irrigation technologies reveal that the two resources are more interdependent than previously thought: Not only does the surface water stock recharge the groundwater stock, but the groundwater stock also replenishes the surface water stock via discharge. This two-way exchange of water between the systems is a key feature of hydrologically connected regions worldwide. However, the implications of hydrologic connectivity for efficient water management at a regional scale remain largely unexplored in the economic literature.

In this paper, I present a general model that describes the dynamic feedback loop between linked surface and groundwater systems when economic agents withdraw water from both for irrigation. I use the model to describe the long-run equilibrium rates of surface water diversions and groundwater pumping under differing management and hydrologic assumptions. The management regimes examined include a system in which the groundwater and surface water stocks are managed by independent social planners and a system of conjunctive management, in which both resources are managed by a single social planner. I further examine the differences between independent and conjunctive management regimes under the assumption that surface and groundwater systems are characterized best by significant recharge but minimal discharge (an "open" system).

In the context of a numerical simulation, I demonstrate that there is a substantial difference in the outcomes under independent versus conjunctive management in the case when the surface and groundwater systems are hydrologically connected. In an open system, the returns to conjunctive management (over independent management of the two stocks) are slim, a result that is broadly consistent with the Gisser-Sanchez effect (1980). However, when the full feedback between ground and surface water stocks is incorporated into the model, the returns to conjunctive management exceed the returns in an open system by over 6.5 times. The results highlight the importance of accounting for the closed feedback loop between water stocks when evaluating the returns to a conjunctive management policy.

That conjunctive management yields positive returns in a hydrologically connected region like the Snake Plain is likely not surprising to the region's water policymakers.[1] Of late, the movement of water from the groundwater to the surface water stock has become an increasingly pressing policy issue. As aquifer levels have declined due to a variety of factors, discharge to the surface water stock has also decreased, reducing surface water flows. Generally, surface water rights are legally senior to groundwater rights per the doctrine of Prior Appropriation. Over the past decade, surface water rights holders have initiated a spate of ongoing lawsuits demanding that junior groundwater users cease pumping until surface water supplies are sufficiently replenished to satisfy surface rights entitlements.

To date, the state has been reticent to curtail groundwater pumping for a number of reasons, foremost of which is the fact that the majority of the highest-value agricultural production in the Snake Plain is dependent upon access to groundwater. The costs associated with curtailing groundwater rights are expected to far exceed the long-term stream of benefits from ensuring adequate surface water supplies. Consequently, the state has yet to rigorously and consistently apply Prior Appropriation across surface and groundwater user groups.

While the legal issues associated with linked ground and surface water supplies have spurred a shift in policy towards conjunctive (or integrated) management of the two resources,

[1] A stakeholder stated, during the course of a conversation about this project, that estimating the returns to conjunctive management seems like an "academic exercise" given that the state will ultimately institute a system of conjunctive management, having already recognized the benefits to doing so, if only anecdotally.

the appropriate design of a conjunctive management policy and the distribution effects of any such measure remain uncertain. This analysis examines the optimal conjunctive management strategy without imposing the constraints required by uniform enforcement of Prior Appropriation doctrine. Although operating outside of the traditional system of water rights enforcement may ultimately prove politically unpalatable, this study comments on the distributional impacts of a first-best conjunctive management policy.

Relevant Literature

Work by Gisser and Sanchez (1980) spurred a large literature investigating the returns to centralized management of a renewable groundwater resource. Their study departs from the premise that groundwater is an exclusive, not open access, resource. Under this assumption, they compare the time paths of withdrawals and the evolution of the groundwater stock under competitive pumping with the outcome under management by a forward-looking social planner. Using parameters based on the Pecos Basin in New Mexico, the authors find that the difference between competitive and optimal control outcomes is negligible for relatively large aquifers. Their concluding assertion that “the economic profession would benefit more from estimating economic and hydrologic parameters than from further discussing optimal control schemes for groundwater management” (641) has, understandably, generated a great deal of discussion in the economic literature over the past three decades.

The vein of literature most relevant to this study is that which explores the returns to managing linked surface and groundwater resources. Burt (1964, 1966) treats groundwater recharge as dependent upon stochastic precipitation and surface water flows. Similarly, Tsur and Graham-Tomasi (1991) and Provencher and Burt (1993) look at the value of groundwater as a buffer to uncertainty in the surface water stock. Knapp and Olson (1994) examine intentional groundwater recharge in years with higher than average surface water supplies. These studies similarly consider systems that are linked only via recharge. In all, they find that groundwater possesses value as a buffer against stochastic surface water flows. Knapp and Olson conclude that optimal conjunctive management of linked surface and groundwater systems yields a low level of benefits, a result consistent with the Gisser-Sanchez effect.

In an extensive literature review on the subject, Koundouri (2004) notes that Burness and Martin (1988) is one of the first to explicitly model the two-way feedback between surface and groundwater systems. Their study documents that groundwater pumping imposes a negative externality upon those dependent on surface water flows via “river effects”, or discharge. However, they do not estimate the returns to conjunctive management under these circumstances. Koundouri further notes that “there exists no literature on models focusing primarily on the hydrologic link between ground and surface water and at the same time acknowledging the stochastic nature of surface water supplies” (712). The review suggests that incorporating the full feedback between surface and groundwater systems may increase the returns to conjunctive groundwater management, and that incorporating the stochastic nature of surface water supplies may further increase the estimated returns (perhaps even more so when irrigators are risk-averse).

Burness and Martin (1988) present an analytical model of the decline in the surface water stock resulting from a drawdown in the groundwater table. Per basic hydrology, groundwater pumping reduces the water table, reducing hydrostatic pressure between the stream and the groundwater stock, causing a greater amount of surface water to be drawn into the aquifer. To simplify the analysis sufficiently, they assume no return flows, natural recharge, or fluctuations in the surface water stock. Under these assumptions, they find that the time path of pumping involves monotonically decreasing pumping rates which eventually converge to a steady state. They remark that this differs substantially from the standard case in which pumping is constant over time.

This study expands upon the previous literature by explicitly incorporating the welfare of both surface and groundwater users into a model of water management in a hydrologically connected region. The model formulation is similar to many in the literature in its use of optimal control theory to conceptualize the dynamic optimization problem. Further, it takes an aggregated approach to the problem, examining returns to management across surface and groundwater user groups. Adopting a modeling approach similar to that literature spurred by Gisser and Sanchez (1980) facilitates a comparison of the results herein with those in the previous literature. Thus, this analysis can comment on the importance of incorporating hydrologic connectivity into a model of water management.

An Optimal Control Model of Water Management

In any period, precipitation enters the surface water system. Herein, I assume that precipitation is exogenous and that the hydrological system is closed to other types of inflows and outflows. I denote precipitation-driven natural recharge to the surface water system R_t. Two variables describe the state of the surface and groundwater systems at a point in time: S_t denotes the amount of water in the surface water system, and H_t measures the elevation of the groundwater table above sea level. The subscript t indexes time period.

Inflows into the surface water stock come from precipitation and discharge, the process whereby groundwater moves from a hydrologically linked aquifer into the surface water stock via springs and seeps. The surface water stock loses water each period to recharge, which occurs when surface water percolates into the groundwater stock. Recharge and discharge are each defined as a proportional amount of the originating stock. They are, respectively, αS and βH. If there are no withdrawals for irrigation, the equation-of-motion for the surface water stock is:

(1) $$\dot{S}_t = R_t - \alpha S_t + \beta H_t.$$

Similarly, the equation-of-motion describing the change in the water table is

(2) $$AS \cdot \dot{H}_t = \alpha S_t - \beta H_t.$$

Expression **(2)** is similar to the equation-of-motion used by Gisser and Sanchez (1980), where inflows and outflows affect the water table by changing the volume of water in the aquifer. As in their analysis, *AS* is the area times the specific yield (or "storativity") of the aquifer. In **(2)**, recharge from the surface water stock, αS, plays the role of exogenous natural recharge, *R*. This equation-of-motion presumes a single-cell aquifer (with vertical sides) in which lateral flow is transmitted instantaneously.

To incorporate irrigator withdrawals, I define two control variables: W_t, which denotes withdrawals for irrigation from the surface water system in each period, and M_t, which denotes groundwater pumping in each period. I assume that water from either source is a perfect substitute in irrigation.[2] Whenever irrigation water is applied to the land surface, a certain amount of the total is consumed by the plant and leaves the system via evapotranspiration. The remainder, termed return flows, re-enters the stock. I assume for simplicity that the return flows arising from irrigation use from either system return to the system from which they were

[2] This is reasonable if the water is used for crop production or stockwater. In the case of aquaculture this assumption is not reasonable. Aquaculture in Idaho relies predominantly on groundwater-fed springs, which emit water at a temperature appropriate for trout production. Much of the conflict between surface and groundwater users has actually been due to water shortages for aquaculture producers, who hold surface water rights. The linkage between the height of the groundwater table and the amount of water exiting springs is particularly transparent in this case.

withdrawn. This assumption is appropriate when groundwater is used on land more distant from the surface water system (and water from surface water withdrawals is used on land adjacent to surface water bodies or irrigation canals). I model return flows as a constant proportion, *γ*, of the water withdrawn for irrigation.

With irrigation withdrawals, the equations-of-motion become

(3) $\dot{S}_t = R_t - \alpha S_t + \beta H_t + (\gamma - 1)W_t$ and

(4) $AS \cdot \dot{H}_t = \alpha S_t - \beta H_t + (\gamma - 1)M_t$

Equation-of-motion **(4)** differs from that used by Gisser and Sanchez because it accounts explicitly for the effect of the surface water stock on the groundwater table. Moreover, the rate of change in the groundwater table depends on its level in period *t*, which determines the amount of discharge lost to the surface water stock. Equation-of-motion (3), which is not typically included in groundwater allocation models, highlights the way in which the surface water stock determines transfers to the groundwater stock via recharge and, conversely, the water table determines the rate at which the groundwater stock replenishes the surface.

I continue to follow Gisser and Sanchez in constructing the economic optimization problem. I begin by treating the groundwater and surface water stocks as though they are managed separately by distinct social planners. This abstracts away from the behavior of the individual decision-maker. It is consistent with the way in which groundwater and surface water is currently administered to assume that, at a system level, the amount of water that may be extracted from either system is capped.[3] In this scenario, strategic externalities between individual users within a larger group are limited. While cost externalities may still exist among groundwater users in the sense that one user's withdrawals may lower the water table and

[3] Limiting the rate of withdrawal for groundwater rights holders is one major objective of the Snake River water rights adjudication process.

increase another user's costs of extraction, the adjudication process for water rights provides a means for individuals to address personal harm caused by another's extractions. Given that individuals have legal recourse and that the total amount of withdrawals has been constrained by a central authority, I assume that externalities between individual water users within a group are negligible, particularly relative to the scale of the entire system.

However, the model does permit the potential for externalities to arise between aggregate surface and groundwater user groups, as has been the case to date on the Snake Plain. While the adjudication process separately specified the amount of water allocated to surface and groundwater users, the specification of rights has never explicitly recognized the potential for negative impacts by one user group on the other. I model the two systems as though a distinct planner administers each stock independently. The two planners seek to maximize the returns to each user group, but do not engage in a strategic game with the other planner (a tenable assumption if the two planners are housed within the same government agency, such as the Idaho Department of Water Resources). Thus, each planner chooses a long-term plan of resource extraction that maximizes the net benefits to irrigation water users across a single group.

To construct the economic optimization problem, I specify separate demand and water cost functions for surface and groundwater users. The demand functions are $W = h + mP$ and $M = g + kP$ for surface and groundwater, respectively. The cost functions are given by $C_{sw} = cW$ and $C_{gw} = (a + bH)M$. The marginal cost of groundwater pumping depends on the depth of the water table. For simplicity, I assume that the marginal cost of surface water diversions is constant and does not depend on the total amount of water in the surface water system. This assumption may be untenable during periods with severely low surface flows.

An Open System

I first consider the case in which the surface water stock recharges the groundwater stock, but there is no significant movement of water from the groundwater to the surface stock via discharge. In this case, equations (3) and (4) are modified:

(3′) $\dot{S}_t = R_t - \alpha S_t + (\gamma - 1)W_t$ and

(4′) $AS \cdot \dot{H}_t = \alpha S_t + (\gamma - 1)M_t$.

The surface water planner's problem is given by

$$\max_W \int_0^\infty e^{-rt}\left(\frac{1}{2m}W^2 - \frac{h}{m}W - cW\right)dt$$

subject to (3′) and standard non-negativity constraints. Setting up the Hamiltonian and using the first-order conditions yields a system of two first-order differential equations:

(5s) $\dot{W} = (\alpha + r)W - (\alpha + r)(h + cm)$ and

(6s) $\dot{S} = R - \alpha S + (\gamma - 1)W$.

Similarly, the groundwater planner faces the problem

$$\max_M \int_0^\infty e^{-rt}\left[\frac{1}{2k}M^2 - \frac{g}{k}M - (a + bH)M\right]dt$$

subject to (4′) and standard non-negativity constraints. These conditions yield the system of differential equations

(5g) $\dot{M} = rM - rbkH + \frac{bk\alpha}{AS}S - r(g + ak)$ and

(6g) $\dot{H} = \frac{\alpha}{AS}S + \frac{(\gamma - 1)}{AS}M$.

The conjunctive manager maximizes the unweighted sum of producer surplus across surface and groundwater users subject to constraints (3′) and (4′), which yields the system of four differential equations:

(5j.1) $\dot{W} = (\alpha + r)W - \frac{\alpha m}{k} M + \alpha mbH - (\alpha + r)(h + cm) + \alpha m\left(\frac{g + ak}{k}\right),$

(5j.2) $\dot{M} = rM - rbkH + \frac{\alpha bk}{AS} S - r(g + ak),$

(6j.1) $\dot{S} = R - \alpha S + (\gamma - 1)W,$ and

(6j.2) $\dot{H} = \frac{\alpha}{AS} S + \frac{(\gamma - 1)}{AS} M.$

Comparing (5j.1) with (5s), the rate of change in surface withdrawals is increasing in the groundwater table and decreasing in the amount of groundwater withdrawals in the conjunctive management system (5j.1), while neither groundwater withdrawals nor the groundwater table affect the level of withdrawals in (5s). In contrast, the rate of groundwater pumping in (5j.2) is identical to that in (5g). In either case, the groundwater planner recognizes the influence of the surface water stock on recharge and the groundwater table. Because water moves between systems in only one direction, the decisions governing groundwater use in the conjunctive system are identical to that in the non-conjunctive management system. Based on this result, the benefit to groundwater users, in particular, of engaging in conjunctive management is only derived indirectly via the effect of conjunctive management on the surface water stock and the rate of recharge.

A convenient means of analyzing the difference in outcomes under independent and conjunctive management is by examining the steady-state levels of withdrawals and stocks, if the parameters of the problem ensure a steady-state exists. Table 1 presents the steady state solutions under the two management regimes in an open system. If it is the case that

(i) $R > -(\gamma - 1)(h + cm)$,

then a positive steady-state value for surface water withdrawals and groundwater withdrawals exists under a conjunctive management regime. Condition (i) implies that precipitation coming into the system is sufficient to replace the proportion of surface water demanded (under perfect competition) that is lost due to evapotranspiration.

Table 1. Steady-state solution, open system

Independent Management

$$W^* = h + cm$$

$$M^* = -\frac{1}{(\gamma - 1)} R - W^*$$

$$S^* = \frac{1}{\alpha} R + \frac{(\gamma - 1)}{\alpha} W^*$$

$$H^* = \left[\frac{bk(\gamma - 1) - rAS}{rASbk(\gamma - 1)}\right] R + \left[\frac{bk(\gamma - 1) - rAS}{rASbk}\right] W^* - \frac{1}{bk}(g + ak)$$

Conjunctive Management

$$W^* = \left[\frac{-\alpha bm}{rAS(\alpha + r) + \alpha bm(\gamma - 1)}\right] R + \left[\frac{rAS(\alpha + r)}{rAS(\alpha + r) + \alpha bm(\gamma - 1)}\right] (h + cm)$$

$$M^* = -\left[\frac{1}{(\gamma - 1)}\right] R - W^*$$

$$S^* = \frac{1}{\alpha}[R + (\gamma - 1)W^*]$$

$$H^* = \left[\frac{bk(\gamma - 1) - rAS}{rASbk(\gamma - 1)}\right] \alpha R + \left[\frac{bk(\gamma - 1) - rAS}{rASbk}\right] W^* - \frac{1}{bk}(g + ak)$$

The difference in surface water withdrawals under independent and conjunctive management is given by

$$W^*_{IP,O} - W^*_{CM,O} = \frac{\alpha bm}{rAS(\alpha + r) + \alpha bm(\gamma - 1)}[(\gamma - 1)(h + cm) + R].$$

Under condition (7), $W^*_{IP,O} > W^*_{CM,O}$. It follows that $M^*_{IP,O} < M^*_{CM,O}$ and $S^*_{IP,O} < S^*_{CM,O}$. The steady-state solution also reveals that the water table is always higher under a system of conjunctive management than under the independent planner regime, holding W^* constant. Under condition (i), the reduction in surface water diversions under conjunctive management reinforces the water table effect, further increasing the level of the water table over the independent planner case. Thus, conjunctive management in an open system involves decreasing surface diversions. Doing so increases the water table by boosting recharge and by increasing the amount of groundwater pumped in each period. The returns to conjunctive management decrease with increases in the size of the aquifer, a result consistent with the findings of Gisser and Sanchez (1980).

A Closed System

The closed system problem differs from the open system problem in its inclusion of discharge in the equations of motion. The surface water planner's problem is defined by the two conditions

(7s) $\dot{W} = -(\alpha + r)(h + cm) + (\alpha + r)W$ and

(8s) $\dot{S} = R - \alpha S + \beta H + (\gamma - 1)W.$

where the latter corresponds to equation (3) and the equations are derived from the first-order conditions for optimization. The groundwater planner's problem is defined by the system

(7g) $\dot{M} = \left(r + \frac{\beta}{AS} \right) M - bk\left(r + 2\frac{\beta}{AS} \right) H + \frac{bk\alpha}{AS} S - \left(r + \frac{\beta}{AS} \right)(g + ak)$ and

(8g) $\dot{H} = \frac{\alpha}{AS} S - \frac{\beta}{AS} H + \frac{(\gamma - 1)}{AS} M.$

Condition (7g) differs from condition (5g) in that the groundwater planner faces a different effective discount rate. Specifically, when discharge is included in the problem, the groundwater planner faces a discount rate that includes the rate at which the value of pumped groundwater decays into the future (*r*) and the rate at which the groundwater table declines due to recharge (β/AS).

The conjunctive manager's problem is given by the system of four differential equations

(7j.1) $\dot{W} = (\alpha + r)W - \frac{\alpha m}{k} M + \alpha mbH - (\alpha + r)(h + cm) + \alpha m\left(\frac{g + ak}{k} \right),$

(7j.2) $\dot{M} = \left(r + \frac{\beta}{AS} \right) M - \frac{k\beta}{mAS} W - bk\left(r + 2\frac{\beta}{AS} \right) H + \frac{bk\alpha}{AS} S - \left(r + \frac{\beta}{AS} \right)(g + ak) + \frac{k\beta}{mAS}(h + mc),$

(8j.1) $\dot{S} = R - \alpha S + \beta H + (\gamma - 1)W,$ and

(8j.2) $\dot{H} = \frac{\alpha}{AS} S - \frac{\beta}{AS} H + \frac{(\gamma - 1)}{AS} M.$

Equation (7j.1) is identical to that in the open system (5j.1). The primary difference between the two conjunctive management systems is the difference between (7j.2) and (5j.2). The former explicitly accounts for the impact of surface water withdrawals when determining the optimal rate of groundwater pumping. Moreover, the optimal rate of groundwater pumping depends on the parameters of the surface water demand function.

Comparing the steady-state solutions implied by the independent planner and conjunctive management problems is once again informative, though more complex than in the case of an open system. Table 2 presents the steady state solutions under the two management regimes in an open system. Under an independent planner, the withdrawal rates for both surface and groundwater are identical to those in the open system. The stock levels, however, differ due to the exchange of water from the ground to the surface water stock.

Table 2. Steady-state solutions, closed system

Independent Management

$$W^* = h + cm$$

$$M^* = -\frac{1}{(\gamma - 1)} R - W^*$$

$$S^* = \frac{1}{\alpha} R + \frac{\beta}{\alpha} H^* + (\gamma - 1) W^*$$

$$H^* = \left[\frac{bk(\gamma-1) - (rAS + \beta)}{bk(\gamma-1)(rAS+\beta)}\right] R + \left[\frac{bk(\gamma-1) - (rAS+\beta)}{bk(rAS+\beta)}\right] W^* - \frac{1}{bk}(g + ak)$$

Conjunctive Management

$$W^* = \left\{\frac{-\alpha bm}{r[(\alpha + r)AS + \beta] + b\alpha^2 m(\gamma - 1)}\right\} R + \left[\frac{r[(\alpha + r)AS + \beta]}{r[(\alpha + r)AS + \beta] + b\alpha^2 m(\gamma - 1)}\right](h + cm)$$

$$M^* = -\left[\frac{1}{(\gamma - 1)}\right] R - W^*$$

$$S^* = \frac{1}{\alpha} R + \frac{\beta}{\alpha} H^* + (\gamma - 1) W^*$$

$$H^* = \left[-\frac{1}{bk(\gamma - 1)}\right] R - \left[\frac{k(\alpha + r) + \alpha m}{bk\alpha m}\right] W^* + \frac{(\alpha + r)}{b\alpha m}(h + cm) - \frac{1}{bk}(g + ak)$$

If it is the case that

(ii) $R > -\alpha(\gamma - 1)(h + cm)$,

then a positive steady-state value for surface and groundwater withdrawals exists under a conjunctive management regime. Condition (ii) is less straightforward to interpret than condition (i): The precipitation coming into the system must be sufficient to replace the proportion of surface water demanded (under perfect competition) that is lost from the system due to evapotranspiration times the recharge coefficient. Because $\alpha < 1$ condition (ii) is less stringent than condition (i), i.e. there exists a steady-state for a larger range of precipitation values in a closed than in an open system.

Under condition (ii), it is straightforward to verify that $W^*_{IP,C} > W^*_{CM,C}$, $M^*_{IP,C} < M^*_{CM,C}$, $S^*_{IP,C} < S^*_{CM,C}$ and $H^*_{IP,C} < H^*_{CM,C}$. Because of the complexity of the analytical solutions, I further explore the differences in the returns to conjunctive management in an open and closed system using a simple numerical example that draws on the parameter values used by Gisser and Sanchez. The parameters of the problem and the steady-state solutions under different hydrological assumptions and management regimes are reported in Table 3.

Table 3. Parameter values and steady-state numerical solutions

Parameter Values							
Gisser and Sanchez (1980)				*Additional assumptions*			
r	*0.10*	*a*	*125*	*h*	*470,365*	*R*	*450,000*
g	*470,365*	*b*	*-0.035*	*m*	*-3,259*	*α*	*0.27*
K	*-3,259*	*AS*	*135,000*	*c*	*0.035*	*β*	*0.15*
(γ-1)	*-0.73*						

	Management System, Hydrologic Assumption			
	Indep., Open	Conj., Open	Indep., Closed	Conj., Closed
Surface diversions (W*)	470,251	469,590	470,251	468,045
Groundwater pumping (M*)	146,187	146,848	146,187	148,393
Surface stock (S*)	395,248	397,035	395,248	401,211
Water table height (H*)	737	743	737	775

Without quantifying the monetary stream of benefits into the future, Table 3 indicates that the benefits to conjunctive management in a closed system, and the corresponding welfare distribution, are different than in an open system. While there is a greater reduction in the amount of water diverted from the surface water system than in the conjunctive/open case, the amount of groundwater pumping is much larger in the conjunctive/closed case. Further, the amount of water in the surface stock and the height of the water table significantly exceed that under the conjunctive/open solution. In a closed system, the results suggest that optimal management necessarily redistributes welfare from surface to groundwater users, concerns about weighting the social welfare function aside.

Under the assumed parameters, the returns to conjunctive management in a closed system are over 6.5 times as great as those in an open system. A change in any factor that tends to increase the returns to conjunctive management in an open system, such as those demonstrated by Feinerman and Knapp (1983), will only tend to further augment the returns to conjunctive management in a closed system. Interestingly, the solutions are insensitive to even substantial changes in the rate of discharge from the ground to the surface water system. Continuing work in the immediate future will involve testing the sensitivity of the model results to other parameters. The literature generally concurs that management benefits are sensitive to the slope of the demand function and interest rate and moderately sensitive to aquifer size and specific yield (Koundouri 2004).

Conclusion

In a hydrologic system with either an open or a closed feedback loop between surface and groundwater stocks, conjunctive management involves a redistribution of welfare from surface water users to groundwater pumpers. A system of conjunctive management requires that surface water withdrawals are lower than if surface water is managed by an independent planner. This result is perhaps not surprising given that surface water withdrawals impose an externality on groundwater users. Specifically, removal of a unit of water from the surface water stock reduces the amount of recharge, increasing the marginal pumping cost for groundwater users. However, the removal of surface water has a second-round impact that is likely less recognized even among surface water users themselves: Reducing the surface water stock by a unit today decreases recharge, lowering the water table, and reducing future discharge back into the surface water stock. Thus, under a conjunctive management policy, the shadow value of a unit of surface water *in situ* incorporates the impact of removing a unit on both recharge and future discharge.

This analysis suggests that a first-best system of conjunctive management may imply much larger welfare gains over the long-run than the groundwater management literature suggests. This result is driven by the closed feedback loop between the surface and groundwater stocks. Future analysis will explore the sensitivity of this result to changes in the model's parameters and to conditions specific to the Snake Plain in Idaho. A limitation of this analysis is the assumption throughout that policymakers place equal weight on surface and groundwater users' welfare. While inconsistent with the doctrine of Prior Appropriation, strictly interpreted, this assumption is borne out to date in the reticence of policymakers to curtail junior groundwater users. Whether a system of conjunctive management like the one examined here is politically viable is uncertain. The gains to conjunctive management may be significantly lower than those estimated here if state water planners must operate within the confines of traditional water rights law.

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