Bargaining for recharge: an analysis of cooperation and conjunctive surface water-groundwater management

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Bargaining for recharge: an analysis of cooperation and conjunctive surface water-groundwater management

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Abstract
Recent negotiations between surface water and groundwater users in Idaho highlight a potential mechanism to resolve costly conflict that has arisen in many areas of the western U.S. where surface and groundwater resources are hydraulically connected. This article studies this type of agreement by developing a simple, dynamic model of cooperative bargaining between surface and groundwater users. The model reflects the potential gains to both types of water users from bargaining over a sustained reduction in groundwater pumping to increase surface water flows. In a non-cooperative setting, surface water users choose the groundwater pumping reduction to maximize their net production rents, but doing so is costly, which creates an incentive for surface water users to negotiate with groundwater users. With the theoretical model, we demonstrate that the Nash bargaining path of curtailments is lower than that in the non-cooperative outcome, but that it may be larger or smaller than the first-best outcome. The difference between the bargaining and first-best outcomes depends on the efficiency of groundwater irrigation and the relative bargaining power of surface water and groundwater users. In a numerical simulation, we show that when surface water users possess greater bargaining influence, the bargaining solution involves larger curtailments than is socially optimal and an improvement in irrigation efficiency drives the bargaining solution closer to the non-cooperative outcome. Conversely, when groundwater users possess greater bargaining influence, curtailments are lower than the socially optimal level and an improvement in efficiency drives the bargaining solution closer to the first-best.

Keywords: Nash bargaining, groundwater, prior appropriation, water rights

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In the summer of 2015, surface water and groundwater users in Idaho's Eastern Snake River Plain negotiated a landmark agreement over the joint management of surface water and groundwater resources, potentially bringing to an end a costly, decade-long water dispute. The conflict between surface water and groundwater users arose as groundwater pumping reduced the surface water flows available for irrigation, aquaculture, and other uses throughout the region. This stream depletion externality arises when surface water and groundwater resources are hydraulically connected (Burness and Martin 1988; Cobourn 2015; Kuwayama and Brozovic 2013; Taylor et al. 2014; Young, Morel-Seytoux, and Daubert 1986). Though hydraulic connectivity is widespread and occurs in diverse landscapes, property rights for surface water and groundwater in the western U.S. were developed independently and do not generally reflect the physical interdependencies between the two resources. As a result, surface water and groundwater property rights are often not fully exclusive and similar instances of costly conflict between surface water and groundwater users have arisen in many areas, such as the Republican River Basin of Nebraska, the South Platte River in Colorado, and the Scott River Region of California.

In recognition of the connectivity between surface and groundwater, many states in the western U.S. have developed conjunctive administration policies that jointly regulate surface and groundwater property rights in hydraulically connected areas.[1] Though the details of these nascent policies differ widely across states, a common approach taken by many, including Idaho, is to allow the state restrict groundwater pumping to protect surface water rights.[2] This approach is based in the doctrine of prior appropriation ("first in time, first in right"), which is used to administer surface water rights, and sometimes groundwater rights, in much of the western U.S. Because groundwater rights were generally established later in time than surface water rights, the latter are often senior to groundwater rights and thus receive higher priority in access to scarce water. Idaho's conjunctive administration policy applies the doctrine of prior appropriation across surface and groundwater rights in hydraulically connected areas. Under this system, if a surface water user can demonstrate that groundwater pumping by junior users reduces surface water flows and harms their senior right, they can file a curtailment call requiring the state water agency to reduce pumping by hydraulically connected groundwater users.

In the last decade, numerous calls have been issued by senior surface water users in the Eastern Snake River Plain requiring the state to curtail pumping by junior groundwater users. Some of these calls would have curtailed pumping on up to 157,000 acres of irrigated land (Idaho Department of Water Resources 2015). In exchange for safe haven from curtailment calls, Idaho groundwater users agreed to phase in a permanent reduction in groundwater pumping of 13 percent. This reduction is expected to offset the ongoing decline in the region's groundwater stock within five years; within 11 years, the aquifer is expected to reach a new, higher equilibrium level equivalent to that observed from 1991-2001 (O'Connell 2015b). By making this agreement, groundwater users averted the possibility of a severe curtailment in future years when surface water flows are insufficient to satisfy senior surface water rights in the region.

The potential for gains to groundwater users from accepting a less stringent, albeit longer-term, reduction in pumping is clear. Groundwater users forfeit some water diversions in exchange for reduced curtailments in the future and more stable and secure access to water. What is perhaps less apparent is that surface water users involved in this conflict also stand to gain from the agreement. By accepting a fixed level of pumping reductions, surface water users avoid the transaction and enforcement costs associated with filing a curtailment call against groundwater users on an annual basis. These costs include the administrative costs of filing paperwork and providing evidence of the harm caused to surface water users by groundwater pumping; the administrative time lags associated with processing and honoring a call; and the costs of enforcing a reduction in groundwater pumping. The significance of these costs is perhaps best evidenced by the prolonged nature of the surface water-groundwater disputes in the region to date (Idaho Department of Water Resources 2015).

The economic literature has examined in detail the dynamic externalities that arise as the extraction of groundwater from an aquifer by one agent reduces the stock of water and increases the marginal cost of pumping for other agents into the future (Gisser and Sanchez 1980; Provencher and Burt 1993; Saak and Peterson 2007; Pfeiffer and Lin 2012). A subset of this literature examines the streamflow externality that arises in hydraulically connected surface water-groundwater systems (Burness and Martin 1988; Burt, Baker, and Helmers 2002; Cobourn 2015; Kuwayama and Brozovic 2013; Taylor et al. 2014; Young, Morel-Seytoux, and Daubert 1986). These studies consider a host of policy instruments to conjunctively manage groundwater and surface water, including water markets, groundwater trading permits, payments for aquifer recharge, and the joint administration of groundwater and surface water rights. No work we are aware of considers the scope for and nature of bargaining between surface water and groundwater users. On the other hand, there exists a rich economic literature on bargaining among surface water or groundwater users, but this literature has not yet examined a problem that captures the defining features of a hydraulically connected surface water-groundwater system (see Carraro, Marchiori and

Sgobbi 2007 for a review). The negotiations now present in Idaho provide an immediate need and motivation for extension of this literature to include bargaining between surface water and groundwater users.

This article bridges these two lines of inquiry in the economic literature to develop an understanding of the factors that affect the viability and performance of bargaining as a mechanism to resolve surface water-groundwater conflicts. We develop a simple, dynamic model of cooperative bargaining between surface and groundwater users in a hydraulically connected system. Our theoretical approach casts the problem as an axiomatic Nash bargaining game (Nash 1950) that is appropriate for the problem and captures the potential gains to surface and groundwater users from a bargaining agreement over groundwater pumping reductions. Our model captures two unique features of the surface water-groundwater problem. First, the model reflects that the connectivity of surface and groundwater resources in a region is not a fixed physical relationship. Rather, connectivity is a function itself of groundwater pumping: as reductions in groundwater pumping elevate the groundwater table, connectivity between the systems is enhanced and surface water flows are augmented in future years. Second, the model incorporates the efficiency with which groundwater is used, and thus reflects the difference between the quantity of groundwater extracted (diversions) and the quantity of groundwater consumed (consumptive use).

In a non-cooperative setting without bargaining, surface water users would choose groundwater pumping reductions to maximize the dynamic benefits of augmenting surface water flows net of their costs associated with a curtailment call. Compared with both the bargaining and first-best solutions, the level of curtailments is too large because it fails to take into account the costs of foregone consumptive groundwater use. We demonstrate that both the Nash bargaining outcome and the full cooperation, first-best outcome reduce groundwater curtailments relative to that of the status quo disagreement outcome. In the Nash bargaining solution, the level of curtailments may be greater or lesser than in the first-best case, depending on the relative net gains from bargaining to surface water and groundwater users as well as the relative bargaining power of each group.

We also show that the divergence between the bargaining and first-best outcomes depends on the efficiency of groundwater irrigation, but with the caveat that bargaining influence is also important. If groundwater users possess a bargaining advantage over surface water users, an increase in irrigation efficiency implies that the bargaining and first-best curtailment paths converge. However, if surface water users possess a bargaining advantage, an increase in irrigation efficiency has the opposite effect of pushing the bargaining solution toward that of the disagreement outcome and away from the first-best solution. We demonstrate these results with a numerical simulation and then conclude by discussing the scope for bargaining over irrigation efficiency in addition to groundwater curtailments and by suggesting a way forward for future work on this topic.

Theoretical Framework

Suppose that there are two water users or groups of water users, one of which relies exclusively on groundwater for agricultural irrigation and the other on surface water.[3] As noted above, in a hydraulically connected system groundwater pumping reduces surface water flows and harms surface water users. We assume that rights to divert both surface water and groundwater are administered using the doctrine of prior appropriation and that surface water rights are senior to groundwater rights. Given the seniority of surface water rights, legal precedent exists for surface water users to file a water right call to curtail groundwater pumping.[4] While filing a call is an effective means of reducing groundwater extraction, it is also a costly approach to enforcing the priority of surface water rights. From the perspective of groundwater users, a curtailment call is costly because it results in a loss of access to water for irrigation.

Groundwater and surface water users may have an incentive to bargain if groundwater users can offer a reduction in pumping in exchange for reduced curtailment effort by surface water users. In doing so, groundwater users may gain if the agreement involves pumping reductions that are less stringent than the privately optimal level of curtailment by surface water users. Surface water users also stand to gain from a bargaining agreement if the cost savings from reduced curtailment calls exceed the loss in benefits from accepting a smaller reduction in pumping.[5] A bargaining agreement will likely involve a lower level of pumping reductions than would be privately optimal for surface water users, but they will be compensated for accepting a lower level of pumping reductions with a reduction in enforcement costs.

Surface Water-Groundwater Hydrology

We adapt a simple representation of surface water-groundwater exchange from Sophocleous (2002). At a point in space and time, the quantity of water flowing between an aquifer and a surface waterway, q_t, is given by:

$$q_t = \begin{cases} k\left(h_{gt} - h_s\right) \; if \; h_{gt} > s_{min} \\ k(s_{min} - h_s) \; if \; h_{gt} < s_{min} \end{cases} \tag{1}$$

where $k > 0$ is a physical parameter that describes the hydraulic conductivity of the bed of the surface waterway; h_s is the elevation of the surface water stage, defined as the upper limit of water in the surface waterway; h_{gt} is the elevation of the groundwater table, defined as the upper limit of the saturated zone, at time t; and s_{min} is the elevation of the bottom of the surface water stage.[6] At a single point in space and time, the system is hydraulically connected when $h_{gt} > s_{min}$ or hydraulically disconnected when $h_{gt} < s_{min}$. The key difference between a connected and a disconnected system is that in a connected system the height of the groundwater table influences surface water flows.

Equation (1) describes a surface water–groundwater system at a single point in space and time, but our interest in this model is in examining incentives for bargaining in a regional surface water-groundwater system. Following Cobourn (2015), we let s_{min} vary continuously in the interval $[s_l, s_h]$ across a region. Let $F(s)$ represent the proportion of surface waterways in the system with a value of $s_{min} < s$ such that $F(s_l) = 0$ and $F(s_h) = 0$. The proportion of the system that is hydraulically connected in period t is given by $F(h_{gt})$. Letting $f(s) = F'(s)$ be the proportion of the surface water system for which $s_{min} = s$, the net exchange of water between the aquifer and the region's surface water system in period t is:

$$Q(h_{gt}) = \int_{s_l}^{h_{gt}} k(h_{gt} - h_s) f(s) ds + \int_{h_{gt}}^{s_h} k(s - h_s) f(s) ds \tag{2}$$

The first term on the right-hand side of (2) captures the exchange of water at all hydraulically connected points in the region. This term may be positive or negative. The second term on the right-hand side of (2) captures the movement of water from the surface into the aquifer at hydraulically disconnected points in the region. This second term is necessarily negative since $h_s > s_{min}$. If $Q(h_{gt}) > 0$, the regions' surface waterways are gaining water from the aquifer on balance. Conversely, if $Q(h_{gt}) < 0$, the region's surface waterways are losing water to the aquifer on balance.

Based on equation (2), a marginal change in the elevation of the groundwater table generates two effects: it influences the amount of water moving between the aquifer and the surface waterways in the region and it influences the extent of hydraulic connectivity across the region (the proportion of points in space and time that are connected versus disconnected). The effect of a marginal change in the elevation of the groundwater table on the exchange of surface water and groundwater is: $Q' = kF(h_{gt}) > 0$. Regardless of the direction of water exchange, a decline in the elevation of the groundwater table results in a reduction in the amount of surface water available for diversion: if $Q(h_{gt}) > 0$, a decline in the groundwater table will reduce discharge from the aquifer into the surface waterways; if $Q(h_{gt}) < 0$, a decline in the groundwater table will induce an increase in the amount of water drawn out of surface waterways into the aquifer.

Groundwater Pumping and Curtailment Decisions

In each period, groundwater users earn net benefits given by the concave function $B_g(et_t)$, where et_t denotes consumptive groundwater use. Consumptive use is defined as $et_t = \varphi w_t$, where φ is the efficiency of irrigation technology in application and w_t is the quantity of groundwater pumped. The parameter φ is defined as the average proportion of water pumped that is consumed by plants via evapotranspiration. This parameter depends on the irrigation technology used to apply water.[7] The present value of net benefits for groundwater users over an infinite time horizon is therefore:[8]

$$J_g = \int_0^\infty e^{-\rho t} B_g(et_t) dt \tag{3}$$

where ρ is the discount rate.

When groundwater rights are administered using prior appropriation, groundwater pumping in each period is constrained by a diversion limit, i.e. $w_t \leq W$. The maximum quantity of groundwater that can be pumped each period, W, is exogenous and time-invariant. This assumption is reasonable because diversion constraints are often quite difficult to change administratively and the administrative time lags associated with any such change are substantial.[9] This diversion constraint is a key feature of the theoretical model, and also a key water rights feature from a policy perspective, because this constraint is the mechanism by which surface water users can influence groundwater pumping by filing a curtailment call. Thus, we let a_t denote the quantity of groundwater pumping curtailed in period t. The pumping constraint for groundwater users under a curtailment call in period t is then:

$$w_t \leq W - a_t \tag{4}$$

The consumptive use of groundwater reduces the level of the groundwater table, h_{gt}. Water that is consumptively used in each period is lost from the groundwater system; any water that is pumped but unconsumed percolates back into the aquifer as return flows. The following equation of motion describes dynamic changes in the height of the groundwater table:

$$\dot{h}_{gt} = r - \varphi w_t - Q(h_{gt}) \tag{5}$$

where r is exogenous natural recharge to the aquifer and $Q(\bullet)$ is defined in equation (2).

Surface water users earn net benefits each period that depend on surface water-groundwater exchange and the costs of enforcing curtailment calls against groundwater users. The per-period net benefit function for surface water users is:

$$NB_s(a_t, h_{gt}) = B_s\left(Q(h_{gt})\right) - E(a_t) \tag{6}$$

Each period, surface water users receive benefits from surface water-groundwater exchange given by the function $B_s(\bullet)$. These may include the benefits from diverting water for irrigation and aquaculture or the benefits associated with in-stream flows for hydropower production or environmental uses. Equations (5) and (6) illustrate how groundwater pumping causes harm to surface water users by reducing surface water-groundwater exchange and, as a consequence, surface water benefits. Conversely, curtailing groundwater pumping elevates the groundwater table, increases surface water-groundwater exchange, and increases surface water benefits. Although this increase in surface water benefits surface water users, it comes at a cost. The convex function $E(a_t)$ in equation (6) captures the costs of curtailing groundwater pumping. The present value of net benefits for surface water users over an infinite time horizon is:

$$J_s = \int_0^\infty e^{-\rho t} N B_s\left(a_t, h_{gt}\right) dt \tag{7}$$

Disagreement Outcome

The net gains from bargaining depend on the disagreement outcome, defined as the outcome for surface water and groundwater users when no bargaining agreement is reached. When there is no bargaining agreement, we assume that groundwater users pursue a myopic strategy, choosing pumping in each period to maximize their own net benefits of groundwater pumping in each period subject to the diversion constraint (4), where curtailments are exogenous from the standpoint of groundwater users. We assume that in each period the water right diversion constraint is binding, so that $w_t = W - a_t$ for all t. The choice to represent the groundwater extraction problem as a period-by-period decision-making problem is consistent with institutional features of prior appropriation, such as prohibitions on storing water for use across periods. The assumption that the diversion constraint is binding simplifies the theoretical development of the model, but is also reasonable from an institutional perspective because the forfeiture clause ("use it or lose it") of prior appropriation provides a disincentive to consistently divert less water than permits allow. This assumption is also consistent with observed behavior in prior appropriation groundwater systems (Pfeiffer and Lin 2012).[10]

When choosing curtailments, surface water users recognize the dynamic effects of a groundwater pumping reduction on surface water flows. Surface water users choose a path of pumping curtailments to maximize (7) subject to (5) and the initial condition $h_g(0) = h_{g0}$. The Hamiltonian for this problem is:

$$H\left(h_g, a, \lambda, t\right) = B_s\left(Q\left(h_{gt}\right)\right) - E(a_t) + \lambda_t\left(r - \varphi(W - a_t) - Q\left(h_{gt}\right)\right) \tag{8}$$

where $Q(\bullet)$ is defined in (2) and we have used the fact that the groundwater diversion constraint is binding. Along with (5), the following conditions are necessary for a solution to this problem:[11]

$$\frac{\partial H}{\partial a_t} = -E' + \varphi\lambda_t = 0 \tag{9}$$

$$-\frac{\partial H}{\partial h_{gt}} = kF\left(h_{gt}\right)(\lambda_t - B_s{}') = \dot{\lambda}_t - \rho\lambda_t \tag{10}$$

$$\lim_{t\to\infty} \lambda_t = 0 \tag{11}$$

where (11) is the standard transversality condition for an infinite-horizon problem, which ensures that the marginal value of an additional unit of groundwater converges to zero in present value terms.

Combining (9) and (10) yields the path of curtailments in the disagreement case:

$$\dot{a}_t^D = \frac{\left(\rho + kF\left(h_{gt}\right)\right)E' - \varphi kF\left(h_{gt}\right)B_s{}'}{E''} \tag{12}$$

Given our curvature assumptions for the enforcement and surface water benefit functions, the sign of (12) is ambiguous and depends on the relative magnitudes of the marginal cost of curtailments and the irrigation efficiency weighted marginal benefits of an increase in surface water flows. Though it is not possible to solve explicitly for the path of curtailments without specifying functional forms for the enforcement cost and benefit functions, it is clear from equation (12) that the path of curtailments depends on the hydraulic connectivity parameter k as well as the groundwater irrigation efficiency parameter φ.

Equations (5) and (12) define a system of two first-order ordinary differential equations that can be solved for the optimal path of groundwater pumping and the path of the groundwater table when no bargaining agreement is reached. The present value of net benefits in this disagreement case for groundwater and surface water users, respectively, are:

$$d_g = \int_0^\infty e^{-\rho t} B_g(\varphi w_t^D)dt \tag{13}$$

$$d_s = \int_0^\infty e^{-\rho t} \left\{B_s\left(Q\left(h_{gt}^D\right)\right) - E(a_t^D)\right\}dt \tag{14}$$

where a_t^D and h_{gt}^D denote the disagreement path of pumping curtailments and the groundwater table and $w_t^D = W - a_t^D$ is the disagreement path of groundwater pumping.

Nash Bargaining

As the Snake River case demonstrates, surface and groundwater users may bargain over a path of pumping reductions. The simplicity of a Nash bargaining approach allows us to characterize this interaction while also focusing on the important new features we examine in these negotiations, such as groundwater and surface water dynamics. Nash bargaining has also commonly been used in cases like ours where the elements of the problem are the improvements in net rents for both parties negotiating over alternative offers and counteroffers.[12] Examples are found in Gertler and Trigari (2006) for multi-period wage bargaining negotiations, Koskela and Schöb (1999) and Koskela, Schöb, and Sinn (1998) for emissions tax bargaining and wage bargaining with polluting firms, and Amacher, Ollikainen and Koskela (2012) for the allocation of rents from natural resource harvesting concessions under corruption.

Following the Nash problem, they do this in order to maximize the product of the net gains from bargaining:

$$\max_{a_t} \left(J_g - d_g\right)^{\gamma_g} (J_s - d_s)^{\gamma_s} \tag{15}$$

subject to (5), an initial condition, and where J_g and J_s are as defined in equations (3) and (7), and d_g and d_s are as defined in equations (13) and (14).

The parameters γ_g and γ_g capture the potential for surface water and groundwater users to possess differing levels of relative bargaining power. The bargaining power parameters are specified such that $0 \leq \gamma_g \leq 1$, $0 \leq \gamma_s \leq 1$, and $\gamma_g + \gamma_s = 1$. These coefficients affect the trajectory of groundwater pumping curtailments by skewing the bargaining agreement in favor of the party with greater bargaining power. In the extreme case in which surface water users possess all bargaining power, i.e. $\gamma_s = 1$, problem (15) is equivalent to the disagreement case in which surface water users choose curtailments to maximize their own net benefits. In our example, surface water users are likely hold a bargaining power advantage given that surface water rights are senior to, and take priority over, groundwater rights. However, it is unlikely that surface water users hold perfect bargaining power. The presence of transaction and enforcement costs for surface water calls endows groundwater users with some bargaining power. Moveover, groundwater users may have additional bargaining power because the courts have sometimes denied calls by senior surface water users because limiting groundwater pumping would generate an economic hardship for communities (Idaho Department of Water Resources 2014). Assigning some bargaining power to groundwater users reduces the path of curtailments relative to that in the disagreement case.

To solve problem (15), we use the proof of Ehtamo et al. (1988), who demonstrate that the Hamiltonian for this problem can be written as a weighted sum of the net gains from bargaining for the parties negotiating, or in our case groundwater and surface water users' net gains from bargaining:

$$H(h_g, a, \mu_g, \mu_s, \lambda, t) = \tag{16}$$

$$\mu_g\{B_g(\varphi(W - a_t)) - d_g\} + \mu_s\left(B_s\left(Q(h_{gt})\right) - E(a_t) - d_s\right)$$

$$+ \lambda_t\left(r_g - \varphi(W - a_t) - Q(h_{gt})\right)$$

where μ_g and μ_s are weights for groundwater users and surface water users, respectively. These weights are defined as:

$$\mu_g = \gamma_g\left(J_g(a_t^B) - d_g\right)^{\gamma_g - 1}(J_s(a_t^B) - d_s)^{\gamma_s} \tag{17}$$

$$\mu_s = \gamma_s\left(J_g(a_t^B) - d_g\right)^{\gamma_g}(J_s(a_t^B) - d_s)^{\gamma_s - 1} \tag{18}$$

where a_t^B denotes the path of curtailments that solves (15). These weights depend on the net gains from bargaining to surface and groundwater users as well as the bargaining power held by each group. If surface water users hold perfect bargaining power, then $\mu_g = 0$ and the problem becomes equivalent to that of the disagreement case.

Under the assumptions that: the constraint set is convex; the objective functionals for groundwater and surface water users are concave over the constraint set; and there exists a contract space such that both groups of water users gain from bargaining, i.e. $J_g(a_t^B) > d_g$ and $J_s(a_t^B) > d_s$, the following conditions, along with (5) and (11), are necessary for problem (15):

$$\frac{\partial H}{\partial a_t} = -\mu_g \varphi B_g' - \mu_s E' + \varphi \lambda_t = 0 \tag{19}$$

$$-\frac{\partial H}{\partial h_t} = kF(h_{gt})(\lambda_t - B_s{}') = \dot{\lambda}_t - \rho \lambda_t \tag{20}$$

Combining (19) and (20) yields:

$$\dot{a}_t^B = \frac{\left(\rho + kF(h_{gt})\right)\left(\mu_s E' + \mu_g \varphi B_g{}'\right) - \mu_s \varphi k F(h_{gt}) B_s{}'}{\mu_s E'' - \mu_g \varphi^2 B_g{}''} \tag{21}$$

The first term in the numerator differs from that in expression (12): this term now includes the weighted cost of a curtailment in terms of the forsaken benefits of consumptive groundwater use. The second term in the numerator on the right-hand side of (21) is similar to that of the disagreement outcome in (12) with the exception of the Hamiltonian weight for surface water users. The denominator in (21) also differs from that in expression (12) due to the addition of the Hamiltonian weights and the second order effect of a marginal change in curtailments on the benefits of consumptive groundwater use.

Provided that groundwater users have some bargaining power, i.e. $\mu_g > 0$, the bargaining solution will differ from that in the disagreement outcome because it will reflect the effect of a curtailment on groundwater users. The degree to which this effect influences the bargaining outcome depends on the magnitude of μ_g, which depends on the net gains to groundwater users from bargaining as well as their relative bargaining power. The Hamiltonian weight also depends on the hydraulic connectivity parameter *k* and groundwater irrigation efficiency φ, which thus influence the degree to which bargaining power creates a wedge between the disagreement and bargaining solutions.

First-best Problem

The solution to the full cooperation, first-best problem maximizes the sum of the net benefits to surface water and groundwater users:

$$\max_{a_t}\left(J_g + J_s\right) \tag{22}$$

subject to (5) and the initial condition.

The Hamiltonian for problem (22) is:

$$H\left(h_g, a, \lambda, t\right) = B_g\left(\varphi(W - a_t)\right) + B_s\left(Q\left(h_{gt}\right)\right) - E(a_t) + \lambda_t\left(r_g - \varphi(W - a_t) - Q\left(h_{gt}\right)\right) \tag{23}$$

Along with (5) and (11), the following conditions are necessary for problem (22):

$$\frac{\partial H}{\partial a_t} = -\varphi B_g' - E' + \varphi\lambda_t = 0 \tag{24}$$

$$-\frac{\partial H}{\partial h_t} = kF\left(h_{gt}\right)(\lambda_t - B_s{}') = \dot{\lambda}_t - \rho\lambda_t \tag{25}$$

Combining (24) and (25) yields:

$$\dot{a}_t^F = \frac{\left(\rho + kF\left(h_{gt}\right)\right)\left(E' + \varphi B_g{}'\right) - \varphi kF\left(h_{gt}\right)B_s{}'}{E'' - \varphi^2 B_g{}''} \tag{26}$$

The bargaining and first-best curtailment paths are identical only when $\mu_s = \mu_g$. This condition requires more than equal bargaining power; it requires that the ratio of bargaining power coefficients equals the ratio of the maximized net gains from bargaining across groups, i.e. $\gamma_g/\gamma_s = \left(J_g(a_t^B) - d_g\right)/(J_s(a_t^B) - d_s)$. Given the asymmetric costs and benefits of curtailment for each group of water users, this is unlikely to be the case, and expression (26) will generally differ from (21).

Comparison of the Disagreement, Bargaining, and First-best Outcomes

Without imposing functional form assumptions, it is difficult to compare the expressions found for the path of curtailments in expressions (12), (21), and (26) in order to derive intuition about the differences in the curtailment paths under the disagreement, bargaining, and first-best outcomes. Greater insight about these differences can be gained by examining the properties of steady state level of curtailments in each case. There is precedent in the economic literature on groundwater use for examining the steady state values of the state and control variables to derive insight into the problem (Provencher and Burt 1993, 1994; Roseta-Palma 2002).

Presuming the existence of a steady state in each problem, the equilibrium levels of groundwater curtailments that ensure that the groundwater table is unchanging through time are given by the following expressions for the disagreement, bargaining, and first-best problems, respectively:

$$E'^{D} = \left(\frac{\varphi k F\left(h_g\right)}{\rho + kF\left(h_g\right)}\right) B_s{}' \tag{27}$$

$$E'^{B} = \left(\frac{\varphi k F\left(h_g\right)}{\rho + kF\left(h_g\right)}\right) B_s{}' - \frac{\mu_g}{\mu_s}\varphi B_g{}' \tag{28}$$

$$E'^{F} = \left(\frac{\varphi k F\left(h_g\right)}{\rho + kF\left(h_g\right)}\right) B_s{}' - \varphi B_g{}' \tag{29}$$

where time subscripts have been dropped to denote steady state values.

In (27), the steady state level of curtailments in the disagreement outcome balances marginal enforcement costs with the weighted marginal benefits of enhanced surface water flows. The marginal benefits are weighted by a term that depends on irrigation efficiency, the hydrologic parameter *k*, the extent of connectivity between the surface water and groundwater systems, and the discount rate. The denominator of this weight, $\rho + kF(h_g)$, may be thought of as an adjusted discount rate that takes into account the rate at which the value of a unit of groundwater *in situ* erodes as that water is lost to surface water-groundwater exchange. The numerator in (27) captures the extent to which a unit of groundwater pumping reductions reduces consumptive groundwater use and the effect of those water savings on hydraulic exchange and surface water flows. The irrigation efficiency and hydraulic conductivity parameter both influence this term, and therefore play a key role in determining the equilibrium level of the groundwater table and groundwater curtailments.

In equations (28) and (29), the first term on the right-hand side is identical to the right-hand side of (27). However, the bargaining and first-best solutions include a new, second term that takes into account the marginal cost of reductions in consumptive groundwater use due to a curtailment. In both cases, this cost implies that steady state curtailments are lower than in the disagreement outcome. How much lower curtailments are in the bargaining versus first-best outcomes is ambiguous and depends on the relative magnitudes of the Hamiltonian weights, μ_s and μ_g. The difference in expressions (28) and (29) is:

$$E'^B - E'^F = \left(\frac{\mu_s - \mu_g}{\mu_s}\right) \varphi {B_g}' \tag{30}$$

If $\mu_s > \mu_g$, surface water users are assigned greater weight in determining the bargaining solution, and the steady state level of curtailments in the bargaining solution lies between the disagreement and the first-best outcomes, $a^F \leq a^B \leq a^D$. Conversely, if groundwater users are assigned greater weight in determining the bargaining solution, i.e. $\mu_s < \mu_g$, the steady state level of curtailments in the bargaining solution is less stringent than in the first-best solution, $a^B \leq a^F \leq a^D$.

Expression (30) illustrates two key points. The first is that the difference between the bargaining and first-best outcomes depends on the magnitude of the irrigation efficiency parameter, via two pathways. It influences the outcome directly on the right-hand side of (30), but it also influences the outcome indirectly by altering the Hamiltonian weights. These two factors together imply that an increase in irrigation efficiency can either increase the divergence between the two paths by pushing the bargaining solution toward that of the disagreement outcome, or it can decrease the divergence between the two paths by pushing the bargaining solution toward that of the first-best outcome. The second key point is that the steady state curtailments in the disagreement and first-best problems depends in the same way on the hydraulic connectivity parameter, k. However, this parameter influences the outcome for the bargaining solution by affecting the relative magnitudes of the Hamiltonian weights.

The theoretical model presented in this section is designed to apply generally to a problem in which there is scope for cooperation between surface and groundwater users to augment surface water flows by reducing groundwater pumping, in part because failure to cooperate implies costly enforcement must be spent by surface water users to reduce groundwater pumping. The model also incorporates the dynamic effects of groundwater pumping reductions on the connectivity of the surface water-groundwater system and surface water flows into the future. The theoretical model demonstrates that the disagreement, bargaining, and first-best problems differ and that those differences are a function of groundwater irrigation efficiency and bargaining power. The bargaining solution may result in higher or lower levels of agreed-upon curtailment than the first-best solution, depending on the relative bargaining power of surface and groundwater users. Interestingly, in cases where surface water users hold a bargaining power advantage, a bargaining agreement is likely to more closely approximate that of the first-best outcome when the irrigation efficiency of groundwater pumpers is relatively low. In effect, we have shown that the types of negotiations currently being developed in practice are much more complex than has been discussed in the literature. In the next section, we apply the theoretical framework to simulate the path of curtailments and steady state values in the context of a simple numerical example.

Numerical Simulation

To illustrate the applicability of our modeling approach and some of the differences we uncover in our model between the bargaining outcome and the first-best and disagreement outcomes, we present the results of a simple numerical simulation model that is calibrated to reflect general conditions in the Eastern Snake River Plain. This is a location where negotiations are currently active between surface water and groundwater regional groups created to represent individual water users. We use this simulation to show how hydraulic conductivity and groundwater irrigation efficiency are important to the results. We assume symmetric bargaining power for surface and groundwater users, though recall that even in this case the Hamiltonian weights will still differ and generate a relative bargaining advantage for one group as long as the two groups face unequal net gains from bargaining.

The parameters used in the simulation are presented in table 1. The surface water and groundwater net benefit functions are quadratic in surface water flows and consumptive groundwater use respectively, where $B_s(Q) = b_1Q - 0.5b_2Q^2$ and $B_g(et) = d_1et - 0.5d_2et^2$. The surface water net benefit function is calibrated using the estimated gains for surface water irrigators and aquaculture producers from a groundwater curtailment of 60 percent in the Eastern Snake River Plain (Snyder and Coupal 2005). The same study and that by Elbakidze et al. (2012) suggest that the costs of reduced groundwater consumption are likely to exceed by a substantial margin the benefits from enhanced surface water flows. To reflect this, we scale the groundwater net benefit function by a factor of 1.5 relative to the surface water net benefit function. Little empirical data is available on the transaction and enforcement costs associated with pursuit of a groundwater curtailment by surface water users. However, we will assume these costs are conventionally convex and increasing in effort, i.e. $E(a) = 0.5ca^2$.

To describe surface water-groundwater exchange, we assume that the water level at the minimum of the surface water stage s_{min} is distributed uniformly in the interval $[0,s_h]$ so that $F(h_g) = h_g/s_h$. Even with this simplification, equation (2) is analytically intractable. To linearly approximate this highly nonlinear function, we use a first-order Taylor expansion around the initial level of the groundwater table, h_{g0}. Other biophysical parameters, such as the rate of groundwater recharge and the average thickness of the aquifer, are taken from a comprehensive study of the surface water-groundwater system by Kjelstrom (1995). The hydraulic conductivity parameter is consistent with the range of values typically observed for a fractured basalt system. A real interest rate of 2 percent is used throughout.

We solve for steady state level of curtailments under various outcomes (table 2). For the bargaining problem, the simulation is solved by iterating over the Hamiltonian weights and the solution to problem (15) until convergence (Ehtamo et al. 1988). Referring to table 2, we have presented the steady state level of curtailments, the elevation of the groundwater table, and net surface water-groundwater exchange for various values for hydraulic conductivity, defined as k in (1), and the efficiency of groundwater irrigation, defined as φ in (5).

Even in this simple simulation, we discover results that both are interesting and in support of our findings in the theory. When hydraulic connectivity is low (k = 0.015), the bargaining outcome curtailment level lies between the first-best and disagreement outcomes. This result arises because surface water users possess a relative bargaining advantage in this case, as reflected by a Hamiltonian weight that exceeds that for groundwater users. If, however, the relative bargaining advantage is held by surface water users, an increase in irrigation efficiency drives a greater wedge between the bargaining and first-best curtailments, as predicted by the theoretical framework. An increase in hydraulic connectivity (k = 0.025) tips the bargaining advantage toward groundwater users. As a result, the level of curtailments in the bargaining solution falls short of that in the first-best outcome. Interestingly, an increase in irrigation efficiency under this case drives the agreed-upon level of curtailments under bargaining toward that of the first-best outcome, again as predicted by the theoretical framework.

Comparing across outcomes in table 2, it is also interesting that curtailments appear more responsive to efficiency and hydraulic connectivity changes in the disagreement outcome (at least for the parameter values from in table 1). In fact, changes in curtailment from these parameter differences are substantially muted in the bargaining outcomes compared to the others. This occurs because, should a bargaining outcome exist, surface water users agree to cut back on curtailment while groundwater users in return agree to reduce pumping.

Conclusions

We examine negotiation between groundwater users and surface water users in a dynamic setting, using a cooperative Nash bargaining approach where parties may reach an agreement that yields net gains over their status quo water decisions. Groundwater pumping reduces the availability of water for surface water users (through water table changes), who in turn may engage in costly curtailment to ensure protection of their net production rents. We propose a mechanism for cooperation whereby surface water users agree to reduce curtailment levels over time to a path below a level that maximizes their present value rents net of curtailment costs. In return, groundwater users agree to pump less through time than the level that maximizes their present value net rents.

There are two additional novel aspects that we introduce into this cooperative bargaining problem. First, we incorporate hydraulic connectivity that can change through time along with corresponding changes in the groundwater table. Second, we consider the efficiency of water use by groundwater pumpers, as measured through a technology parameter in the groundwater users' net benefit function. Hydraulic connectivity is not a feature of surface water rights bargaining problems, but in the groundwater-surface water case it defines an important link between water availability and pumping decisions over time. The efficiency of water use is also important, proving critical to the desirability of negotiated agreements relative to the first-best (unattainable) outcome of a social planner. A simulation illustrates our theoretical findings under a set of parameters calibrated for the Eastern Snake

River Plain. There, regional groups representing surface water and groundwater users are currently engaged in active negotiation of the type we study in this article.

We find that the path of curtailment is too large in the disagreement outcome compared with both the bargaining and first-best outcomes. Unexpectedly, however, the path of curtailments through time is not always larger in the Nash bargaining solution than in the first-best case; the difference depends critically on both the bargaining power of the surface and groundwater groups and on the efficiency of groundwater irrigation. To wit, if groundwater users hold greater relative bargaining power, then an increase in irrigation efficiency implies that the bargaining and first-best curtailment paths converge. We might expect this if the political process is an impediment to curtailment. Conversely, if surface water users hold greater relative bargaining power, perhaps because of strong implementation of prior appropriation doctrine and/or a smoother curtailment process, then an increase in irrigation efficiency results in a bargaining outcome that is closer to the worst-case disagreement outcome.

Our first study of this problem reveals new and rich opportunities for future research. First, because irrigation efficiency and bargaining power are closely related in their effects, additional study of these aspects will be essential in designing future policies that encourage the adoption of water saving technologies while also encouraging cooperation as a means to reduce social costs. In cases where bargaining arises, or could arise, it may not always be true that encouraging efficiency among one user group is socially desirable. In fact, the largest gains from a social perspective would be to invest in efficiency improvements for the group with the lowest bargaining power, in our case the groundwater users. While this desirability ultimately relies on comparing second-best outcomes, of which there may be more than one, our work nonetheless demonstrates that the problem of negotiated ground and surface water use in a hydraulically connected system is far more complicated than a cursory look might suggest.

The second opportunity for further work is to relax our assumption that the technology of groundwater users is exogenous and instead examine it as a choice. Previous work in emissions regulation settings has shown that technology adoption by polluters can enhance bargaining agreements by moving them closer to the theoretical first-best outcome if an eventual agreement is reached (see Amacher and Malik 1996 and the more recent work by Arguedas 2005 and Heyes and Kapur 2011). In this work, the technology choice creates scope for bargaining that otherwise would not exist. For example, firms agree to adopt a cleaner technology that reduces regulatory enforcement costs in return for less stringent policy instruments. A key consideration is the timing of technology adoption relative to the bargaining phase, and in some cases there may be first-mover advantages to either party involved in negotiations. The interaction of the technology choice and its effect on hydraulic connectivity and curtailment in the groundwater-surface water problem is fundamentally different and will likely to lead to different conclusions concerning bargaining and technology adoption.

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Table 1. Parameter Values for Simulation

Parameter	Description (units)	Initial value
ρ	Discount rate	0.02
k	Hydraulic conductivity of surface water bed (feet per day)	0.015
r	Groundwater recharge (million acre-feet)	2.0
s_h	Upper limit of the elevation of the bottom of a surface waterway (feet above base of aquifer)	350
h_s	Surface water stage (feet above base of aquifer)	400
h_{g0}	Initial level of the groundwater table (feet above base of aquifer)	250
W	Maximum per-period groundwater diversions (million acre-feet)	3.8
φ	Groundwater irrigation efficiency	0.60
b_1	Surface water net benefit function, linear parameter	22.5
b_2	Surface water net benefit function, quadratic parameter	9.6
d_1	Groundwater net benefit function, linear parameter	33.8
d_2	Groundwater net benefit function, quadratic parameter	14.4
c	Curtailment cost function, quadratic parameter	9.6
γ_s	Bargaining power, surface water users	0.50

Table 2. Steady State Outcomes in the Disagreement, Bargaining, and First-Best Solutions

	Groundwater curtailment (million acre-feet)	Groundwater table (feet above base of aquifer)	Surface water-groundwater exchange (million acre-feet)
Disagreement outcome			
$k = 0.015$; $\varphi = 0.60$	2.10	450.7	0.98
$k = 0.015$; $\varphi = 0.75$	1.76	423.6	0.47
$k = 0.025$; $\varphi = 0.60$	3.20	451.0	1.64
$k = 0.025$; $\varphi = 0.75$	2.77	438.1	1.23
Bargaining outcome			
$k = 0.015$; $\varphi = 0.60$	1.68	437.6	0.73
$k = 0.015$; $\varphi = 0.75$	1.69	420.6	0.42
$k = 0.025$; $\varphi = 0.60$	2.56	439.0	1.26
$k = 0.025$; $\varphi = 0.75$	2.48	431.1	1.01
First-best outcome			
$k = 0.015$; $\varphi = 0.60$	1.66	436.9	0.71
$k = 0.015$; $\varphi = 0.75$	1.60	417.1	0.35
$k = 0.025$; $\varphi = 0.60$	2.70	441.6	1.34
$k = 0.025$; $\varphi = 0.75$	2.49	431.3	1.02

[1] Conjunctive management refers to a diverse set of activities that coordinate and regulate the use of surface and groundwater (State of California 2015). Conjunctive administration, defined as the joint administration of surface water and groundwater property rights, is sometimes defined as a separate policy instrument (Tuthill, Rassier, and Anderson 2013) and sometimes defined as a type of conjunctive management policy (State of Idaho 2012).

[2] Other states that have followed a similar approach include Colorado, Kansas, Nebraska, and Oregon (Oklahoma Water Resources Board 2010).

[3] This assumption is for convenience and does not come at a loss. A user who has access to both surface water and groundwater would likely not act independently, but would choose to side with whatever group is most likely to increase their marginal net benefit of water use.

[4] This suggests a first-mover problem in which the first move by senior surface water users is their non-cooperative curtailment strategy.

[5] We assume commitment exists between the two groups of water users, which is a common assumption in the bargaining literature. Moreover, this assumption is consistent with the observed bargaining agreement in Idaho, which establishes legal mechanisms to ensure commitment between the two parties. For example, the agreement requires that wells be metered to monitor groundwater pumping, and a legal mechanism has been established to ensure that groundwater users involved in the agreement are protected from future curtailment calls (O'Connell 2015a). The State of Idaho has also supported the agreement by committing resources to recharge the aquifer.

[6] The surface water stage is measured by the U.S. Geological Survey and state water agencies to track surface water flows. It is nonlinearly related to the volume of surface water, where

the relationship between flow volume and stage depends on the shape of the surface waterway. To sharpen our focus on the role of groundwater pumping on surface water flows, we assume that surface water inflows to the region are exogenous and time-invariant.

[7] We do not make endogenous the discrete technology adoption decisions of groundwater irrigators. Decisions to adopt more efficient technology are often lagged in time and undertaken after sustained drought conditions rather than in response to annual variation in water availability (Cobourn 2015; Zilberman et al. 2002). Moreover, once a new technology is adopted, it is likely to be used for a number of years, which suggests a discrete shift in the trajectory of the optimal path of groundwater pumping rather than period-to-period adjustments in efficiency. We revisit the effect of irrigation efficiency on the bargaining outcome in our numerical simulation.

[8] The recent bargaining agreement reached on the Eastern Snake River Plain involves a permanent reduction in groundwater pumping, which suggests that, at least in this context, considering a bargaining agreement over an infinite time horizon is reasonable. To simplify the theoretical exposition, we follow Chakravorty and Umetsu (2003) and model the marginal cost of groundwater pumping as a constant, rather than as a function of the groundwater table. Were there a substantial user cost associated with groundwater pumping due to the dynamic effects on the groundwater table, our results would understate the optimal elevation of the groundwater table in the bargaining and first-best outcomes.

[9] In Idaho, this assumption is further justified by a moratorium on groundwater rights establishment in Idaho, which prevents any expansion in the amount of groundwater that irrigators are legally permitted to pump.

[10] Were the constraint non-binding, curtailments by surface water users could potentially have no effect on groundwater pumping decisions, which would render this problem trivial.

[11] Sufficiency becomes difficult to establish in the general case because of the presence of the convex function $Q(\bullet)$ in the concave surface water benefit function $B_s(\bullet)$. The objective function is jointly concave in the state and control variables if:

$$-\frac{B_s{}'}{B_s''} > k\frac{F\left(h_{gt}\right)^2}{f\left(h_{gt}\right)}$$

Whether this condition holds is an empirical question that depends on the relative curvature of the surface water benefit function and the surface water-groundwater exchange function. A similar condition is required to ensure that Arrow's weaker sufficiency condition holds (Kamien and Schwartz 1991).

[12] Nash proved that under certain conditions an agreement in this context maximizes the product of gains defined as the gains from cooperation relative to the disagreement outcome (e.g. see Binmore, Rubinstein, and Wolinsky 1986; Osbourne and Rubinstein 1994). These conditions are: invariance of the solution to monotonic transforms of utility, a fact that holds here given water users bargain over rent functions with constant forms over time and known prices and costs; the impossibility of further Pareto improvements if a solution to the bargaining problem exists, which is guaranteed by the definition of the objective function for our problem and the fact that regional representatives would underlie the negotiation process among water user groups; and independence of irrelevant alternatives, that, although normally fairly stringent, holds in our case because inefficient agreement points can be removed from consideration since by definition the agreement outcome must improve net

present value rents over the disagreement outcome before such an outcome is part of the agreement contract set. As in most problems of this type, commitment on the part of both ground and surface water users to the outcome in the bargaining problem must also hold. This is likely in our case because the negotiated agreement in a given region would be enforced by a legal and administrative system that implements the solution.