Property Rights and Conjunctive Management: The Implications of Hydraulic Connectivity between Surface and Ground Water

Kelly M. Cobourn
Department of Economics, Boise State University
kellycobourn@boisestate.edu

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Abstract

Across the western U.S., property rights for surface and groundwater have historically been allocated and administered independently. Dwindling water supplies and the adoption of increasingly efficient irrigation technologies reveal that the two resources are highly interdependent. This is particularly evident in the Snake Plain of Idaho, where ground water augments surface water flows. The presumed effect of ground water pumping on surface water supplies has become a source of ongoing legal conflict in the region. The State's approach to resolving the problem to date involves curtailing ground water pumping to ensure adequate water supplies for senior owners of surface water rights.

This paper develops a method to conduct a first empirical analysis of the relationship between ground water pumping and surface water availability. The analysis relies on a panel dataset of ground and surface water measurements from 1956 to 2005 across the Snake Plain. The results reveal that the connectivity of surface and ground water stocks decreased substantially over the study period. The implication is that curtailing ground water pumping may be an increasingly ineffective means of ensuring surface water availability in the future.

JEL: Q15, Q25

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Across the U.S. West, property rights for surface and ground water resources were historically allocated and administered independently. However, in many areas the two resources are highly interdependent. One such case is the Eastern Snake Plain in Idaho, which relies heavily on both surface and ground water for agricultural irrigation. Since the mid-1950s, the region has seen a simultaneous decline in both water supplies (Cosgrove et al. 1999). The result has been an increase in the incidence of conflict between irrigators holding rights to surface water and those with rights to ground water. Specifically, surface water users have interpreted the correlated decline in the two stocks as evidence that ground water users are intercepting water to which they are legally entitled. To date, the State has supported claims from surface water users whose rights are legally senior to those of ground water pumpers.

However, the empirical impact of ground water pumping on surface water resources is difficult, if not impossible, to measure directly. The majority of the evidence upon which the State bases its decisions comes from small-scale field experiments and regional-level simulation modeling. This study marks a first attempt to empirically isolate the extent to which ground water pumping has altered surface water flows in the Plain over the last half century. The key conclusion from the analysis is that is that the degree to which surface and ground water resources are interconnected has diminished over time. The implication for policy is that attempting to increase surface water flows by reducing ground water diversions is likely to be ineffective. This is perhaps due to the adoption of increasingly efficient irrigation technology: as irrigation efficiency increases and permitted water diversions remain relatively constant, the amount of water consumed by plants and lost from the system increases. The ultimate effect is to increase the extent to which water in the system is legally over-appropriated.

To conduct the empirical analysis, I develop a theoretical framework that captures the dynamic effect of ground and surface water users' diversion decisions on surface and ground water supplies. The model builds conceptually on hydrologic studies of the region to describe the mechanics by which water moves between surface water bodies and the Eastern Snake Plain Aquifer. This model demonstrates, qualitatively, the complex way in which climatic factors, irrigation technology, and water withdrawals from both stocks interact to affect surface water availability over time.

The theoretical model development also establishes a method to address a significant barrier to empirical analysis in this case: Irrigators' diversion decisions are unobservable. The dearth of data on withdrawals is common across the West, and has prohibited all but a few empirical studies of externalities among irrigators, most of which are focused on ground water pumping alone (e.g. Pfeiffer and Lin 2009; Savage and Brozovic 2011). To accommodate this limitation, I develop state equations of the type used in optimal control theory to indirectly trace the impact of ground water pumping on the surface water stock via pumpers' effects on the ground water table. Furthermore, I exploit the relatively rigid structure of water rights institutions in the study region to use maximum diversion rates as a proxy for irrigators' diversion decisions. The difficulty of changing water rights allocations in the state allows me to do so without introducing endogeneity into the model. The approach developed herein thus uniquely facilitates an analysis of whether the hydrologic relationships observed in small-scale field experiments bear out in the data over a long time horizon and at a regional level.

Background on the Study Region

The Eastern Snake Plain occupies a 10,000m^2 area in southeastern Idaho, stretching from King Hill to Ashton, as depicted in Figure 1. The boundaries of the region are defined by its hydrologic characteristics: The Eastern Snake Plain Aquifer underlies the entire study area and is hydrologically closed at the boundary. The Snake River is the dominant surface water resource and is the only means by which water exits the region. Elevation varies from 5000 feet above sea level in the Northeast to 2600 feet above sea level in the Southwest (Cosgrove et al. 1999). The region receives little precipitation during the summer months, relying on water stored as snowpack to feed irrigated agriculture. The Plain is relatively sparsely populated. As such, irrigation accounts for over 92 percent of all water used in the region (USGS 2005).

An interesting feature of the region is the degree to which the Snake River and the aquifer are hydraulically connected. This is not a feature unique to this particular study area. Connectivity between surface and ground water has also been observed in other western states, particularly as an increased reliance on ground water for irrigation has resulted in diminished surface water supplies (Glennon 2003). Other states that have recognized complications due to hydraulic connectivity include California, Colorado, Kansas, Nebraska, and Oregon. However, the Snake River Plain is an interesting study region because the degree to which surface and ground water is connected is particularly pronounced and widespread.

Overview of Hydraulic Connectivity

Whenever a surface water body overlies an aquifer, the two water stocks may be classified, at any point in space and time, as hydraulically connected or disconnected.[1] The key difference between the two regimes is that ground water pumping does not affect the quantity of surface water available in a disconnected system, but does reduce surface water availability in a connected system. In a hydraulically disconnected regime, an unsaturated zone separates the aquifer (or saturated zone) from an overlying surface water stock (Figure 2a). No water can be

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[1] This study does not consider confined aquifers, which are separated from the surface by an impermeable layer, and, by definition, cannot interact with surface water bodies.

pumped from the intermediate unsaturated zone. In a hydraulically connected system, the saturated zone and the surface water stock are connected. In a hydraulically connected system, the height of the water table—the upper surface of the saturated zone—determines the direction of water exchange between surface water bodies and the aquifer. If the water table lies below the top of the surface water body, water from the surface stock seeps into the saturated zone, recharging the aquifer (Figure 2b). If the water table sits above the top of the surface water body, water will discharge from the aquifer into the surface water stock (Figure 2c). In the former case, the surface body loses water to the aquifer; in the latter, it gains.

The relationship between hydraulically connected surface and ground water systems may vary spatially and temporally, shifting between losing and gaining regimes. For example, a single stream may recharge the aquifer in one reach and gain from the aquifer in others. Likewise, during periods of high precipitation, the water table may rise in altitude and a losing stream may become a gaining stream temporarily. However, there are cases in which a surface water body, at a given point in space, perennially loses or gains water from an aquifer. The rate at which water moves between the surface and the aquifer, in either direction, depends on a host of regional characteristics, such as climate, soil type and porosity, land use, vegetation, physical geography, and geology.

Each hydraulic regime implies differing effects for ground water pumping and surface water diversions. Winter (1998) illustrates the potential effect of ground water pumping on a gaining stream. Prior to any development, a dynamic equilibrium exists in which the amount of water entering the aquifer via recharge equals that exiting via discharge into the stream (Figure 2d). At a minimum, ground water pumping intercepts lateral flows into the surface water body, reducing discharge into the stream (Figure 2e). With higher rates of groundwater pumping, the water table may fall below the top of the stream surface, reversing the movement of water and switching the stream from a gaining to a losing regime (Figure 2f). Thus, at the extreme, ground water pumping may not only eliminate discharge into the surface water stock, but also increase the rate of seepage from the surface into the aquifer. In either case, ground water pumping reduces the amount of water available for diversion from the surface water stock.

Hydraulic Connectivity on the Snake River Plain

The Snake River and the aquifer are considered hydraulically connected along four major reaches, as depicted in Figure 3. Discharge from the aquifer into the Snake River occurs predominantly within the Blackfoot to Neeley reach and the Kimberley to King Hill reach. In the latter, discharge feeds an increase in average annual flows from 1.3 to 6.7 million acre feet over the length of the reach (Cosgrove et al. 1999). Each of the four hydraulically connected reaches has exhibited decreasing flows as ground water pumping increased substantially over the latter half of the 20th century. The south-central portion of the Plain has seen the greatest decline in the water table over that period, and the greatest reduction in surface water flows.

Surface water rights were allocated along the Snake River long before ground water pumping began. As is common throughout the West, Idaho allocates surface water according to Prior Appropriation, or “first in time, first in right.” Idaho also allocates ground water on the basis of Prior Appropriation. Thus, ground water users generally hold rights with later priority dates than do surface water users. As ground water pumping increased and the water table fell, the amount of surface water flows in the region’s hydraulically connected reaches also declined. As a result, senior water users have filed a number of ongoing lawsuits against ground water users, requesting that pumping be curtailed to ensure adequate surface water supplies.

As a result of its policy importance in the region, the relationship between ground water pumping and surface water flows has been a topic of significant interest and study in the region. For example, Cosgrove and Johnson (2004) estimate response functions that express the way in which a unit of ground water pumping in the current period affects the nearest surface water stock in future periods. Miller et al. (2003) include response functions in a region-level simulation analysis that estimates the impacts of ground water pumping on surface water availability.

The hydrologic literature on the region highlights two key issues to consider in any analysis of the problem. First, ground water pumping propagates radially, stopping when it reaches a connected surface water body. Thus, pumping may decrease the surface water stock upstream of the well; the impacts do not necessarily flow down-gradient. Second, the effects of pumping are attenuated over time. The effect of pumping at a single well increases after the initial date of pumping, reaching a maximum at some point, and then declining. The time required to reach the maximum effect can be on the order of days to decades, and depends on the distance between the well and the surface water body (Johnson 1999).

While these response functions highlight the impact that pumping on one date at a single well can potentially have on a surface water body, they are primarily a conceptual tool. They do not consider a number of complicating issues, such as how continuous pumping affects a surface water body or how the surface water supply, or its use for irrigation, affects the depth of the water table in a hydraulically connected region. What has not been attempted to date is to quantify empirically the effect that ground water pumping has on surface water flows.

Related Economic Literature

While the hydrologic literature widely recognizes the potential for hydraulic connectivity between surface and ground water resources, the economic literature does not. A substantial literature exists on the optimal management of ground water when the potential exists for externalities among pumpers (e.g. Gisser and Sanchez 1980; Koudouri 2004; Saak and Peterson 2007; Brozovic et al. 2010). Another branch of the economic literature focuses specifically on the returns to conjunctive management of ground and surface water when the two stocks are hydraulically disconnected (Knapp and Olson 1995; Tsur and Graham-Tomasi 1991).

A notable exception is Burness and Martin (1988). They examine theoretically the case in which a surface water body is perennially losing to a connected aquifer. In this scenario, ground water pumping generates an externality for surface water users by decreasing surface water flows. The analysis presented in this article extends this line of inquiry, but considers surface-ground water hydrology more generally, permitting a surface water body to be gaining and losing from an aquifer, as is the case in the Snake Plain along different reaches and in different time periods. This study is the first that explicitly considers the dynamic implications of hydraulic connectivity within an economic model. Moreover, it is one of few that econometrically analyzes the extent to which irrigators generate externalities for one another.

Theoretical Framework

Consider an individual irrigator who is a risk-neutral and myopic profit maximizer. In each time period, *t*, the producer, indexed by *j*, faces a concave benefit function $B(w_{jt}, \mathbf{X}_{jt})$, where benefits depend on irrigation water applied in that period, w_{jt}, and a vector of other factors $\mathbf{X}_{jt}$. The irrigator may obtain water either by pumping ground water (*GW*) or by diverting surface water (*SW*). The irrigator is constrained to obtain water from only one source, as specified by his legal water right. The marginal cost of irrigation is given generally by the function $C_i(S_{it})$ where $i = GW, SW$ indexes the source of irrigation water. The marginal cost function is twice differentiable and $C' > 0$, $C'' > 0$, for either stock. The marginal cost of irrigation each period depends upon the amount of water in the stock from which the irrigator is withdrawing, denoted by *S*. The irrigator faces a legal constraint on water withdrawals, denoted $\overline{w}_j$.

The individual irrigator's problem in each time period is given by

(1) $$\max_{w_{jt}} B(w_{jt}, \mathbf{X}_{jt}) - C_i(S_{it}) w_{jt} \quad s.t. \quad w_{jt} \le \overline{w}_j .$$

Solving the optimization problem yields the irrigator's demand for irrigation water in each time period as a function of the stock of water available in that time period (from the relevant stock), the individual's water right constraint, and the vector **X**, i.e. $w_{jt}^*(S_{it}, \overline{w}_j, \mathbf{X}_{jt})$. Irrigation water demand is determined at the level of the individual producer, but the stock of ground or surface water is determined by aggregate water use. Denote aggregate demand for water by source and time period as $W_{it} = \sum_j w_{jt}^*(S_{it}, \overline{w}_j, \mathbf{X}_{jt})$.

Though individual producers may be myopic, the problem is dynamic as the amount of water in either stock in any period depends on water use decisions in all previous periods. The evolution of the surface and ground water stocks is captured by two simultaneous equations that capture the way in which water moves into, out of, and between the two stocks. Water enters the surface water stock via exogenous precipitation. Some of the water in the surface water stock is lost each period to natural aquifer recharge. Water is also diverted from the surface water stock for irrigation. Of the water diverted, some leaves the system via evapotranspiration (consumptive use). Of the remainder, some percolates directly into the aquifer and some returns to the surface water stock. The percolation of irrigation water into the aquifer is termed "incidental recharge," and has historically accounted for over half of all aquifer recharge in the Snake Plain (Cosgrove et al. 1999). The proportion of applied water that is consumed, percolates, or returns to the surface water stock depends on the efficiency of the irrigation technology used. The term irrigation efficiency is used here to broadly capture the efficiency of conveyance infrastructure as well as the efficiency of application systems. Water also enters the surface stock in each period via aquifer discharge, where the quantity of discharge depends on the height of the water table.

The surface water stock in any period *t* is given by

(2) $$S_{SW,t} = f_{SW}\left(S_{SW,t-1}, R_t, W_{SW,t}, T_t, G\left(S_{SW,t}, W_{SW,t}, T_t\right), D\left(S_{GW,t}\right)\right).$$

The potential for storage in the surface water system links the stock in *t*-1 and *t*. A greater surface water stock yesterday implies the availability of more water today, or $\partial f_{SW} / \partial S_{SW,t-1} > 0$. The surface water stock in *t* is also a function of precipitation, R_t, aggregate diversions from the surface water stock, $W_{SW,t}$, and irrigation efficiency, T_t. Precipitation increases the stock and diversions decrease the stock: $\partial f_{SW} / \partial R > 0$ and $\partial f_{SW} / \partial W_{SW} < 0$. Irrigation efficiency determines what proportion of the water leaves the surface water system via evapotranspiration. Note also that the technology in a region at any point in time is actually a suite of technologies, rather than a single technology. I index *T* so that an increase indicates a more efficient suite of irrigation technologies, and assume that $\partial f_{SW} / \partial T < 0$.

The surface water stock also depends on recharge, *G*, and discharge, *D*. Recharge captures water moving from the surface to the aquifer. Recharge depends on the amount of water in the surface water stock (natural recharge) and the amount of water diverted from the surface and used for irrigation (incidental recharge), where $\partial G / \partial S_{SW} > 0$, $\partial G / \partial W_{SW} > 0$, and $\partial G / \partial T < 0$. Discharge captures that water moving from the aquifer back into the surface water stock, where $\partial f_{SW}/\partial D > 0$. Discharge from the aquifer back into the surface water stock is a function of the ground water stock in period *t*, $\partial D/\partial S_{GW} > 0$.

A similar equation governs the dynamics of the groundwater stock, where

$$\textbf{(3)} \qquad S_{GW,t} = f_{GW}\left(S_{GW,t-1}, R_t, W_{GW,t}, T_t, G\left(S_{SW,t}, W_{SW,t}, T_t\right), D\left(S_{GW,t}\right)\right).$$

The change in the ground water stock between two periods is a function of water in the aquifer in the previous period, recharge via precipitation, the amount of water pumped from the aquifer, and irrigation technology. Signs are identical to those in (2), except $\partial f_{GW}/\partial G > 0$ and $\partial f_{GW}/\partial D < 0$.

The implicit function theorem can be applied to equation (3) to show that $\frac{dS_{GW,t}}{dW_{SW,t}} > 0$, $\frac{dS_{GW,t}}{dW_{GW,t}} < 0$, and $\frac{dS_{GW,t}}{dT_t} < 0$. By combining these results with equation (2) and again using the implicit function theorem, the model demonstrates three key relationships defining the impacts of withdrawals and irrigation technologies on the surface water stock. The first pertains to the relationship between ground water pumping and the surface water stock:

$$\textbf{(4)} \qquad \frac{dS_{SW,t}}{dW_{GW,t}} = -\frac{1}{m}\left[\underbrace{\frac{\partial f_{SW}}{\partial D}\frac{\partial D}{\partial S_{GW,t}}\frac{dS_{GW,t}}{dW_{GW,t}}}_{<0}\right] < 0,$$

where $m = \frac{\partial f_{SW}}{\partial G}\frac{\partial G}{\partial S_{SW,t}} < 0$. Equation (4) demonstrates that the effect of ground water pumping on the surface water stock is unambiguously negative: An increase in pumping decreases the ground water stock, which reduces discharge from the aquifer back into surface water bodies.

The second and third relationships highlight the impact of surface water withdrawals and irrigation technology on the surface water stock:

(5)
$$\frac{dS_{SW,t}}{dW_{SW,t}} = -\frac{1}{m}\left[\underbrace{\frac{\partial f_{SW}}{\partial W_{SW,t}}}_{<0} + \underbrace{\frac{\partial f_{SW}}{\partial G}\frac{\partial G}{\partial W_{SW,t}}}_{<0} + \underbrace{\frac{\partial f_{SW}}{\partial D}\frac{\partial D}{\partial S_{GW,t}}\frac{dS_{GW,t}}{dW_{SW,t}}}_{>0}\right], \text{ and}$$

(6)
$$\frac{dS_{SW,t}}{dT_t} = -\frac{1}{m}\left[\underbrace{\frac{\partial f_{SW}}{\partial T_t}}_{<0} + \underbrace{\frac{\partial f_{SW}}{\partial G}\frac{\partial G}{\partial T_t}}_{>0} + \underbrace{\frac{\partial f_{SW}}{\partial D}\frac{\partial D}{\partial S_{GW,t}}\frac{dS_{GW,t}}{dT_t}}_{<0}\right].$$

Both are ambiguous in sign and contain three terms: the first component of the bracketed term on the right-hand side is the direct effect, the second is an indirect recharge effect, and the third is an indirect discharge effect. Equation (5) indicates that an increase in surface water diversions negatively impacts the surface water stock by reducing the surface water stock directly and by increasing recharge into the aquifer, which reduces the surface water stock indirectly. An increase in surface water diversions also positively impacts the surface water stock by increasing the ground water stock, which increases discharge. If the direct and recharge effects dominate the discharge effect, surface water diversions have a net negative effect on the surface water stock.

Equation (6) illustrates the complex effect of irrigation technology on the surface water stock. Irrigation technology directly reduces the surface stock by reducing return flows. Improved irrigation efficiency, however, indirectly increases the surface water stock by decreasing aquifer recharge. Finally, improved irrigation technology decreases the surface water stock indirectly by reducing the ground water stock and discharge from the aquifer back into the surface water stock. Whenever the direct and indirect discharge effects dominate the recharge effect, an improvement in irrigation technology will decrease water in the surface water stock.

The theoretical framework demonstrates that the way in which surface water diversions and irrigation efficiency affect the surface water stock is an empirical matter. Furthermore, in order to produce unbiased estimates of the impacts of those variables on the surface water stock, the model must account for the simultaneous impacts of irrigator behavior on both the surface and ground water stocks.

Empirical Framework and Data

Equations (2) and (3) form the basis for the empirical analysis. Because of the difficulty associated with observing recharge and discharge directly, I estimate each state variable as a linear function of the fundamental variables that drive discharge and recharge. With some rearranging (see Appendix), the econometric models can be written

(7) $S_{SW,t} = \beta_0 + \beta_1 S_{SW,t-1} + \beta_2 R_t + \beta_3 W_{SW,t} + \beta_4 T_t + \beta_5 S_{GW,t} + \varepsilon_{SW,t}$, and

(8) $S_{GW,t} = \alpha_0 + \alpha_1 S_{GW,t-1} + \alpha_2 R_t + \alpha_3 W_{GW,t} + \alpha_4 T_t + \alpha_5 S_{SW,t} + \alpha_6 W_{SW,t} + \varepsilon_{GW,t}$.

In this formulation, the marginal effects for several of the dependent variables are net effects. For example, the coefficient β_3 in equation (7) is the combined direct effect of surface water diversions on the surface water stock and the effect of surface water diversions on recharge. In this case, both of these effects work in the same direction, which is to remove water from the surface stock. Similarly, β_4 is the combined effect of irrigation technology on the surface stock. An improvement in irrigation technology reduces return flows, which lowers the stock, but also reduces recharge, which enhances the surface water stock. Similar reasoning holds for the parameter α_4 in equation (8). The Appendix outlines the derivation of these equations, the interpretation of the marginal effects, and their expected signs (table 1A).

Identification

Equations (7) and (8) constitute a system of simultaneous equations with at least two endogenous variables, $S_{SW,t}$ and $S_{GW,t}$. The derivation of optimal water diversions based on equation (1) demonstrates that $W_{SW,t}$ and $W_{GW,t}$ are also endogenous, creating an identification problem. Furthermore, these variables are unobservable, precluding the use of instrumental variables.[2]

To surmount this problem, I use legal water rights allocations as a proxy for diversions. There are two features of legal water rights allocations that I exploit. The first is that every right has an associated priority date, or date on which the water right was first claimed. After the claim is established, every irrigation right has a specified upper limit on the rate at which water can be diverted from either a surface water body or from a ground water well. The upper limit on diversions is extraordinarily difficult to change after the date on which the right is claimed. There are currently applications for changes to water rights that have been in process with the Idaho Department of Water Resources for over a decade (IDWR 2011). This rigidity in the specification of the water right is specific to Idaho. Because they system is hydraulically interdependent to such a high degree, it is difficult to change any feature of a water right without generating a reduction in water available for a claimant somewhere else in the system. As a result, the number of water rights modifications or changes during the study period is minimal.

I use this cap on diversions to estimate an aggregate upper limit on diversions from each stock, or $\overline{W_{it}} = \sum_j \overline{w}_{jt}$. While the upper limit on a single water right is time-invariant, the sum of water allocated across users in a given area differs by year due to the establishment of new water rights. Based on equation (1), I assume that aggregate diversions from either water source can be

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[2] Surface water diversions are measured by the Idaho Department of Water Resources as the change in surface water flows between two gauges. Ground water withdrawals are not monitored.

expressed as a function of the permitted maximum diversion rate, the level of the relevant water stock, and a vector of control variables, **X**,

$$(9) \qquad W_{it}^{*} = \gamma_0 + \gamma_1 \overline{W}_{it} + \gamma_2 S_{it} + \delta \mathbf{X}_{it} + v_{it}$$

where v is an idiosyncratic error term.[3]

The critical conditions needed to ensure identification are that the aggregate upper limit on diversions for each stock is orthogonal to the error terms in equations (7) and (8), and that the error term v is uncorrelated with any of the regressors in equations (7)-(9). With regards to the former condition, it is likely not the case that more water rights are established (or their cap is increased) whenever ground or surface water stocks are high. Due to the significant lag time between when an application is filed with the State and when it is approved (or more likely rejected), there should be little correlation between the quantity of water allocated in any one year and the contemporaneous stock level.

Whether the latter condition holds depends on whether any of the variables included in (7) or (8) are correlated with the deviation of water demand from the maximum permitted amount. I anticipate that deviations in water demand from the maximum permitted diversion rate are due primarily to precipitation and temperature, both of which affect the amount of water required by plants. It is possible that irrigation technology or the type of crops grown in the region systematically affect deviations from $\overline{W}_{it}$. However, if it is the case that the water is the most binding production constraint that agricultural producers face in the region, it is unlikely that producers would consistently and systematically operate below their permitted quantity.[4] I

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[3] Theoretically, there should be a truncation problem here. However, the lack of monitoring suggests that it may be the case that aggregate diversions exceed the permitted amount.

[4] In addition, producers have a legal incentive to withdraw their full permitted amount: If they withdraw less than that quantity for five consecutive years, they are subject to loss of all or a portion of their water right. Recently, water rights banking has allowed some producers to abstain from using their full water right. However, banking

assume that this is the case for the remainder of the empirical analysis. I also assume throughout that irrigation efficiency is exogenous.[5]

The Appendix develops a version of empirical equations (7) and (8) that explicitly reflects the incorporation of the proxy. The development of the empirical model highlights that the coefficients estimated in the empirical analysis capture the net effect of any one variable on the surface and ground water stock levels. With the use of a proxy for ground and surface water withdrawals, and assuming that all other right-hand side variables are exogenous or pre-determined, equation (7) is overidentified (via the previous period's ground water stock and contemporaneous permitted ground water pumping), and equation (8) is just identified (via the previous period's surface water stock).

Data and Methodology

This analysis relies on three spatially explicit datasets: Two that include observations on surface and ground water levels, both from the United States Geological Survey (USGS), and one that contains data on water rights allocations from the Idaho Department of Water Resources (IDWR). The USGS maintains a panel database of stream flow and ground water level observations for Idaho, from which they compile and verify a variety of statistics (USGS 2011). For surface water measurements, I rely on monthly and annual stream flow gauge data, which are computed from daily time-series data by the USGS. Within the Snake Plain, data are available from 637 gauging stations. Of those 637, the preliminary analysis uses 26 stations that the IDWR consistently monitors to measure surface water diversions and enforce water rights limitations. Those 26 stations are uniquely equipped to collect real-time observations on stream

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activity was negligible prior to 2005 (personal communication, Michael Ciscell, Idaho Department of Water Resources).

[5] Data does not exist for irrigation technology, forcing me to use a time trend as a proxy for neutral technological change. Future work will include using what little data is available to determine whether this approach is tenable.

flow and other surface water data, thus yielding the most complete and accurate time-series available. Between 1910 and 2010, 1160 annual observations were recorded across the Eastern Snake Plain.

Similarly, the USGS monitors a number of ground water wells across the state. The most complete dataset for ground water measurements includes manual measurements of the depth to water in 18,981 sites. Electronic real-time measurements similar to those used to track stream flow are not available. Within the Snake Plain, data are collected from a total of 966 monitoring wells. Monitored wells may be unused, or used for irrigation, stock water, industrial, or domestic purposes. Regardless of use, I retain only observations of static water levels, or those that represent an equilibrium depth to the water table that is observed when the well is not being pumped or affected by other factors, like recent pumping, pumping in close proximity, ice, or tides. Figure 1 depicts the study area, surface water gauges, and ground water monitoring wells used in the analysis.

A weakness of the ground water data is that the measurement dates vary widely in terms of timing within a year, consistency across years, and the start and end dates of monitoring activity. Figure 3 illustrates the difference in number of observations by year, mean elevation of the water table above sea level, and standard deviation of the water table elevation between 1920 and 2011. Data collected prior to the mid- to late-1950s are problematic due to a paucity of observations (foremost because of the limited amount of ground water pumping at the time). I use observations collected from 1956 to 2005 in the analysis. During that period, greater than 1700 observations were recorded in the study region annually.

As a first step, I conduct a region-level analysis. This approach is advantageous because it allows me to aggregate across wells within each region, formulating a balanced panel dataset with minimal gaps in ground water observation data.[6] However, it does not fully capitalize on the spatial nature of the datasets. I define three sub-regions in the Eastern Snake Plain. The East region includes Bonneville, Butte, Clark, Fremont, Jefferson, and Madison Counties; the Southeast contains Bannock, Bingham, and Power Counties; and the Magic Valley, in the Southwest portion of the region includes Blaine, Cassia, Gooding, Jerome, Lincoln, Minidoka, and Twin Falls Counties. The Magic Valley is the area in which the greatest conflict between surface and ground water users has been observed to date.

For each region and year, I calculate the average water table elevation above sea level and the cumulative sum of water rights allocations to date for ground and surface water. I associate each of these observations with average annual flow across gauging stations in a region by year. Data on precipitation is from the U.S. Climate Divisional Database (NCDC 2011). Precipitation data are sum totals for the calendar year and are aggregated by zone: Zone 7 corresponds to the Magic Valley region; Zone 9 includes the East and Southeast regions. I also control for temperature by including a simple average temperature by year and zone.

Unfortunately, data on irrigation efficiency does not exist for the region at any useful level of temporal or spatial disaggregation. By interpreting periodic satellite images over the study region, Contor (2004) estimates a quadratic adoption curve for the transition from gravity (flood) to sprinkler irrigation in various sub-regions of the Snake Plain. Prior to 1970, all irrigation water was applied in gravity, or flood irrigation systems. To capture the transition from the relatively low efficiency gravity systems to relatively high efficiency sprinkler irrigation in the region, I incorporate a quadratic time trend into the model that is allowed to differ before and

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[6] Aggregation also avoids any sample selection issues associated with the systematic addition or retirement of individual monitoring wells, though the USGS intentionally selects wells to avoid this problem.

after 1970. I recognize that this variable is imperfect as a proxy for irrigation technology, and interpret it with caution.

With the addition of variables for temperature, a time trend as a proxy for irrigation technology, and a quadratic term for the time trend, I estimate the system of simultaneous equations given in (7) and (8). I do so using three-stage least squares with fixed effects by region and year. Fixed effects capture time-invariant location-specific differences among regions and across years. A Hausman test indicates that fixed effects is appropriate, rather than pooled estimation.

It is possible that the relationship between surface and ground water stocks has changed with changes in irrigation technology over time. I estimate a second specification that accounts for this possibility. Specifically, I include an interaction term between the ground water stock in period t and the time trend T (i.e. $S_{GW,t}$ x T) in equation (7) and an interaction term between the surface water stock in period t and the time trend T (i.e. $S_{SW,t}$ x T) in equation (8).

Results

Table 1 displays the estimation results from both specifications. The first two columns of results are those for equations (7) and (8) without the interaction terms; the second two contain the interactions. The fixed effects coefficients by year are not reported for brevity.

In the specification without interaction terms, the results indicate that the lagged surface water stock is positively correlated with the current period’s stock. This result is expected given the capacity for storage carry-over between years in the system. The current period’s ground water stock is also positively correlated with surface water flows, a result that supports hydraulic connectivity in the region. Were the systems disconnected, I would not expect to see a positive and significant relationship between the two, all else constant.

In specification (1), the coefficient for the time trend is negative and for the quadratic term positive, indicating that increasing irrigation efficiency has resulted in a decrease in surface water flows, though at a decreasing rate. The sign of each of these coefficients corresponds with expectation. The coefficient for precipitation is positive, which indicates that precipitation the stock-enhancing effect of precipitation outweighs the demand-enhancing effect. However, this coefficient is insignificant. The coefficient on temperature is positive and significant, which does not correspond to expectation. *Ex ante*, I expected an increase in temperature to increase water demand, decreasing the stock. The coefficient for surface water appropriations is also positive, which is counter to expectation, though it is insignificant.

In the ground water equation, the lagged ground water stock is positively correlated with today's ground water stock. The same holds for the contemporaneous surface water stock. Even in a hydraulically disconnected system, I would expect the coefficient on surface water flows to be positive and significant because increased surface water flows imply an increase in recharge. The results also indicate that surface water appropriations are negatively correlated with the ground water table: An increase in diversions by surface water users is associated with a decrease in the elevation of the ground water table. The same holds for ground water appropriations, though the coefficient is insignificant. In the ground water specification, the coefficients on both time trend terms are insignificant, which suggests that technology change has had less of an impact on the ground water stock than on the surface water stock. Indeed, technological change has been the greatest among surface water users (Contor 2004). In particular, surface water users and canal companies have invested a great amount into lining conveyance infrastructure to reduce losses to the aquifer.

In the ground water equation, precipitation has a positive, but insignificant effect. Temperature has a negative, but similarly insignificant effect on the ground water table. The fixed effects are large and significant, indicating that the Southeast has a lower water table than the Northeast, and that the Magic Valley has a substantially higher water table than the Northeast. There are substantial unexplained differences in the water table that are constant across time within a region. This may be due to a number of factors, such as topography or the geologic characteristics of the aquifer.

In the surface water specification with an interaction term, the lagged surface water flow coefficient remains positive and significant. The coefficient describing the relationship between the ground water table and surface water flows is substantially greater than in specification (1). However, the coefficient describing the effect of the ground water table on the surface stock is decreasing over time. The coefficients indicate that, in 1956, a one foot increase in the water table was associated with an increase in average surface water flows of 60 cubic feet per second (cfs) across the Plain. By 1970, a similar increase in the water table led to an average increase in flows of 52.63cfs. At the end of the sample period, the increase in surface flows associated with an increase in the water table fell by nearly half of its original level, to 33.28cfs. This result is indicative of a decrease in hydraulic connectivity between the surface and ground water systems in the Snake Plain. If the time trend is a good proxy for technological change, this indicates that as irrigation technology has improved, the consequence has been to reduce the degree of connectedness between the two systems. However, it may also be the case that as ground water levels have fallen across the Plain, more areas have become hydraulically disconnected, in which case the ground water stock will augment the surface water stock by a smaller amount, on average.

Figure 4 illustrates the in-sample predictive power of both specifications for the surface and ground water stocks. The model performs least well for surface water in the Northeast region, but performs very well for both surface and ground water in the Magic Valley, where the linkage between the two has been, at least legally, of greatest interest to date. Across all water stocks in the three regions, model specification (2) outperforms model specification (1), lending further support to the fact that the relationship between the ground and surface water stocks has changed over time. The poor performance of the model for the Northeast may be due to a poor proxy for precipitation. This region is particularly dependent upon snow pack in the Jackson Lake region for its surface water flows. I intend to explore alternative specifications of the precipitation variable using regional Snotel monitoring data (NRCS 2011).

The results presented herein come with an important caveat. They are likely to be particularly dependent on the accuracy of the two proxies used herein, namely the water rights diversion limit and the time trend for irrigation efficiency. It is possible to test the validity of the water rights proxy for surface water using irrigation gate flow gauge data that is maintained by the Idaho Department of Water Resources. It is not possible to do the same for ground water in the study region. The proxy for irrigation efficiency is problematic. However, very little data is available on the historical use of gravity versus sprinkler irrigation across the study region. Contor (2004) interpreted satellite imagery to generate efficiency data at a spatially disaggregated level for four years between 1980 and 2005. I intend to use this data to check the robustness of the model results for a subset of sample years.

Conclusions

This model demonstrates that hydraulic connectivity between surface and ground water in the Snake Plain has diminished over time. While the State supports curtailing ground water pumping to ensure adequate surface flows, the results presented suggest that may not be an effective means of addressing the problem moving into the future. This result holds for a regional change in the ground water stock, which requires a larger-scale ground water curtailment program than the State has undertaken to date. In practice, the state chooses individual ground water rights to curtail. This analysis does not take into account how small-scale curtailments affect regional surface flows, though I surmise that the impact would be orders of magnitude lower than that estimated here. Cutting off pumping at an individual well will likely have a small marginal effect on the surface water stock and that effect will be attenuated over time in proportion to the distance of the well(s) from the nearest surface water reach (Cosgrove and Johnson 2004).

The model presented herein avoids several empirical issues that have thus far prohibited an econometric analysis of the conjunctive management problem. There remain some unresolved issues with the methodology, primarily related to the accuracy of the proxies and any endogeneity associated with irrigation technology adoption. However, this approach is a first step towards answering an important policy question that has been debated in the study region for over a decade (Johnson 1999). The implications of this analysis are by no means unique to the region. Recent attention to developing conjunctive management systems in Oregon, Kansas, Nebraska, and Colorado, all of which retain the authority to curtail ground water use to protect surface water supplies, attests to the widespread policy relevance of the issue (OWRB 2010). Moreover, the results of this analysis hold general implications for the assignment and enforcement of property rights to a coupled resource.

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Appendix: Derivation of Econometric Models

To derive the econometric models in equations (7) and (8), I first assume linear econometric models for specifications (2) and (3) with an additive error term. Specifically, for equation (2),

(1A) $$S_{SW,t} = \gamma_0 + \gamma_1 S_{SW,t-1} + \gamma_2 R_t + \gamma_3 W_{SW,t} + \gamma_4 T_t + \gamma_5 S_{SW,t} + \gamma_6 W_{SW,t} + \gamma_7 T_t + \gamma_8 S_{GW,t} + \nu_{SW,t}.$$

Collecting terms and rearranging,

$$S_{SW,t} = \frac{\gamma_0}{(1-\gamma_5)} + \frac{\gamma_1}{(1-\gamma_5)} S_{SW,t-1} + \frac{\gamma_2}{(1-\gamma_5)} R_t + \frac{(\gamma_3+\gamma_6)}{(1-\gamma_5)} W_{SW,t} + \frac{(\gamma_4+\gamma_7)}{(1-\gamma_5)} T_t + \frac{\gamma_8}{(1-\gamma_5)} S_{GW,t} + \frac{\nu_{SW,t}}{(1-\gamma_5)}.$$

Therefore,

$$\beta_0 = \frac{\gamma_0}{(1-\gamma_5)};\ \beta_1 = \frac{\gamma_1}{(1-\gamma_5)};\ \beta_2 = \frac{\gamma_2}{(1-\gamma_5)};\ \beta_3 = \frac{(\gamma_3+\gamma_6)}{(1-\gamma_5)};\ \beta_4 = \frac{(\gamma_4+\gamma_7)}{(1-\gamma_5)};\ \beta_5 = \frac{\gamma_8}{(1-\gamma_5)} S_{GW,t};$$
$$\varepsilon_{SW,t} = \frac{\nu_{SW,t}}{(1-\gamma_5)}$$

The key terms to consider are β_3 and β_4. β_3 captures the net effect of surface water withdrawals on the stock, via both direct diversions and via an increase in aquifer recharge. β4 captures the net effect of irrigation technology on the surface water stock, by reducing return flows and by reducing recharge into the aquifer.

Similarly,

(2A) $$S_{GW,t} = \delta_0 + \delta_1 S_{GW,t-1} + \delta_2 R_t + \delta_3 W_{GW,t} + \delta_4 T_t + \delta_5 S_{SW,t} + \delta_6 W_{SW,t} + \delta_7 T_t + \delta_8 S_{GW,t} + \nu_{GW,t}$$

and

$$S_{GW,t} = \frac{\delta_0}{(1-\delta_8)} + \frac{\delta_1}{(1-\delta_8)} S_{GW,t-1} + \frac{\delta_2}{(1-\delta_8)} R_t + \frac{\delta_3}{(1-\delta_8)} W_{GW,t} + \frac{(\delta_4+\delta_7)}{(1-\delta_8)} T_t + \frac{\delta_5}{(1-\delta_8)} S_{SW,t} +$$
$$\frac{\delta_6}{(1-\delta_8)} W_{SW,t} + \frac{\nu_{GW,t}}{(1-\delta_8)}$$

where

$$\alpha_0 = \frac{\delta_0}{(1-\delta_8)}; \alpha_1 = \frac{\delta_1}{(1-\delta_8)}; \alpha_2 = \frac{\delta_2}{(1-\delta_8)}; \alpha_3 = \frac{\delta_3}{(1-\delta_8)}; \alpha_4 = \frac{(\delta_4+\delta_7)}{(1-\delta_8)}; \alpha_5 = \frac{\delta_5}{(1-\delta_8)};$$
$$\alpha_6 = \frac{\delta_6}{(1-\delta_8)}; \varepsilon_{GW,t} = \frac{v_{GW,t}}{(1-\delta_8)}$$

Thus, α_4 captures the net effect of improved irrigation efficiency, which directly reduces the amount of water returning to the aquifer via return percolation, and also reduces recharge into the aquifer from surface water applications. Ex ante sign expectations for the parameters in specifications (1A), (2A), (7), and (8) are given in Table 1A.

With the addition of a proxy for water withdrawals, as in equation (9), and assuming that the vector X contains precipitation, R_t, and temperature, H_t, equations (7) and (8) become

$$\begin{aligned} S_{SW,t} &= \beta_0 + \beta_1 S_{SW,t-1} + \beta_2 R_t + \beta_3\left(\gamma_0^{SW} + \gamma_1^{SW}\overline{W}_{SW,t} + \gamma_2^{SW} S_{SW,t} + \delta_1^{SW} R_t + \delta_2^{SW} H_t + v_{it}\right) \\ &+ \beta_4 T_t + \beta_5 S_{GW,t} + \varepsilon_{SW,t} \end{aligned}$$

and

$$\begin{aligned} S_{GW,t} &= \alpha_0 + \alpha_1 S_{GW,t-1} + \alpha_2 R_t + \alpha_3\left(\gamma_0^{GW} + \gamma_1^{GW}\overline{W}_{GW,t} + \gamma_2^{GW} S_{GW,t} + \delta_1^{GW} R_t + \delta_2^{GW} H_t + v_{GW,t}\right) \\ &+ \alpha_4 T_t + \alpha_5 S_{SW,t} + \alpha_6\left(\gamma_0^{SW} + \gamma_1^{SW}\overline{W}_{SW,t} + \gamma_2^{SW} S_{GW,t} + \delta_1^{SW} R_t + \delta_2^{SW} H_t + v_{SW,t}\right) + \varepsilon_{GW,t}. \end{aligned}$$

Rearranging and combining terms yields

$$\text{(3A)} \quad S_{SW,t} = \tilde{\beta}_0 + \tilde{\beta}_1 S_{SW,t-1} + \tilde{\beta}_2 R_t + \tilde{\beta}_3 \overline{W}_{SW,t} + \tilde{\beta}_4 T_t + \tilde{\beta}_5 S_{GW,t} + \tilde{\beta}_6 H_t + u_{SW,t}$$

where

$$\tilde{\beta}_0 = \frac{\beta_0 + \beta_3\gamma_0^{SW}}{1-\beta_3\gamma_2^{SW}}, \tilde{\beta}_1 = \frac{\beta_1}{1-\beta_3\gamma_2^{SW}}, \tilde{\beta}_2 = \frac{\beta_2 + \beta_3\delta_1^{SW}}{1-\beta_3\gamma_2^{SW}}, \tilde{\beta}_3 = \frac{\beta_3\gamma_1^{SW}}{1-\beta_3\gamma_2^{SW}}$$
$$\tilde{\beta}_4 = \frac{\beta_4}{1-\beta_3\gamma_2^{SW}}, \tilde{\beta}_5 = \frac{\beta_5}{1-\beta_3\gamma_2^{SW}}, \tilde{\beta}_6 = \frac{\beta_3\delta_2^{SW}}{1-\beta_3\gamma_2^{SW}}, u_{SW,t} = \frac{\beta_3 v_{SW,t} + \varepsilon_{SW,t}}{1-\beta_3\gamma_2^{SW}}$$

The denominator in each term above is positive given that $\beta_3 < 0$ and $\gamma_2^{SW} > 0$. The signs of the coefficients will not change from that listed in table 1A, with the exception of $\tilde{\beta}_2$, which becomes ambiguous as it captures the positive effect of precipitation on the surface water stock and the negative effect that precipitation has on the surface water stock because it increases water demand. The ground water equation can be similarly expressed as

$$\text{(4A)} \quad S_{GW,t} = \tilde{\alpha}_0 + \tilde{\alpha}_1 S_{GW,t-1} + \tilde{\alpha}_2 R_t + \tilde{\alpha}_3 \overline{W}_{GW,t} + \tilde{\alpha}_5 T_t + \tilde{\alpha}_6 S_{SW,t} + \tilde{\alpha}_7 \overline{W}_{SW,t} + \tilde{\alpha}_8 H_t + u_{GW,t}$$

Each of the parameters in expressions (3A) and (4A) is interpreted as the net effect of a variable on the stock level.

Table 1A. Ex Ante Sign Expectations for Empirical Model Parameters

Surface Water Equations				Ground Water Equations			
Equation (1A)		Equation (7)		Equation (2A)		Equation (8)	
Parameter	Sign	Parameter	Sign	Parameter	Sign	Parameter	Sign
γ_1	+	β_1	+	δ_1	+	α_1	+
γ_2	+	β_2	+	δ_2	+	α_2	+
γ_3	–	β_3	–	δ_3	−	α_3	−
γ_4	–	β_4	+/–	δ_4	−	α_4	−
γ_5	–	β_5	+	δ_5	+	α_5	+
γ_6	–			δ_6	+	α_6	+
γ_7	+			δ_7	−		
γ_8	+			δ_8	−		

Tables and Figures

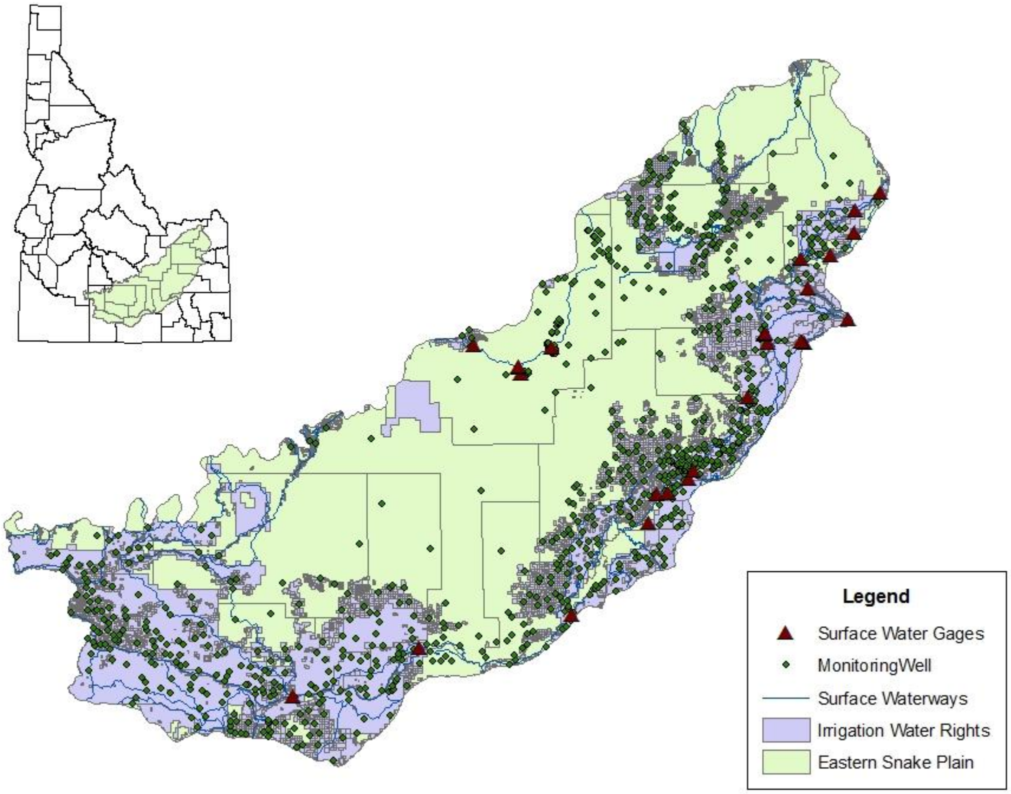

Figure 1. Eastern Snake Plain Study Area with USGS Surface Water Gauges, Monitoring Wells, and Irrigation Water Rights by Place of Use

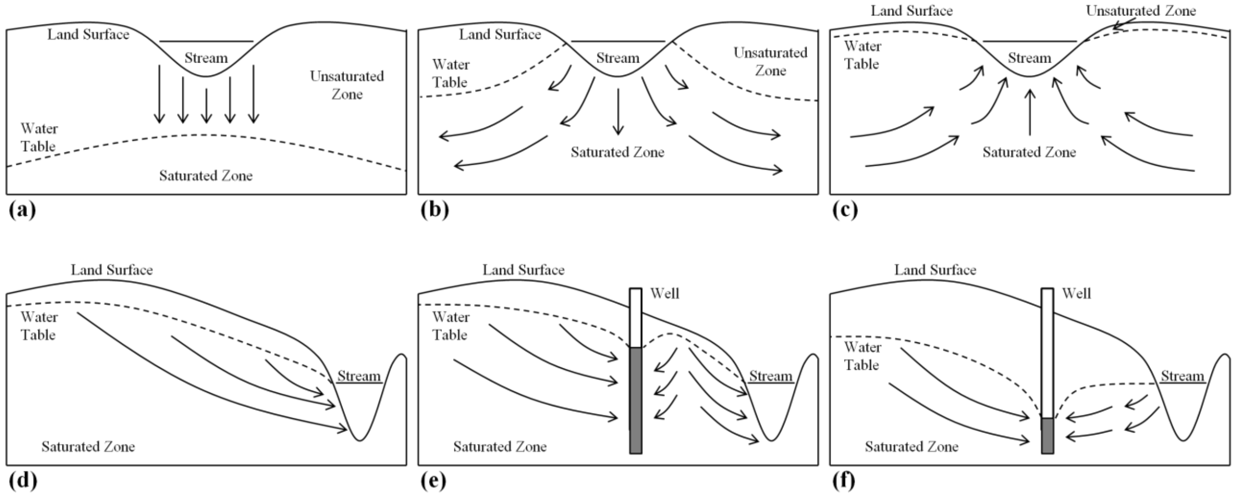

Figure 2. Hydraulic Connectivity and the Effect of Groundwater Pumping on Surface Water Resources

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

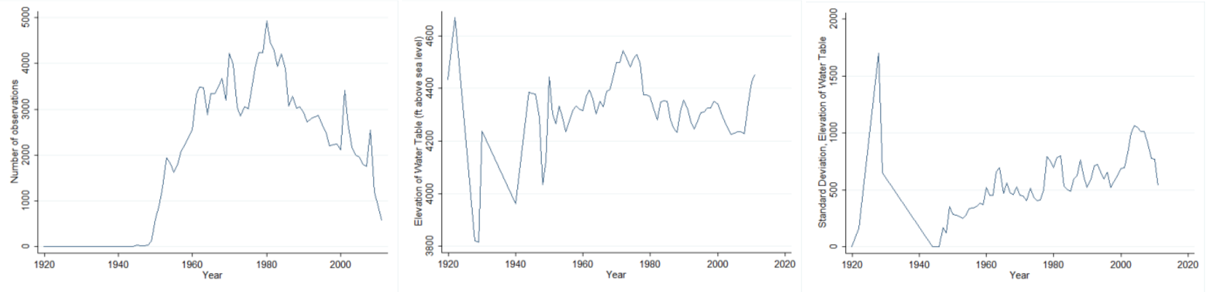

Figure 3. Summary of USGS Ground Water Level Data, 1920-2011

Notes: Panel (a) plots a count of well level observations. Panel (b) plots the mean annual static water table elevation (in feet above sea level) across observation wells. Panel (c) plots the standard deviation of water level observations each year.

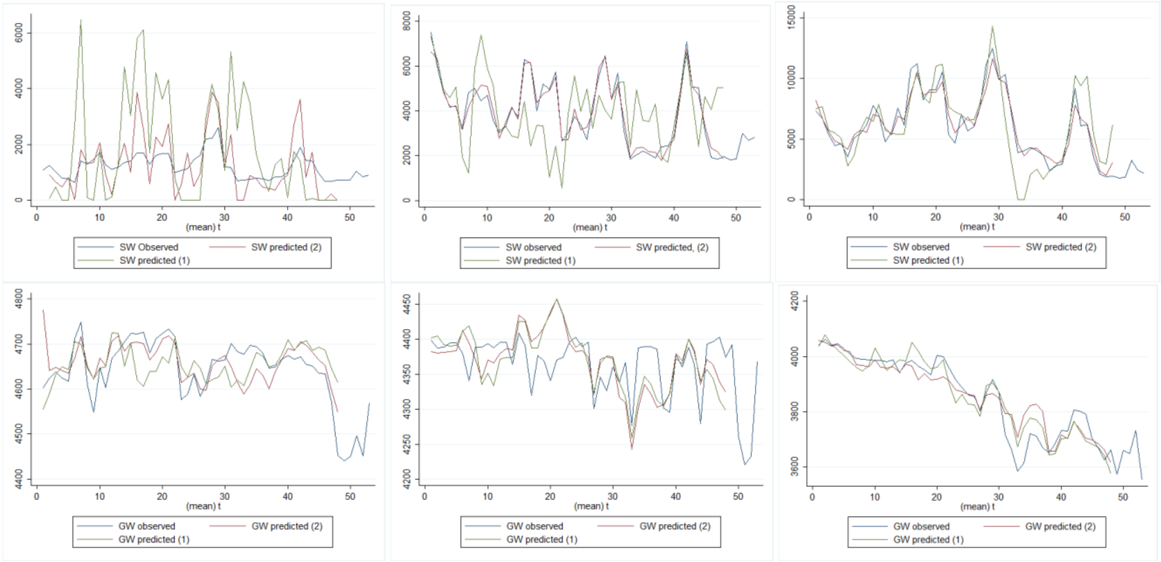

Figure 4. In-Sample Predictive Power of the Empirical Model

Notes: In both rows, panel (a) is for the Northeast; panel (b) is for the Southeast; panel (c) is for the Magic Valley.

Table 1. Estimated Model Parameters using Three Stage Least Squares with Fixed Effects

	Specification (1)		Specification (2)	
Independent Variable	SW Flows_t	GW Table_t	SW Flows_t	GW Table_t
SW Flows_t	–	0.001*	–	0.053***
SW $\text{Flows}_{t\text{-}1}$	0.675***	–	0.571***	–
GW Table_t	2.723**	–	60.375***	–
GW $\text{Table}_{t\text{-}1}$	–	0.496***	–	0.226***
SW Appropriations_t	0.286	–0.162***	4.640***	–0.186***
GW Appropriations_t	–	–0.034	–	0.053**
Time Trend (T)	–1858.77***	45.472	842.424	75.837
Quadratic Time Trend (T^2)	59.285***	–1.366	50.196	–2.018
Total Precipitation_t	131.585	2.743	174.543	0.590
Average Temperature_t	504.932**	–15.468	341.135	–19.162
Southeast Region	7,542.93	–3,578.36***	110,650.0***	–4,175.59***
Magic Valley Region	–19,557.61	13,582.68***	–366,353.8***	15,576.6***
SW Flows_t x T	–	–	–	–0.001***
GW Table_t x T	–	–	–0.553***	–
Constant	–39,093.6*	7,647.77***	–418,481.6***	9,468.9***

***, **, * denote significance at the one, five, and ten percent level, respectively.