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Abstract

This paper introduces a game theoretic model of groundwater extraction in a two-cell aquifer under incomplete information. A novel assumption is that individual users have incomplete knowledge of the speed of lateral flows in the aquifer: although a user is aware that his neighbor's water use has some influence on his future water stock, he is uncertain about the degree of this impact. We find that the lack of information may either increase or decrease the rate of water use and welfare. In a two-period framework, the relevant characteristic is the ratio of the periodic marginal benefits of water use. Depending on whether this ratio is convex or concave, the average speed with which the aquifer is depleted decreases or increases when users learn more about the local hydrologic properties of groundwater. In principle, welfare may decrease even in cases when the groundwater allocation is closer to the efficient groundwater allocation.

Keywords: common property resource, groundwater, information

1. Introduction

In a seminal article, Gisser and Sanchez (GS) [10] found that the welfare gain from groundwater management policies is likely to be negligible. GS analytically obtained the infinite-horizon trajectory of water use from competitive (open access) pumping, as well as the optimal control trajectory that maximizes users' discounted welfare. Applying a computable version of their model to the Pecos Basin in New Mexico, GS calculated that the welfare difference in the two trajectories, representing the gain from optimal management, was on the order of 0.01%. Intrigued by this result, several researchers applied the GS model to other regions, often with refinements allowing for more detailed user responses to resource depletion. Across a wide range of settings and behavioral assumptions, the findings in these studies were generally similar to those of GS.[1]

Another related line of research relaxed GS's assumption of an openly accessed aquifer. As Negri [17] pointed out, this assumption does not hold for most aquifers; access to groundwater usually is restricted because of the need for users to acquire the overlying land as well as a water right. Negri [17], Dixon [5], and Provencher and Burt [21] developed dynamic game-theoretic models of groundwater use in a restricted access setting. Competitive pumping levels in these models were derived as a Nash equilibrium in closed-loop strategies, where each user takes the decision rules of his rivals as given. This line of research identified the precise individual incentives leading to welfare losses.[2]

Yet another line of research replaced the simple "bathtub aquifer" in GS's model with a more accurate depiction of groundwater hydrology. The bathtub or single cell aquifer model assumes instantaneous lateral flow of groundwater, so that consumption by one user has an immediate and equal impact on the water available to other users. In reality, the speed of lateral flow (known as aquifer transmissivity) is quite slow on average, but depends on a number of spatially variable aquifer features. Thus, a spatially explicit model is required to accurately portray groundwater availability over time. Extending earlier work [3,19], Brozovic [4] solved the social planner's problem with spatially disbursed users and finite transmissivity. Dynamically optimal extraction rates were found to be highly variable spatially, a result with important policy implication that the GS model could not reveal. However, the common property equilibrium in this setting was not addressed.

In this paper, we build on both the game theoretic and spatial groundwater models, while focusing on an issue not previously addressed in the groundwater literature. Namely, our aim is to determine the role of incomplete information about aquifer transmissivity in shaping the common property equilibrium and its attendant welfare losses. While users in most aquifers are surely aware that their water availability depends on the extraction histories at nearby wells, they are unlikely to know the degree of these impacts with precision. Due to the geologic variability noted above, even hydrologic scientists have limited data on transmissivity at specific locations. Moreover, it would be difficult for an individual user to infer local transmissivity from observed water levels and pumping rates at nearby wells, as these rates are private information.

We construct a game-theoretic, restricted access model, where use at one well affects future water availability at the neighboring well depending on the (unknown) aquifer transmissivity. Extreme possibilities are that the aquifer is a "bathtub" with infinite transmissivity and that it consists of independent aquifers (cells) with no lateral flows. To sharpen the analysis, we employ the simplest possible setting with the essential features, which has two periods and two symmetric users. We then isolate the effect of incomplete information on: (*a*) the equilibrium rate of extraction, and (*b*) the welfare loss due to the common pool nature of the resource. These effects are determined by comparing the Nash solution under incomplete information to the socially efficient solution and to the Nash outcome under complete information.

We find that better information may either increase or decrease the equilibrium withdrawal rate, and also may either increase or decrease equilibrium welfare. Moreover, it is possible that better information brings the withdrawal rate closer to the efficient level but nevertheless causes welfare to fall. We establish that the direction of impact from better information depends on a specific curvature property of users' net benefit functions.

Our results fit within the broader literature on the effects of information on equilibrium outcomes. It is well known that more information may not improve welfare if it decreases the scope of risk-sharing opportunities among the agents in the economy.[3] This result occurs because under better (private or public) information about the environment, not only does decision-making become better tailored to circumstances, but the set of feasible choices may also become constrained. Our line of inquiry is also related to the literature on experimentation and learning in the multi-agent setting. For example, Harrington [12] explores price-setting behavior in the context of a duopoly in which firms are uncertain about the degree of product differentiation. He finds that firms' incentive to acquire more information about the extent of product differentiation (i.e. a potential externality imposed by the firms on each other) depends on their prior beliefs. In contrast, we consider the case of a dynamic externality.

Although this paper presents a model of groundwater use, our findings apply to other common property resources (such as fish, wildlife, or oil) where spatially distributed users are uncertain about the degree to which the resource is non-exclusive. In the case of groundwater, exclusivity depends on aquifer transmissivity, while for fisheries it is determined by the rates of biomass dispersal across space [22]. In general, better public information amplifies (or lessens) the tragedy of the commons and decreases (increases) social welfare when, upon observing the signal, the agents revise upward (downward) the extent to which the resource is non-exclusive and is shared among them. The goal of this paper is to formalize this trade-off and establish conditions under which the effect of better public information about the resource extraction and social welfare is unambiguous.

2. Model

There are two periods, $t = 1,2$, and two identical users (farmers), $i = 1,2$. The model of the aquifer is depicted in Figure 1. In the beginning of period 1, the stocks of groundwater on each farm, $x_{i,1}$, $i = 1,2$ are the same. In what follows, the first symbol, *i*, in double subscripts on variables identifies the farm and the second, *t*, identifies the period; single subscripts of functions denote first derivatives. For concreteness, we normalize the initial stocks of groundwater to unity, $x_{1,1} = x_{2,1} = 1$. Let $u_{i,t}$ denote the amount of groundwater pumped on farm i in period t. The amount that can be used for irrigation on each farm cannot exceed that farm's groundwater stock:

(1) $u_{i,t} \le x_{i,t}$ for $t = 1,2$ and $i = 1,2$.

For simplicity, we assume no aquifer recharge, although recharge could easily be incorporated in the analysis and would not change the qualitative nature of our results.

[Figure 1 about here]

2.1 Lateral groundwater flows

Condition (1) above distinguishes our model from the standard common property setting, as it assumes groundwater is essentially a private resource *within* each irrigation season: farmer *i* cannot access the groundwater lying beneath farm *j* within a given period. This assumption reflects the spatial separation of the wells and the notion that groundwater flows too slowly for the extractions to interact within seasons. Extraction at each well creates a "cone of depression" in the groundwater surface that grows wider and deeper as more water is extracted during the irrigation season. However, this extraction period is typically much shorter than the recovery period between seasons, during which the cones are eliminated by lateral flow. For example, in the High Plains aquifer region, irrigation withdrawals for summer crops last about 75 days (mid-June to late August), leaving about a 9.5-month recovery period. Our assumption of intra-seasonally private use presumes either that neighboring cones of depression do not overlap or that the resulting intra-seasonal flow across farms is negligible.

Between periods 1 and 2, groundwater will flow toward the well with the greater extraction in period 1. In particular, the inter-period flow of groundwater from farm 2 to farm 1 is given by Darcy's law:

$$Q = -\alpha((1-u_{1,1}) - (1-u_{2,1})) = \alpha(u_{1,1} - u_{2,1}),$$

where $\alpha \in [0,0.5]$ summarizes the hydrological properties of the region, $(x_{1,1} - u_{1,1}) - (x_{2,1} - u_{2,1}) = u_{1,1} - u_{2,1}$ is the hydraulic gradient (the difference in hydraulic head between wells).[4] The flow of groundwater from farm 1 to farm 2 is $-Q$. The stocks of groundwater available in period 2 are

(2) $$x_{1,2} = 1 - u_{1,1} + Q = 1 - (1-\alpha)u_{1,1} - \alpha u_{2,1}, \qquad x_{2,2} = 1 - u_{2,1} - Q = 1 - \alpha u_{1,1} - (1-\alpha)u_{2,1}.$$

While groundwater is always an intra-seasonally private property resource, $\alpha = 0.5$ corresponds to the inter-seasonally common property resource because it implies that groundwater levels are equalized across farms in period 2, $x_{1,2} = x_{2,2}$, for any pumping in period 1, while $\alpha = 0$ corresponds to the purely private resource.

2.2 Benefits of groundwater use

The net benefits of water use on each farm is given by

(3) $$g(u,x) = v\left(py(u) - c(u,x) - k\right),$$

where p is the per unit price of the crop, y is yield, c is the cost of pumping groundwater, k is the cost of other farming inputs, and v is a utility-of-income function. An empirically estimated specification of (4) is provided in Peterson and Ding [20]. In the analysis that follows, the curvature properties of g will play a central role. In general, these properties are inherited both from the utility function, v, and from the income function, $r(u,x) = y(u) - c(u,x) - k$.

To understand the relevant curvature conditions, it will be helpful to consider examples where either utility or income is linear, so that there is no ambiguity about the source of the curvature of g. Thus, in some of the examples in later sections, v is specified linearly (i.e., farmers are risk neutral) and the source of curvature is from the yield and cost functions; in other examples v is concave and farmers are risk averse, while the yield and cost functions are linear. The latter examples provide helpful intuition about the relevant curvature properties, as they can be related to standard indicators of risk preferences. Throughout, we assume that g is strictly increasing, strictly concave, twice differentiable over the relevant domain, and has the property that $g(0,\cdot) = 0$ and $g_u(0,\cdot) = \infty$.[5]

2.3 Information about the hydrology of the region

We distinguish between two information regimes. Under *complete* information, in period 1 farmers know with certainty the "speed" of lateral groundwater flow, α. Under *incomplete* information, in period 1 farmers view $\tilde{\alpha}$ as a random variable and only know its probability distribution, $\Pr(\tilde{\alpha} \le \alpha) = H(\alpha)$, where H represents the variation in geologic conditions throughout the aquifer.[6] In the latter case, information is assumed to be symmetric across farmers, so that their subjective probabilities, H, are identical.

Farmers maximize the sum of discounted per period profits:

(4) $g(u_{i,1},1) + \beta g(u_{i,2}, x_{i,2})$ subject to (1) and (2),

where $\beta \le 1$ is the discount factor. Let $\pi_i(\alpha)$ and $\pi_i(E[\tilde{\alpha}])$ denote the maximum expected profits attained ex ante by the non-cooperating farmers, $i = 1,2$, respectively under complete and incomplete information about the hydrology of the region.

3. Social planner

Before we turn to the analysis of equilibrium groundwater use, we characterize the efficient allocation. We assume that social planner has perfect information about α. Conditional on α, the planner's problem is to maximize joint profits by choosing $u^s_{i,t}$, $i = 1,2$, $t = 1,2$:

(5) $$\max_{u^s_{1,1},u^s_{2,1},u^s_{1,2},u^s_{2,2}} \sum\nolimits_{i=1,2} g(u^s_{i,1},1) + \beta g(u^s_{i,2}, x_{i,2})$$ subject to (1) and (2).

Let

(6) $$f(u) = \frac{g_u(u,1)}{\beta(g_u(1-u,1-u) + g_x(1-u,1-u))}$$

denote the ratio of the marginal benefits of water, and $f^{-1}(\cdot)$ denote the inverse of f. The (strict) concavity of g implies that f and its inverse are (strictly) decreasing. Our first result shows that the efficient allocation of groundwater is independent of the speed of groundwater lateral flows (the extent to which the resource is public or private).

Proposition 1. (Efficient pumping) *The efficient intertemporal allocation of groundwater is independent of the speed of lateral flows, and is given by*

(7) $u_{i,1}^{s}(\alpha) = f^{-1}(1) \;\; \forall \alpha \in [0,0.5]$.

Proof: First, note that in period 2, the planner optimally exhausts the remaining stock on each farm because g is strictly increasing in u. This symmetry implies that constraint (1) binds for t = 2 (i.e., $u_{i,2} = x_{i,2}$), so that (5) can be written

(8) $\max_{u_{1,1}^{s},u_{2,1}^{s}} \sum_{i=1,2} g(u_{i,1}^{s},1) + \beta g(x_{i,2}, x_{i,2})$ subject to (1) and (2).

Because (8) is symmetric and concave in $u_{1,1}^{s}$ and $u_{2,1}^{s}$, optimality requires that $u_{1,1}^{s} = u_{2,1}^{s}$. Because farms are identical, this implies that there are no lateral groundwater flows, $Q = 0$. Additionally, corner solutions are ruled out because g is increasing and concave in each argument, $g(0,.) = 0$, and $g_u(0,.) = \infty$. Substituting the law of motion (2), $x_{i,2} = 1 - u_{i,1}$ for $i = 1,2$, into the objective function and differentiating, the first-order conditions for a maximum are

(9) $g_u(u_{i,1}^{s},1) - \beta(g_u(1-u_{i,1}^{s},1-u_{i,1}^{s}) + g_x(1-u_{i,1}^{s},1-u_{i,1}^{s})) = 0$, or

(10) $f(u_{i,1}^{s}) = 1$.

By the concavity of g, f is a strictly decreasing function, implying the existence of an inverse function, f^{-1}. Applying this inverse function to (10) completes the proof. ■

Even though lateral flows are possible, Proposition 1 states that it is efficient to pump the same amount of groundwater on each farm because farms are symmetric. This result implies that detailed data on α are not needed to obtain the efficient solution. At the efficient solution, the average pumping of water use and farmer profits are

$$\text{(11a)}\quad E[u_{i,1}^{s}(\tilde{\alpha})] = \int_0^{0.5} u_{i,1}^{s} dH(\alpha) = f^{-1}(1),\quad i = 1,2,$$

$$\text{(11b)}\quad E[\pi_i^{s}(\tilde{\alpha})] = g(f^{-1}(1),1) + \beta g(1 - f^{-1}(1), 1 - f^{-1}(1)),\ i = 1,2.$$

In this model, farmers' profits are the only relevant portion of social welfare, because the price of the commodity produced, *p*, does not vary and consumers' welfare remains constant. Additionally, symmetry implies that profits will be equal across farmers in both the efficient and equilibrium solutions (the latter are derived below). We therefore use the terms "producer profits" and "welfare" interchangeably throughout this article to refer to the income of the average farmer.

The function *f* in equation (6) can be interpreted as a farmer's intertemporal rate of substitution for water. The numerator represents the benefit of extracting and consuming the marginal unit in period 1, while the denominator is the discounted benefit of saving the marginal unit until period 2. The two terms in the parentheses of the denominator reflect the two types of benefits from saving: g_u is the consumption value of the marginal unit extracted in period 2 and g_x reflects the marginal reduction in pumping costs. Given this interpretation of *f*, condition (10) can be seen as an instance of a well known-result from consumption-savings problems: efficiency requires that agents' intertemporal rate of substitution be set equal to the gross return on savings (i.e., 1 + *r* where *r* is the expected rate of return). From the planner's perspective, the gross return on water saved in the aquifer is exactly one—a unit saved in period 1 is a unit available in period 2.

In what follows, the inverse function f^{-1} and its curvature properties will play important roles.[7] In the context of the planner's problem, this function maps the gross rate of return on groundwater savings into the efficient amount of water consumed in period 1. The easiest case to interpret is when $\beta = 1$ and the water benefits depend only on water use, *u*, and are independent of the groundwater stock. Under these assumptions, $f(u) = g_u(u)/g_u(1–u)$. Function *f* then attains a value of 1 when $u = 0.5$, or equivalently, $f^{-1}(1) = 0.5$. Thus, in the case where pumping costs are unaffected by the stock level and $\beta = 1$, the efficient solution distributes the available water equally across the two periods.

As will be shown below, the same function f^{-1} emerges from farmers' individual decision problems in an unregulated equilibrium. In particular, a farmer's individually optimal consumption in period 1 can be computed by evaluating f^{-1} at the farmer's rationally expected gross return on water saved in the aquifer.

4. Equilibrium

We proceed by first charactering equilibrium allocation under incomplete information. The equilibrium under complete information is then obtained a special case of the incomplete information regime. Finally, we reveal the "tragedy of the commons effect" in our model, showing that pumping levels in both cases exceed the efficient level.

4.1. Incomplete information

In this section, we determine equilibrium pumping by both farmers when they know the probability distribution of the lateral flow speed, $H(\alpha)$, but not the local realization of $\tilde{\alpha} \in [0,0.5]$.

In period 2, both farmers optimally exhaust the available stocks of underground water because *g* is increasing—i.e., $u_{i,2}^{n} = x_{i,2}(\tilde{\alpha})$ for $i = 1,2$. Here superscript "*n*" stands for "no information". Farmer i's net benefits depend on decisions made in period 1 by virtue of the binding constraint (2); i.e., $x_{i,2}\ (\tilde{\alpha}) = (1-\tilde{\alpha})(1-u_{i,1}^{n}) + \tilde{\alpha}\,(1-u_{j,1}^{n})$. The dependence of the groundwater stocks in period 2 on the speed of lateral flows introduces uncertainty into the farmers' decisions problems. And so, in period 1, farmer i chooses $u_{i,1}^{n}$ to maximize

(12) $\pi_i(E[\tilde{\alpha}]) = \max_{u_{i,1}^{n}} E[g(u_{i,1}^{n},1) + \beta g(x_{i,2}(\tilde{\alpha}), x_{i,2}(\tilde{\alpha}))]$ subject to (1) and (2).

Because the speed of lateral flows only affects period 2 profit, for a given $u_{j,1}^{n}$, the best response, $u_{i,1}^{n}$, by farmer $i \neq j$ satisfies

(13) $g_u(u_{i,1}^{n},1) - \beta E[(1-\tilde{\alpha})(g_u(x_{i,2}(\tilde{\alpha}), x_{i,2}(\tilde{\alpha})) + g_x(x_{i,2}(\tilde{\alpha}), x_{i,2}(\tilde{\alpha})))] = 0$.

The Nash equilibrium is a pair of pumping levels, $u_{i,1}^{n}$ (i = 1, 2), that simultaneously satisfy equation (11).

Proposition 2. (Equilibrium pumping) *If both farmers' expected rate of lateral flow is* $E[\tilde{\alpha}]$, *the Nash equilibrium pumping levels are symmetric and unique, and equal*

(14) $u_{i,1}^{n}(E[\tilde{\alpha}]) = f^{-1}(1-E[\tilde{\alpha}])$, *i = 1,2.*

Proof: We will first show that the equilibrium is symmetric. The best response conditions, equation (13), can be written

$$g_u(u_{1,1}^{n},1) - \beta E[(1-\tilde{\alpha})q(1-(1-\tilde{\alpha})u_{1,1}^{n} - \tilde{\alpha}u_{2,1}^{n})] = 0$$

$$g_u(u_{2,1}^{n},1) - \beta E[(1-\tilde{\alpha})q(1-(1-\tilde{\alpha})u_{2,1}^{n} - \tilde{\alpha}u_{1,1}^{n})] = 0,$$

where $q(x) = g_u(x,x) + g_x(x,x)$.Without loss of generality, suppose the equilibrium were asymmetric with $u_{1,1}^{n} > u_{2,1}^{n}$. Then we have

$$g_u(u_{1,1}^n,1) = \beta E[(1-\tilde{\alpha})q(1-(1-\tilde{\alpha})u_{1,1}^n - \tilde{\alpha}u_{2,1}^n)] \geq \beta E[(1-\tilde{\alpha})q(1-(1-\tilde{\alpha})u_{2,1}^n - \tilde{\alpha}u_{1,1}^n)]$$

$$= g_u(u_{2,1}^n,1)$$

The first inequality follows by assumption, $u_{1,1}^n > u_{2,1}^n$, and the concavity of q (see footnote 5) . Note that $u_{1,1}^n > u_{2,1}^n$ implies that, for any $\alpha \in [0,0.5)$, $1-(1-\alpha)u_{1,1}^n - \alpha u_{2,1}^n < 1-(1-\alpha)u_{2,1}^n - \alpha u_{1,1}^n$, so that $q(1-(1-\alpha)u_{1,1}^n - \alpha u_{2,1}^n) \geq q(1-(1-\alpha)u_{2,1}^n - \alpha u_{1,1}^n)$, and hence $(1-\alpha)q(1-(1-\alpha)u_{1,1}^n - \alpha u_{2,1}^n) \geq (1-\alpha)q(1-(1-\alpha)u_{2,1}^n - \alpha u_{1,1}^n)$. Because the last inequality holds for any $\alpha \in [0,0.5)$, taking the expectation over $\tilde{\alpha}$ does not change the sign of the inequality. We therefore have a contradiction since the concavity of g implies that $g_u(u_{1,1}^n,1) < g_u(u_{2,1}^n,1)$ when $u_{1,1}^n > u_{2,1}^n$. Hence, in any Nash equilibrium $u_{1,1}^n = u_{2,1}^n$. Symmetry implies that the stock in period 2 simplifies to $x_{i,2}(\tilde{\alpha}) = (1-\tilde{\alpha})(1-u_{i,1}^n) + \tilde{\alpha}(1-u_{i,1}^n) = 1-u_{i,1}^n$. Substituting this relationship into (13), the best response condition becomes

(15) $$g_u(u_{i,1}^n,1) - (1-E[\tilde{\alpha}])\beta(g_u(1-u_{i,1}^n,1-u_{i,1}^n) + g_x(1-u_{i,1}^n,1-u_{i,1}^n)) = 0.$$

By concavity of g, the left-hand side of (15) is decreasing in $u_{i,1}^n$. Accordingly, equation (15) has a unique solution, $u_{i,1}^n$. By the definition of *f*, this unique solution also satisfies $f(u_{i,1}^n) = 1-E[\tilde{\alpha}]$; applying the inverse function, f^{-1}, to this equation completes the proof. ■

The intuition for Proposition 2 is that each farmer anticipates a fraction, $E[\tilde{\alpha}]$, of each unit of water he saves in period 1 will “escape” to beneath his rival’s farm by period 2. His rationally expected gross return on water saved is then $1-E[\tilde{\alpha}]$, giving him an incentive to increase period 1 consumption above the efficient level in equation (8).

In sum, the groundwater pumped in period 1 and welfare attained by non-cooperative farmers under incomplete information about the speed of lateral flow between the neighboring farms are

(16a) $u_{i,1}^{n}(E[\tilde{\alpha}]) = f^{-1}(1 - E[\tilde{\alpha}])$,

(16b) $\pi_i(E[\tilde{\alpha}]) = g(f^{-1}(1 - E[\tilde{\alpha}]),1) + \beta g(1 - f^{-1}(1 - E[\tilde{\alpha}]),1 - f^{-1}(1 - E[\tilde{\alpha}]))$.

Next we consider the equilibrium under complete information.

4.2. Complete information

Equilibrium pumping under complete information about the speed of groundwater lateral flow, α, can be obtained as a special case of equilibrium characterized above by setting $\Pr(\tilde{\alpha} = \alpha) = 1$ for some $\alpha \in [0,0.5]$. Applying (16a) and (16b), equilibrium pumping, $u_{i,1}^{c}(\alpha)$ and equilibrium profits, $\pi_i(\alpha)$ under complete information are

(17a) $u_{i,1}^{c}(\alpha) = f^{-1}(1 - \alpha)$.

(17b) $\pi_i(\alpha) = g(f^{-1}(1 - \alpha),1) + \beta g(1 - f^{-1}(1 - \alpha),1 - f^{-1}(1 - \alpha))$,

where superscript "*c*" stands for "complete information".

To an observer who knows only the probability distribution of $\tilde{\alpha}$ over the aquifer, the average water pumped in period 1 and welfare attained by non-cooperative farmers with complete hydrologic information are

(18a) $E[u_{i,1}^{c}(\tilde{\alpha})] = \int_0^{0.5} f^{-1}(1 - \alpha) dH(\alpha)$,

(18b) $E[\pi_i(\tilde{\alpha})] = \int_0^{0.5} [g(f^{-1}(1 - \alpha),1) + \beta g(1 - f^{-1}(1 - \alpha),1 - f^{-1}(1 - \alpha))] dH(\alpha)$.

Next we compare the non-cooperative equilibrium under both information regimes to the efficient solution.

4.3. Equilibrium and efficient allocations

From the results above, it is straightforward to show that pumping levels in both information regimes will exceed the efficient level, $u_{i,1}^{s}$, except in the unique case of no transmissivity. Formally, under incomplete information, $u_{i,1}^{n}(E[\tilde{\alpha}]) > u_{i,1}^{s}$ if $E[\tilde{\alpha}] > 0$, while under complete information $u_{i,1}^{c}(\alpha) > u_{i,1}^{s}$ if $\alpha > 0$.[8] Thus, the familiar "tragedy of the commons" arises in this model regardless of the information regime. As should be expected, no externality results when users believe groundwater is a private resource.

As one would also expect, the gap between the equilibrium and efficient extraction grows as (the expectation of) α becomes larger: the more common users perceive the resource to be, the faster the rate of withdrawal. This gap grows to its widest extent in "bathtub" situation $E[\tilde{\alpha}] = 0.5$, where users believe the aquifer to be a pure public resource.[9] These results are depicted in Figure 2 for $g(u,x) = u^{0.8}$ and $\beta = 1$.

[Figure 2 about here]

While these results establish that pumping rates exceed the efficient amount in both information regimes, it does not tell us how the pumping rates in the two regimes compare to each other. To be precise, consider an aquifer where α varies according to the known distribution *H*. If farmers are initially uninformed about the hydrology, we seek to understand how pumping rates and welfare would be affected if they all learned the precise local values of α. In analyzing this question, we obtain the main result of this article: the average speed with which the aquifer is depleted may either increase or decrease when users have better information about local hydrologic properties.

5. Complete versus incomplete information

5.1. Average pumping rates

The foregoing analysis demonstrates that, on the one hand, the uncertainty about the speed of lateral groundwater flow – whether the resource is private or common – may provide a private incentive to pump less to safeguard against a possibly smaller stock in period 2. On the other hand, this uncertainty may also create a private incentive to increase pumping, so as to capture more of the common stock. The following proposition provides conditions under which farmers pump more (less) groundwater under incomplete information about the extent to which the resource is public.

Proposition 3. (Information and pumping) *Suppose that the ratio of the marginal benefits of groundwater in period 1 and 2 is convex (concave) in period 1 pumping, i.e.,* $f'' \geq (\leq) 0$. *Then non-cooperative farmers pump, on average, more (less) groundwater in period 1 under complete information about the speed of lateral flows, i.e.,* $E[u_{i,1}^{c}(\tilde{\alpha})] \geq (\leq)\ u_{i,1}^{n}(E[\tilde{\alpha}])$.

Proof: Using the inverse function theorem and differentiating twice yields, $\partial^2 f^{-1}(x)/\partial x^2 = -f''(f^{-1}(x))/(f'(f^{-1}(x)))^3$. This expression is non-negative (non-positive) depending on whether $f'' \geq (\leq) 0$, because, by assumption, $f' < 0$. Then, using (16a) and (18a), Jensen's inequality implies

$$E[u_{i,1}^{c}(\tilde{\alpha})] = E[f^{-1}(1-\tilde{\alpha})] \geq (\leq)\ f^{-1}(1-E[\tilde{\alpha}]) = u_{i,1}^{n}(E[\tilde{\alpha}])$$

depending on whether $f''(u) \geq (\leq) 0 \ \ \forall u \in [f^{-1}(1), f^{-1}(0.5)]$. ■

And so, the curvature of the intertemporal marginal rate of substitution, $f(u) = g_u(u,1) / \beta(g_u(1-u,1-u) + g_x(1-u,1-u))$, determines whether non-cooperative farmers pump, on average, more or less groundwater under incomplete information about the speed of lateral flows.

To develop the underlying intuition in Proposition 3, consider the case where *f* is concave. As shown above, the equilibrium pumping level under complete information depends on the realized value of α, and can be identified geometrically as the point where $f = 1-\alpha$. Thus, all the possible equilibrium points lie along the function *f*, corresponding to different realizations of $1 - \alpha$. By Jensen's inequality, the average of these equilibrium points will lie to the left of the point where $f = 1 - E[\tilde{\alpha}]$, which is the solution under incomplete information. Thus, when *f* is concave, complete information results in less pumping. By contrast, if *f* is convex the average of the equilibrium points under complete information lies to the *right* of the pumping level under complete information. In this case, complete information results in more pumping. The following examples illustrate.

Example 1. (*Stock and pumping cost externality under risk-neutrality*) Suppose that farmers are risk-neutral and the period net benefit of water use is given by

$$g(u,x) = au - 0.5bu^2 - c(1-x+0.5u)u = (a-c(1-x))u - 0.5(b+c)u^2,$$

where $b+c < a < 2b+c$, $au - 0.5bu^2$ is yield (output price is normalized to one), and $c(1-x+0.5u)u = c\int_0^u (1-x+z)dz$ is the pumping cost that increases with the initial depth from the land surface to the water table, $1-x$, and the quantity of water extracted, u. Then the intertemporal marginal rate of substitution is $f(u) = (1/\beta)(a-(b+c)u) \;/(a-b+(b-c)u)$ and

$$f''(u) = \frac{2b}{\beta}\frac{(2a-b-c)(b-c)}{(a-b+(b-c)u)^3} \geq (\leq) 0 \text{ as } b \geq (\leq) c.$$

Applying Proposition 3, if the quadratic term, *b*, is large (small) relative to marginal pumping costs, c, complete information will lead to more (less) pumping in period 1. ■

Example 2. (*Stock externality under risk-aversion)* In the case where net benefits do not depend on the water stock $g_x(u,x) \equiv 0$, $f'' \geq (\leq) 0$ reduces to

(19) $$A'(u) - A'(1-u) \leq (\geq)(A(u) + A(1-u))^2 \quad \forall u \in [0.5,1],$$

where $A(u) = -g_{uu}(u)/g_u(u)$ is the index of concavity of $g(u)$. Then we can interpret u as monetary income (a linear function of water use), $g(u)$ as the periodic utility of income, and $A(u)$ is the Arrow-Pratt measure of absolute risk-aversion. It is standard to assume that the coefficient of absolute risk aversion is decreasing in wealth. If A is not too convex (or is concave), (19) holds with "≤" sign, and *f* will be a convex function. Thus, by Proposition 3, farmers pump more, on average, when they have more precise information about the environment. For example, (19) is satisfied with "≤" sign for some commonly used utility functions such as $g(u,x) = u - (a/2)u^2$, $g(u,x) = -e^{-au}$, or $g(u,x) = \ln(u)$.

However, this property is not true of all utility functions. For example, for preferences that are characterized by constant relative risk aversion (CRRA), *i.e.*, $g(u) = u^{\gamma}$, $\gamma \in (0,1)$, (19) may hold with either sign and so *f* may be either convex or concave.[10] In the CRRA case, absolute risk aversion is decreasing and convex in wealth, $A'(u) \geq A'(1-u)$ $\forall u \in [0.5,1]$, and (19) holds with "$\geq$" for $u \geq 1-\gamma/2$, and "$\leq$" for $u \leq 1-\gamma/2$. And so, more information may affect pumping in either direction, depending on the degree of risk aversion. This is illustrated in Figure 3, which plots the average pumping under complete and incomplete information (when $\beta = 1$) as a function of γ. In case (a), the speed of lateral flows takes values $\alpha = 0$ and $\alpha = 0.5$ with equal probability. In case (b), the speed of lateral flows is uniformly distributed on

$[0,0.5]$. Of course, pumping rates under incomplete information are identical in case (a) and (b) because the average speed of lateral flows is the same, $E[\tilde{\alpha}] = 0.25$. Also, the efficient pumping rate is $u_{i,1}^s = 0.5$. Farmers pump more under complete information if farmers are sufficiently risk-averse, $\gamma \le 0.615$. However, the extent of the discrepancy due to private information is relatively small. If the farmers are weakly risk-averse (γ is close to 1), they pump less under complete information and the extent of the discrepancy is larger.

[Figure 3 about here]

5.2. Welfare comparison

In the previous section, we showed that the effect of uncertainty about the hydrologic properties of groundwater on the average pumping in period 1 depends on the curvature of the ratio of marginal benefits of irrigation. The effect of this uncertainty on expected welfare is somewhat more subtle because welfare depends not only on the average deviation of equilibrium pumping from the efficient allocation but also on the higher moments of its distribution. Let $\pi(u)$ $= g(u,1) + \beta g(1-u,1-u)$ denote the discounted profits attained by allocating water equally across farmers. The following result identifies the precise condition under which welfare is reduced or enhanced by providing better information to users.

Proposition 4. (Information and welfare) *Suppose that the ratio of the marginal benefits of groundwater in period 1 and 2 satisfies*

(20) $$\frac{f''(u)}{f'(u)} \le (\ge) \frac{\pi''(u)}{\pi'(u)} \quad \forall u \in [f^{-1}(1), f^{-1}(0.5)].$$

Then non-cooperative farmers attain, on average, lower (higher) expected welfare under complete information about the speed of lateral flows, i.e., $E[\pi_i(\tilde{\alpha})] \le (\ge) \pi_i(E[\tilde{\alpha}])$.

Proof: By (16b) and (18b), the effect of incomplete information on the expected welfare depends on the curvature of $\pi_i(\alpha) = \pi(u(\alpha)) = g(u(\alpha),1) + \beta g(1-u(\alpha),1-u(\alpha))$, where $u(\alpha) = f^{-1}(1-\alpha) \in [f^{-1}(1), f^{-1}(0.5)]$ $\forall \alpha \in [0,0.5]$. Differentiation yields $d\pi_i(u(\alpha))/d\alpha = -\pi'(u(\alpha))/f'(u(\alpha)) \le 0$. Differentiating twice yields

$$\frac{d^2\pi_i(u(\alpha))}{d\alpha^2} = \left(\frac{\pi''(u(\alpha))}{\pi'(u(\alpha))} - \frac{f''(u(\alpha))}{f'(u(\alpha))}\right)\frac{\pi'(u(\alpha))}{f'(u(\alpha))^2} \le (\ge) 0$$

depending on whether for $f''(u)/f'(u) \le (\ge) \pi''(u)/\pi'(u)$ $\forall u \in [f^{-1}(1), f^{-1}(0.5)]$ since $\pi'(u(\alpha)) \le 0$ for $\forall \alpha \in [0,0.5]$. Hence, the result follows by Jensen's inequality. ■

Note that f''/f' is an index of concavity of a (decreasing) function f. And so, the effect of information on producer income depends on whether the ratio of the marginal benefits, $f(u) = g_u(u,1)/[\beta(g_u(1-u,1-u) + g_x(1-u,1-x))]$, is less (more) concave than the sum of the benefits, $\pi(u) = g(u,1) + \beta g(1-u,1-u)$, when water is allocated equally across farmers. The producer profit depends on information only via its impact on the pumping rates, which, in turn, can be decomposed into two components. First, better information always increases the *variability* of the pumping rates across farmers with different realizations of $\tilde{\alpha}$. As a result, because the average value of $\tilde{\alpha}$ is unchanged, and the marginal benefits of water are decreasing, the expected profits tend to decrease. Second, better information may lead to, *on average*, allocations either closer to or farther from the efficient allocation (i.e. less or more pumping in period 1). Smaller (greater) average pumping rates in period 1 tend to raise (lower) the expected profit.

Condition (20) in Proposition 4 can be related to the simpler convexity condition in Proposition 3. In particular, convexity of *f* is a sufficient condition for (20) to hold with "≤", because in this case $f''(u)/f'(u) \le 0 \le \pi''(u)/\pi'(u)$, where the inequalities follow from the facts that $f(u)$ is decreasing and $\pi(u)$ is concave and decreasing for $u \ge u_{i,1}^s$. Thus, if *f* is convex, then complete information unambiguously causes pumping to increase (Proposition 3) and welfare to fall (Proposition 4). Welfare falls because pumping rates become more variable *and* shift, on average, further from the efficient allocation.

In contrast, concavity of *f* is *not* sufficient for (20) to hold with "≥." If *f* is concave, better information induces farmers to reduce pumping on average (Proposition 3), thereby bringing pumping rates closer to the efficient solution. However, the welfare loss associated with added variability of pumping rates due to better information about local conditions may outweigh the average gain in welfare. Only if f is "sufficiently" concave, will expected welfare increase under more information. The following examples illustrate.

Example 3. (*Stock and pumping cost externality under risk-neutrality*) Consider the same environment as in Example 1. If the quadratic component of the production function is large relative to marginal pumping costs, $b \ge c$ and f is convex, then, by Proposition 4, farmers' expected welfare is lower under complete information. So suppose that $b < c$, and also let $\beta = 1$. Then the condition in Proposition 4 becomes

$$\frac{f''(u)}{f'(u)} = -2\frac{b-c}{a-b+(b-c)u} \le (\ge) \frac{-2}{1-2u} = \frac{\pi''(u)}{\pi'(u)}, \text{ or}$$

$$u \le (\ge) \frac{a-2b+c}{3(c-b)} \text{ for } u \in [0.5, (a+b)/(3b+c)].$$

This condition holds with sign "$\ge$" for $u = f^{-1}(0.5) = (a+b)/(3b+c)$ if $3b \le c$. And so, if the quadratic component is "sufficiently" small (i.e. $b \le c/3$), and $\tilde{\alpha}$ is known to take values close to 0.5 (so that $u_{i,1}^c$ and $u_{i,1}^n$ are close to $f^{-1}(0.5)$), farmers' expected welfare is higher under better information. ■

Example 4. (*Stock externality under risk-aversion)* Consider the same environment as in Example 2. Figure 4 illustrates the effect of information on the expected farmer profits in case (a). Farmers are worse off under complete information, $E[\pi_i(\tilde{\alpha})] \le \pi_i(E[\tilde{\alpha}])$, if they are sufficiently risk averse, $\gamma \le 0.8615$. On the other hand, if the marginal benefits of irrigation are approximately constant, farmers are, on average, better off when they are able to adjust pumping rates in response to the local hydrological properties, $E[\pi_i(\tilde{\alpha})] \ge \pi_i(E[\tilde{\alpha}])$.

[Figure 4 about here]

Table 1 summarizes the comparison of pumping rates and farmer welfare by combining the results in Figures 3(a) and 4.

[Table 1 about here]

6. Model Extensions and Discussion

To isolate the role of information about the local hydrologic properties, we consider the simplest possible dynamic spatial setting with (i) a two-cell aquifer, (ii) two periods, (iii) identical producers, and (iv) either complete or no information. The derived conclusions are robust to some but not all of these simplifying assumptions. For example, the results can be easily extended to the case when farmers observe a signal that provides partial but not complete information about the local hydrologic properties of the aquifer such as porosity and storativity. Then the informativeness of signals can be ranked based on the sensitivity of the conditional expected value of the likely speed of lateral flows to the observed signal. This criterion is less restrictive than the Blackwell's [2] sufficient statistic approach. Also, the analysis carries over with only slight modifications to the case of multiple users as long as they are symmetric as in Eswaran and Lewis [7].

The analysis of the effect of better information about the environment on equilibrium allocation in a more realistic setting, where one or more of conditions (i) – (iii) are relaxed, is more complicated. In a multi-cell aquifer, it is likely that equilibrium pumping rates differ across, even otherwise identical, farmers. In particular, it can be shown that farmers that are closer to the center of the aquifer pump groundwater faster than farmers that are farther away (however, this relationship may not be monotone). Therefore, incompleteness of information has potentially important distributional consequences across farms.

In a multi-period setting, information about the hydrology of the region impacts not only the speed of pumping but also the useable lifetime of the aquifer. Consider an environment with infinite time-horizon, limited entry, diminishing marginal product of water, per period fixed cost, $g(0,x) = -F < 0$, and no recharge. Then it can be shown that the lifetime of the aquifer may increase or decrease when producers are better informed about the speed of lateral flows depending on the properties of the water benefits and the discount factor. Allowing for a rechargeable aquifer does not change the results as long as the statistic of interest is the time before the level of groundwater in the aquifer falls below a certain level.

The result that the better information about the extent of interconnectedness among the users has an ambiguous effect on the efficiency also extends to renewable resources such as fisheries.[11] In the simplest setting where the rate of growth does not depend on the density of biomass (fish population) and the biomass dispersal is proportional to the difference in biomasses across locations, the equations of motion between the two locations (patches), (2), become:

$$x_{1,2} = a(x_{1,1} - u_{1,1} + Q) = a((1-\alpha)(1-u_{1,1}) + \alpha(1-u_{2,1}))\,,$$

$$x_{2,2} = a(x_{2,1} - u_{2,1} - Q) = a(\alpha(1-u_{1,1}) + (1-\alpha)(1-u_{2,1}))\,,$$

where $a - 1 \geq 0$ is the rate of growth of a renewable resource (e.g., fish population). This formulation presumes that the time during which the resource is extracted is short compared with the time that elapses between the episodes of extraction. Then all of our results continue to hold if we redefine the intertemporal marginal rate of substitution as[12]

$$f(u;a) = \frac{g_u(u,1)}{\beta[g_u(a(1-u),a(1-u)) + g_x(a(1-u),a(1-u))]}\,.$$

Finally, suppose that the users that are located in area overlying the aquifer are heterogeneous in their derived demand for groundwater due to the differences in acreage, soil types, availability of surface water, environmental regulations, etc. Then they likely have different incentives to achieve a more dynamically efficient allocation and to learn more about the hydrologic properties of the groundwater resource. Another important possibility not explored in this paper is that farmers have asymmetric information: some producers may be better informed about the local hydrologic properties than others. Understanding the effect of private and public information on natural resource exploitation in the framework that incorporates these and other realistic features is left for future research.

7. Conclusions and Implications

This paper departs from the existing literature by allowing for incomplete information among groundwater users. Because it is patently unrealistic to assume that producers have perfect knowledge of the local hydrologic properties, we ask the question: What is the effect of incomplete information about the speed of lateral groundwater flows on equilibrium pumping rates and producer welfare? We find that the answer depends on rather subtle properties of the production technology as well as the nature of uncertainty about the speed of lateral flows.

A somewhat counter-intuitive finding is that the effect of information on water use and welfare may be of opposite signs. This can be understood as a consequence of spatial variability. If better information becomes available, users in different locations will either increase or decrease extraction rates, depending on whether the newly learned spatial interactions are stronger or weaker than initially believed. In the areas where resource extraction increases dramatically, welfare will fall sharply. Due to the concavity of the net benefits function, even if extraction rates decrease on average, thereby bringing the system as a whole closer to the efficient path, expected welfare may fall. This implies that (unobservable) changes in welfare cannot be directly inferred from (observable) changes in resource extraction rates.

Users' beliefs about spatial externalities are a sort of self-fulfilling prophecy: if users believe externalities are small or non-existent, they will behave accordingly, and resource use will be approximately efficient. It is in the cases where users believe externalities are significant where policies must be designed with care. Educating and informing users about the true resource dynamics in such cases may actually accelerate their extraction rates. That is, better information is not a substitute for correcting the underlying externalities. As in other cases where incomplete information aggravates other distortions, better information will be unambiguously welfare-improving only if the distortions are eliminated first.

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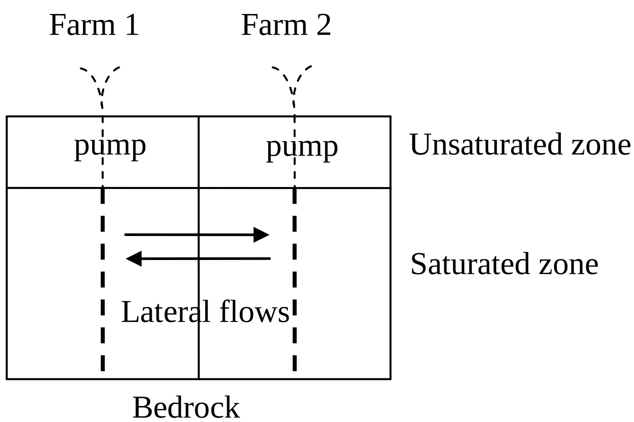


Figure 1. Hydrology of groundwater

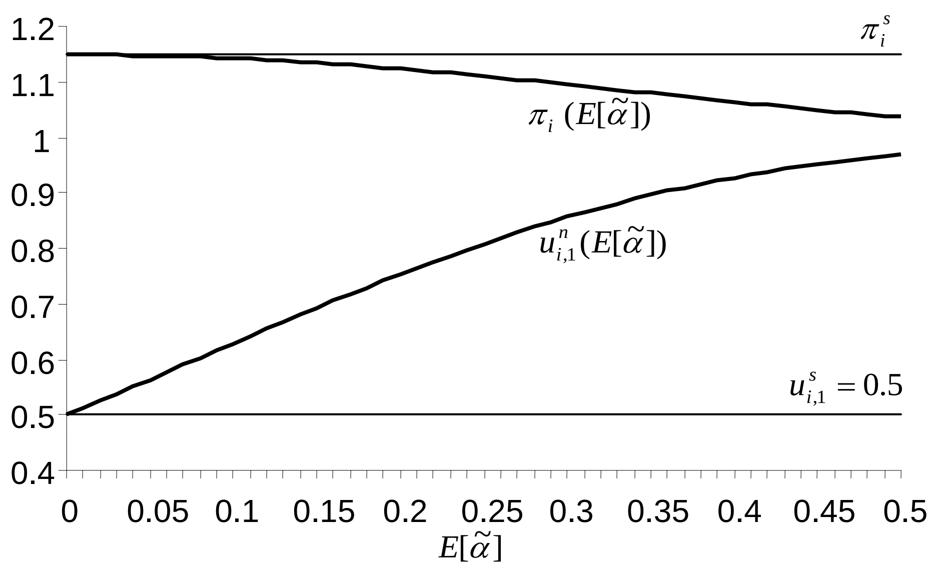
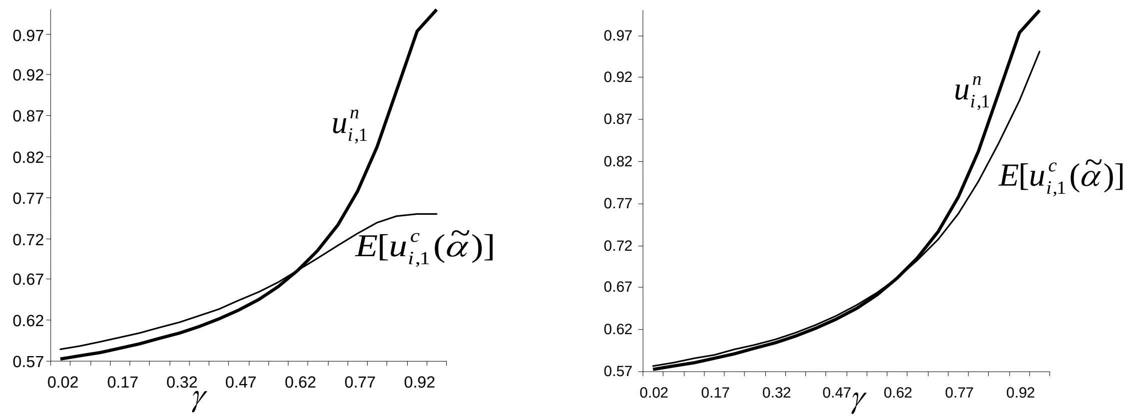


Figure 2. Equilibrium groundwater pumping and profits



a) Two-point probability distribution of $\tilde{\alpha}$ b) Uniform probability distribution of $\tilde{\alpha}$

Figure 3. Pumping, risk aversion, and information

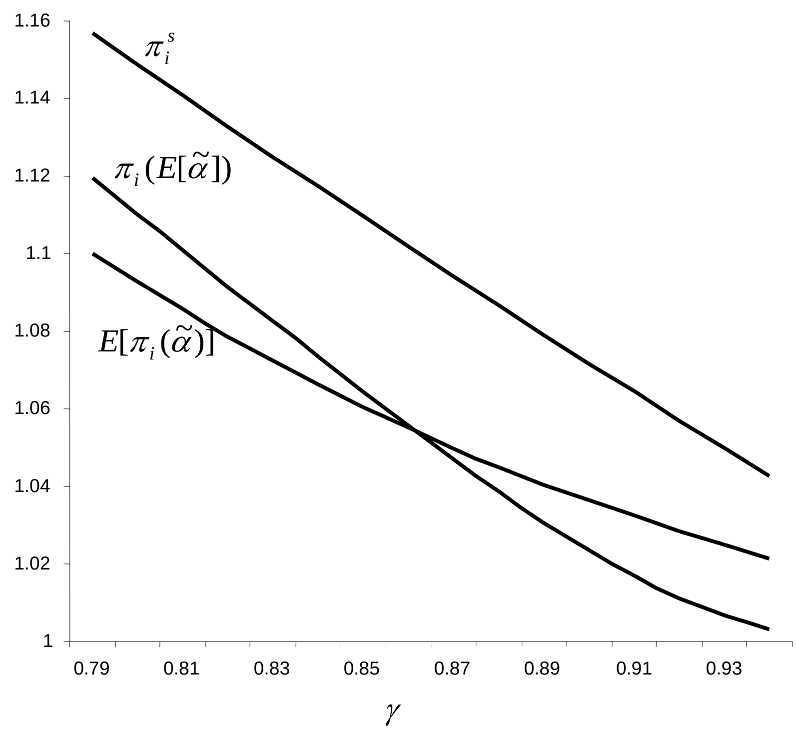


Figure 4. Profit, risk aversion, and information about the hydrology

Table 1. The average pumping rates in period 1, profits, and information

Range in γ	*Degree of risk aversion*	**Effect of complete information on:** Pumping	Welfare
(0, 0.62)	High	Increase	Decrease
(0.62, 0.86)	Moderate	Decrease	Decrease
(0.86, 1)	Low	Decrease	Increase

NOTES

[1] A typical study was that of Kim [15], who applied the basic model to the Texas High Plains based on empirically estimated water demand functions, and also modified the model to allow users to plant different irrigated crops as the aquifer declines. The estimated welfare gains from optimal management were quite small (less than 3.7%). Similarly small gains were found by several other authors including Allen and Gisser, Nieswiadomy, and Fienerman and Knapp [1,18,8]. See Koundouri [16] for a more comprehensive review.

[2] For example, Provencher and Burt [21] identified two distinct externalities from their equilibrium conditions. First, the pumping cost externality arises because consumption by one user lowers the water table and raises pumping costs for other users. Second, the stock externality reflects the costs that one user imposes others because his consumption reduces their future water availability.

[3] There is a large literature that investigates the value of information in various environments. An important early contribution is Hirschleifer [13] who demonstrated that in an exchange economy the value of information may be negative. Eckwert and Zilcha [6] show that sufficiently risk-averse agents may become worse off under better information in production economies. Stiglitz [23] analyzes the efficiency and welfare in screening models with endogenous information acquisition.

[4] $\alpha = kS/L$, where k is hydraulic conductivity, S is the cross-sectional area of flow, L is the distance between wells on each farm [9].

[5] The assumption that $g(u,x)$ is strictly increasing in u for all $u \in [0,x]$ reflects a situation of absolute water scarcity; all of the water remaining in period 2 will be consumed. If water is not scarce in this sense, so that $g(u,x)$ is decreasing in u for $u \in [\hat{u},x]$, the analysis needs only minor

modifications. Also, note that all our results can be obtained under a weaker technical condition than the joint concavity of $g(u,x)$ on $[0,1]\times[0,1]$ such as $g_{uu}(.,x)<0$ and $0.5[g_{uu}(x,x)+g_{xx}(x,x)]+g_{ux}(x,x)<0 \;\; \forall x\in(0,1)$. To interpret this condition, suppose the current groundwater stock is x and that all of this water is consumed in the current period ($u = x$). Under standard assumptions on the irrigation technology [20], the cross-partial derivative term is positive, reflecting the fact that the marginal benefits of water use, g_u, will increase with respect to x (e.g., due to more rapid water delivery or a smaller pumping lift). And so, this condition states that g must be "sufficiently" concave in u and x, so that the cross-partial term does not exceed half of the bracketed term in absolute value.

[6] There is a large variation in local hydrologic properties such as the aquifer's storativity and transmissivity values as well as well-spacing requirements that vary from 4 miles in parts of Kansas to less than 300 feet in Texas [4,14].

[7] Note that the concavity of g implies that f^{-1} exists and is decreasing in u, but does not imply anything about its curvature.

[8] To verify these claims, recall first that by concavity of g, the function f is strictly decreasing in u. It follows that f^{-1} is also a strictly decreasing function. Under the assumption that $E[\tilde{\alpha}] > 0$, a comparison of (7) and (16a) then implies that $u^s_{i,1} = f^{-1}(1) < u^n_{i,1}(E[\tilde{\alpha}]) = f^{-1}(1-E[\tilde{\alpha}])$; while (7) and (17a) imply that $u^s_{i,1} = f^{-1}(1) < u^c_{i,1}(\alpha) = f^{-1}(1-\alpha)$ if $\alpha > 0$.

[9] This assumption also appears in the GS model. Unlike GS, however, we do not obtain complete rent dissipation. In our model, complete rent dissipation would correspond to $u_{i,1} = 1$, where all available resource rents are captured in period 1. This equilibrium cannot arise in our model even when $\alpha = 0.5$, because $f^{-1}(0.5) < 1$ if $g_u(0,.) = \infty$. As a reviewer pointed out, it is

perhaps not obvious whether this result occurs because access is restricted to 2 users, or because we assume that groundwater is a private resource within each season. It can be shown that in the case of instantaneous lateral flow with *n* users, the equilibrium pumping rate converges to $u_{i,1}^{c} = 1$ as $n \to \infty$ (a demonstration of this is available from the authors). Thus, rents would be fully dissipated in the open access limit, proving that incomplete rent dissipation occurs because of restricted access.

[10] Gollier [11] discusses plausible upper bounds on the measure of relative risk aversion, 1-γ (note that γ=1 corresponds to risk-neutrality).

[11] See Sanchirico and Wilen [22] (and the references cited therein) for a state-of-the-art analysis of spatial management of renewable resources under the assumption of perfect information.

[12] Of course, the result that the optimal allocation does not depend on the degree of user interconnectedness (the properties of spatial dispersal) will not hold when users are asymmetric.