Spatial Groundwater Management: A Game Theoretic Framework and Application to California[1]

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Abstract

The sustainable management of groundwater resources for use in agriculture is a critical issue in California and globally. When designing groundwater management policies, it is important to account for spatial considerations that may lead groundwater users to behave non-cooperatively. Spatial considerations arise because groundwater users face a common pool resource problem: because farmers are sharing the aquifer with other farmers, other farmers' pumping affects their extraction cost and the amount of water they have available to pump. Spatial externalities resulting from groundwater users' inability to completely capture the groundwater to which property rights are assigned can lead to over-extraction. In this paper, we present a game theoretic framework for analyzing spatial groundwater management. We apply our framework to discussing spatial groundwater management in California.

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1. Introduction

The sustainable management of groundwater resources for use in agriculture is a critical issue in California and globally. Many of the world's most productive agricultural basins depend on groundwater and have experienced declines in water table levels. The food consumers eat, the farmers who produce that food, and the local economies supporting that production are all affected by the availability of groundwater (Lin Lawell, 2016). Worldwide, about 70 percent of groundwater withdrawn is used agriculture, and in some countries, the percent of groundwater extracted for irrigation can be as high as 90 percent (National Groundwater Association, 2016).

Increasing competition for water from cities and environmental needs, as well as concerns about future climate variability and more frequent droughts, have caused policy-makers to look for ways to decrease the consumptive use of water (Lin Lawell, 2016). Approximately 25% of global crops are being grown in water-stressed areas (Siebert et al., 2013).

California has been experiencing its third-worst drought in 106 years (Howitt and Lund, 2014). From 1960 to the present, there has been significant deterioration in the groundwater level of the Central Valley of California, making current levels of groundwater use unsustainable (Famiglietti, 2014). Groundwater management is particularly important in California as the state produces almost 70 percent of the nation's top 25 fruit, nut, and vegetable crops (Howitt and Lund, 2014). Understanding the economics of sustainable agricultural groundwater management is particularly timely and important for California as legislation allowing regulation of groundwater is being implemented gradually in California over the next several years (York and Sumner, 2015; Sears et al., 2016; Sears, Lim and Lin Lawell, 2017).

When designing groundwater management policies, it is important to account for spatial considerations that may lead groundwater users to behave non-cooperatively. Spatial considerations arise because groundwater users face a common pool resource problem: because farmers are sharing the aquifer with other farmers, other farmers' pumping affects their extraction cost and the amount of water they have available to pump (Pfeiffer and Lin, 2012; Lin and Pfeiffer, 2015; Lin Lawell, 2016; Sears et al., 2016). Spatial externalities resulting from groundwater users' inability to completely capture the groundwater to which property rights are assigned can lead to over-extraction (Sears et al., 2016).

In this paper, we present a game theoretic framework for analyzing spatial groundwater management. We apply our framework to discussing spatial groundwater management in California.

2. Framework

To characterize the differences between non-cooperative behavior and optimal spatial management, we present a game theoretic framework that contrasts the decisions of an individual farmer with that of a social planner. We also examine the case of partial coordination.

2.1. The hydrological system

Our model of the hydrological system follows that of Pfeiffer and Lin (2012) and Lin Lawell (2017c). To capture the important characteristics of groundwater movement, while avoiding the complications of a sophisticated hydrological model, each farmer's land can be thought of as a "patch" that is connected to neighboring patches via a simplified hydrological model.

Although our model is a simplification of the true physical nature of groundwater flows, it has several advantages over the standard groundwater extraction model that assumes that an aquifer is like a bathtub. In the simple bathtub model, a decrease in the level of the aquifer caused by extraction by any individual is transmitted immediately and completely to all other users of the aquifer, and all users are homogeneous (Burt, 1964; Negri, 1989). In reality, however, aquifer systems do not adjust instantaneously to withdrawals, and the response can be complex and heterogeneous, even within a small geographic area (Heath, 1983; Brozovic, Sunding and Zilberman, 2002; Pfeiffer and Lin, 2012; Lin Lawell, 2017c).

We assume that each farmer owns one patch $i \in \{1,...,I\}$ that has one point of extraction, or well, on it. The change in groundwater stock s_i from one period to the next depends on the total amount of water w_i agent *i* is pumping, recharge, and net flow. The equation of motion, which is derived from simplified hydrological mass-balance equations (Freeze and Cherry, 1979), is given by:

$$s_{i,t+1} = s_{it} - w_{it} + g_{it}(w_{it}) + \sum_{j=1}^{I} \theta_{ji}(s_{1t},...,s_{It}) s_{jt} \ . \qquad (1)$$

Recharge $g_{it}(w_{it})$ is a function of return flow (the proportion of the amount pumped that returns to the groundwater table) and precipitation, where $0 \le \frac{\partial g_{it}}{\partial w_{it}} \le 1$.

The stock $s_{i,t+1}$ next period also depends on the net flow into *i*'s land that is caused by physical height gradients or other hydrological factors that determine how water flows within an aquifer. The net flow rate $\theta_{ji}(\cdot)$ is defined as the proportion of the water that starts in patch *j* and disperses to patch *i* by the next period, so $\sum_{j=1}^{I} \theta_{ji}(\cdot) s_{jt}$ is the net amount of water that flows into patch *i* from all other patches in the system (Pfeiffer and Lin, 2012; Lin Lawell, 2017c).

Groundwater flow is generally stock dependent: the net flow rate $\theta_{ji}(\cdot)$ is a function of the stocks of water in all the other patches $s_1,...,s_I$; and the more stock is in patch *i*, the less the net flow from other patches: $\frac{\partial \theta_{ji}}{\partial s_i} \leq 0$. The net flow rate $\theta_{ji}(\cdot)$ from patch *j* to patch *i* may also depend on the transmissivity (or hydroconductivity) k_j of the material holding the water in patch *j*, the distance x_{ji} between plots *i* and *j*, and the physical gradients $\frac{s_j - s_i}{x_{ji}}$ between patches (Brutsaert, 2005; Pfeiffer and Lin, 2012; Lin Lawell, 2017c).

A simple yet hydrologically reasonable functional form assumption for the net flow rate $\theta_{ji}(\cdot)$ can be derived from Darcy's Law for water movement through a porous material and is given by (Pfeiffer and Lin, 2012):

$$\theta_{ji}(\cdot) = k_j \frac{s_j - s_i}{x_{ji}}. \tag{2}$$

The net flow rate $\theta_{ji}(\cdot)$ could also be more complex and consider the effects of aquifer bed topology, continuous cones of depression from pumping, or saltwater intrusion (see e.g., Janmaat, 2005).

2.2. Non-cooperative behavior

Non-cooperative behavior arises among individual farmers extracting groundwater because groundwater users face a common pool resource problem: because farmers are sharing the aquifer with other farmers, other farmers' pumping affects their extraction cost and the amount of water they have available to pump. Consequently, groundwater pumping by one user raises the extraction cost and lowers the total amount that is available to other nearby users (Pfeiffer and Lin, 2012; Lin and Pfeiffer, 2015; Lin Lawell, 2016; Sears et al., 2016).

Groundwater users face two types of spatial externalities that lead to non-cooperative behavior. The first is a pumping cost externality: withdrawal by one user lowers the water table and increases the pumping cost for all users. The second is a strategic externality: what a farmer does not withdraw today will be withdrawn by other farmers, which undermines the farmer's incentive to forgo current for future pumping.

Formally, owing to the dependence of the stock $s_{i,t+1}$ next period on the stock of farmer *i*'s neighbors *j* via the proportion $\theta_{ji}(\cdot)$ of the water that starts in patch *j* and disperses to patch *i* by the next period, it is possible that a farmer considers the effect that his pumping has on future groundwater levels for both his own patch and that of his neighbors. We therefore use a game theoretic framework to model the non-cooperative behavior among farmers sharing an aquifer.

Let $R_{it}(w_{it})$ denote the per-period revenue that can be generated by producing crops with extracted irrigation water w_{it}, assuming crops are chosen optimally to maximize revenue given extracted irrigation water w_{it}. Let $C^w(s_{it})w_{it}$ denote the cost of extracting water, which depends on the distance that the water must be pumped from the aquifer to the surface of the ground. The distance the water must be pumped depends on the stock of water s_{it}; as the stock decreases, pumping cost increases, or $\frac{\partial C^w(s_{it})}{\partial s_{it}} < 0$.

An individual dynamically optimizing farmer behaving non-cooperatively with respect to other farmers will choose groundwater extraction w_{it} each period *t* in order to maximize the present discounted value of his entire stream of per-period profits, conditional on the groundwater stocks s_{jt} of all his neighbors *j*. The optimization problem faced by an individual dynamically optimizing farmer behaving non-cooperatively with respect to other farmers is therefore given by:[2]

$$\max_{\{w_{it}\}_t} \sum_{t=0}^{\infty} \left(\frac{1}{1+r} \right)^t \left(R_{it}(w_{it}) - C^w(s_{it}) w_{it} \right), \tag{3}$$

subject to the equation of motion (1) and to the following transversality condition:

$$\lim_{t \to \infty} \left(\frac{1}{1+r} \right)^t \lambda_{it} s_{it} = 0, \tag{4}$$

and conditional on the groundwater stocks s_{jt} of all of farmer *i*'s neighbors *j*.

The decision of how much water to pump in the current period versus how much water to pump in future periods can be expressed using the following Bellman equation (Bellman, 1957):

$$V_{it}(s_{it}) = \max_{\{w_{it}\}_t} \ R_{it}(w_{it}) - C^w(s_{it}) w_{it} + \frac{1}{1+r} E V_{i,t+1}(s_{i,t+1}), \tag{5}$$

subject to the equation of motion (1).

The first order conditions of the Bellman equation can be used to derive the Euler equation, which holds at all points in time *t*. Taking the derivative of the value function $V_{it}(s_{it})$ with respect to the choice variable w_{it} and setting it equal to zero yields:

$$\frac{\partial R_{it}(w_{it})}{\partial w_{it}} - C^w(s_{it}) = \frac{1}{1+r} \left(1 - \frac{\partial g_{it}}{\partial w_{it}} \right) E V'_{i,t+1}(s_{i,t+1}), \tag{6}$$

[2] Groundwater management, even at the individual level, is generally modeled as a dynamic optimization problem. This is because marginal pumping costs are a function of the stock of groundwater, and that stock is affected by decisions the manager has made in the past. This would more precisely model a farmer's decision if an individual were granted a *total* amount of water (not an allocation per year) to manage as he sees fit; this would pertain to a more complete property rights system like the one described in Anderson, Burt and Fractor (1983). Lin Lawell (2017) develops an empirical model to test whether groundwater users faced with the prior appropriation doctrine behave in a manner consistent with a dynamic model of nonrenewable resource extraction, and finds that despite the incentives given to groundwater users to pump their maximum allowable amount in each year by the prior appropriation doctrine, farmers extract water consistent with a dynamic model of resource extraction.

which can also be written in terms of the previous period as:

$$\frac{\partial R_{i,t-1}(w_{i,t-1})}{\partial w_{i,t-1}} - C^w(s_{i,t-1}) = \frac{1}{1+r}\left(1 - \frac{\partial g_{i,t-1}}{\partial w_{i,t-1}}\right) EV_{it}^{'}(s_{it})\,. \tag{7}$$

The derivative of the value function with respect to the state variable produces what is known as the Benveniste-Scheinkman condition (Benveniste and Scheinkman, 1979), yielding the following relationship of groundwater levels between time periods along the optimal extraction path:

$$V_{it}^{'}(s_{it}) = -\frac{\partial C^w(s_{it})}{\partial s_{it}} w_{it} + \frac{1}{1+r} EV_{i,t+1}^{'}(s_{i,t+1})\left(1 + \sum_{j=1}^{I} \frac{\partial \theta_{ji}(s_{1t},\ldots,s_{It})}{\partial s_{it}} s_{jt}\right). \tag{8}$$

By substituting equations (6) and (7) into equation (8), the following Euler equation is obtained:

$$\begin{aligned}\frac{\partial R_{it}}{\partial w_{it}} - C^w(s_{it}) = &-\frac{1}{1+r}\left(1 - g'\left(w_{it}\right)\right) E\left[\frac{\partial C^w(s_{i,t+1})}{\partial s_{i,t+1}}\right] w_{i,t+1} \\ &+ \frac{1}{1+r}\left(\frac{1-g'(w_{it})}{1-g'(w_{i,t+1})}\right) E\left[\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}} - C^w(s_{i,t+1})\right] \\ &+ \frac{1}{1+r}\left(\frac{1-g'(w_{it})}{1-g'(w_{i,t+1})}\right) E\left[\left(\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}} - C^w(s_{i,t+1})\right) \sum_{j=1}^{I} \frac{\partial \theta_{ji}(s_{1,t+1},\ldots,s_{I,t+1})}{\partial s_{i,t+1}} s_{j,t+1}\right].\end{aligned} \tag{9}$$

The Euler equation is the standard marginal condition for a resource problem; the decision maker will extract until the marginal revenue from pumping water is equal to the marginal cost plus the marginal user cost of the resource. The marginal user cost is the value to the user of leaving the marginal unit in the ground for future extraction. The marginal unit left as stock has value because it reduces future pumping costs. Dasgupta and Heal (1979) note that when the stock of a resource is very large, the marginal user cost is small relative to the cost of extraction, and the resource is treated similarly to a conventional input. However, when the resource becomes more scarce, the marginal user cost makes up a larger and larger component of the total "cost" of extraction (Lin Lawell, 2017c).

The left-hand side of the Euler equation (9) can be interpreted as the marginal net benefits from consuming one additional unit of the resource in period *t*, while the right-hand side is what the user gives up in period $t+1$ by consuming that unit in *t* (Lin Lawell, 2017c).

A unit of groundwater left in the aquifer has value only in proportion to the amount that the owner can capture in the future. Stock dependent net flow implies $\sum_{j=1}^{I} \frac{\partial \theta_{ji}(s_{1t},...,s_{It})}{\partial s_{it}} < 0$, and the $\sum_{j=1}^{I} \frac{\partial \theta_{ji}(s_{1t},...,s_{It})}{\partial s_{it}}$ term captures the extent to which the resource is common. As this term gets larger, less of the water left as stock can be captured by the owner of the land, decreasing the value of the marginal unit of stock. This shifts the extraction path towards the present (Pfeiffer and Lin, 2012).

Higher values of $g'(w_{it})$, the function describing recharge and return flow, decrease the value of the marginal unit of groundwater as stock and increase present period pumping (Pfeiffer and Lin, 2012).

The stock of water affects the user's optimization problem in two ways. First, it affects their marginal cost of extraction. Second, it affects the flow into and out of a user's plot (Pfeiffer and Lin, 2012).

We expect the effect of neighbors' pumping on individual *i*'s pumping to be positive regardless of whether *i*'s stock of water is greater than or less than *j*'s stock of water. If individual *i* has a larger stock or, equivalently, a shorter depth to the water table than does its neighbor *j*, then due to the negative gravitational gradient, water will flow out of *i*'s plot, decreasing *i*'s shadow value of water. To capture the water before it can flow out and extract it at a lower marginal cost, *i* would increase pumping (Pfeiffer and Lin, 2012).

If, on the other hand, individual *i* has a smaller stock than does its neighbor *j*, then the gravitational gradient is positive, causing water from *j* to flow to *i*. This reduces the effect of *i*'s current period pumping on his future pumping by decreasing *i*'s future marginal cost of extraction. Thus, *i*'s current period pumping would increase (Pfeiffer and Lin, 2012).

The linkage between users causes each individual to marginally increase pumping, regardless of who is "uphill" from whom. Anything that increases the linkage between patches will also increase present period pumping, including a greater hydroconductivity, a smaller distance between wells, and higher pumping by neighboring patch owners (Pfeiffer and Lin, 2012).

2.3. Socially optimal coordinated solution

To determine the socially optimal coordinated solution, consider a single owner or social planner who must make pumping decisions for an entire aquifer basin, upon which lie many plots of land $i = 1,...,I$ with groundwater pumps. This social planner seeks to maximize the present value of aggregate profit by planning for this aquifer basin (assuming there is no flow in or out of the aquifer):

$$\max_{\{\{w_{it}\}_t\}_i} \sum_{t=0}^{\infty} \left(\frac{1}{1+r} \right)^t \sum_{i=1}^{I} \left(R_{it}(w_{it}) - C^w(s_{it}) w_{it} \right), \tag{10}$$

where the social planner chooses the set of pumping volumes w_{it} on each plot of land *i* in each time period *t*, subject to the equation of motion (1) and the transversality condition (4) for all plots of land *i*. In this formulation, the social planner is pumping water from each plot for use on that plot's crops.[3] The social planner will consider each plot's shadow value of a unit of groundwater stock when determining the optimal solution, so as to internalize any externality that could occur (Pfeiffer and Lin, 2012).

The social planner's intertemporal choice of water extraction satisfies the following Bellman equation:

$$V_t(s_{1t},...s_{It}) = \max_{\{\{w_{it}\}_t\}_i} \sum_{i=1}^{I} [R^{it}(w_{it}) - C^w(s_{it})w_{it}] + \frac{1}{1+r} EV_{t+1}(s_{1,t+1},...s_{I,t+1}), \tag{11}$$

subject to the system of equations of motion (1) for all plots of land *i*.[4]

The first order conditions of the Bellman equation can be used to derive an Euler equation for each patch *i* at each point in time *t*. By setting the derivative of the social planner's value function $V_t(s_{1t},...s_{It})$ with respect to the choice variables w_{it} equal to zero we find:

$$\frac{\partial R_{it}(w_{it})}{\partial w_{it}} - C^w(s_{it}) = \frac{1}{1+r}\left(1 - \frac{\partial g_{it}}{\partial w_{it}}\right)\frac{\partial EV_{i,t+1}(s_{1,t+1},...s_{I,t+1})}{\partial s_{i,t+1}}, \tag{12}$$

which also holds for the previous time period:

$$\frac{\partial R_{i,t-1}(w_{i,t-1})}{\partial w_{i,t-1}} - C^w(s_{i,t-1}) = \frac{1}{1+r}\left(1 - \frac{\partial g_{i,t-1}}{\partial w_{i,t-1}}\right)\frac{\partial EV_{it}(s_{1t},...s_{It})}{\partial s_{it}}. \tag{13}$$

Once again we can derive the Benveniste-Scheinkman condition by taking the derivative of the value function with respect to each state variable s_{it} to find the relationship of groundwater levels between time periods along the optimal extraction path:

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[3] This is in contrast to the single owner/social planner depicted in Negri (1989) in which the planner controls the entire swath of land, pumps from only one location, and then presumably distributes it to the spatial location where it is needed (Pfeiffer and Lin, 2012).

[4] This program is identical to the single owner/social planner problem normally analyzed using a bathtub aquifer model if we assume that transmissivity is infinite, the aquifer is parallel sided and flat bottomed, return flow is zero, and parcels are perfectly homogeneous Negri (1989). In this case, it would not matter where the wells are located or how many there are, as long as water can be transported costlessly to the entire surface of the parcel (Pfeiffer and Lin, 2012).

$$\frac{\partial V_t(s_{1t},...s_{It})}{\partial s_{it}} = -\frac{\partial C^w(s_{it})}{\partial s_{it}} w_{it} + \frac{1}{1+r} \frac{\partial EV_{t+1}(s_{1,t+1},...s_{I,t+1})}{\partial s_{i,t+1}} \left(1 + \sum_{j=1}^{I} \frac{\partial \theta_{ji}(s_{1t},...,s_{It})}{\partial s_{it}} s_{jt}\right)$$
$$+ \frac{1}{1+r} \sum_{j=1}^{I} \frac{\partial EV_{t+1}(s_{1,t+1},...s_{I,t+1})}{\partial s_{j,t+1}} \left(\frac{\partial \theta_{ij}(s_{1t},...,s_{It})}{\partial s_{it}} s_{it} + \theta_{ij}(s_{1t},...,s_{It})\right) \quad . \tag{14}$$

By substituting equations (12) and (13) into equation (14) for a given plot *i* and time *t*, we can obtain the following Euler equation for the socially optimal coordinated solution:

$$\frac{\partial R_{it}(w_{it})}{\partial w_{it}} - C^w(s_{it}) =$$
$$-\frac{1}{1+r}\left(1-g'\left(w_{it}\right)\right) E\left[\frac{\partial C^w(s_{i,t+1})}{\partial s_{i,t+1}}\right] w_{i,t+1}$$
$$+\frac{1}{1+r}\left(\frac{1-g'(w_{it})}{1-g'(w_{i,t+1})}\right) E\left[\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}} - C^w(s_{i,t+1})\right]$$
$$+\frac{1}{1+r}\left(\frac{1-g'(w_{it})}{1-g'(w_{i,t+1})}\right) E\left[\left(\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}} - C^w(s_{i,t+1})\right) \sum_{j=1}^{I} \frac{\partial \theta_{ji}(s_{1,t+1},...,s_{I,t+1})}{\partial s_{i,t+1}} s_{j,t+1}\right]$$
$$+\frac{1}{1+r} E\left[\sum_{j=1}^{I}\left[\left(\frac{1-g'(w_{it})}{1-g'(w_{j,t+1})}\right)\left(\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})\right)\left(\frac{\partial \theta_{ij}(s_{1,t+1},...s_{I,t+1})}{\partial s_{i,t+1}} s_{i,t+1} + \theta_{ij}(s_{1,t+1},...s_{I,t+1})\right)\right]\right].$$
$$\tag{15}$$

By comparing the Euler equation for the socially optimal coordinated solution in equation (15) to the Euler equation for the non-cooperative solution in equation (9), we find that at the social optimum marginal revenue now is now equal to the sum of marginal cost, marginal user cost, and the marginal social cost to nearby plots of land. The marginal social cost σ_{it} of pumping an additional unit of groundwater from patch *i* at time period *t* is given by:

$$\sigma_{it} = \frac{1}{1+r} E\left[\sum_{j=1}^{I} \left[\left(\frac{1-g'(w_{it})}{1-g'(w_{j,t+1})} \right) \left(\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^{w}(s_{j,t+1}) \right) \left(\frac{\partial \theta_{ij}(s_{1,t+1}, \ldots s_{I,t+1})}{\partial s_{i,t+1}} s_{i,t+1} + \theta_{ij}(s_{1,t+1}, \ldots s_{I,t+1}) \right) \right] \right]. \tag{16}$$

Using Darcy's Law in equation (2) as the functional form for the net flow rate $\theta_{ji}(\cdot)$ in the social marginal cost, the Euler equation for the socially optimal coordinated solution becomes:

$$\begin{aligned}
\frac{\partial R_{it}(w_{it})}{\partial w_{it}} - C^{w}(s_{it}) = & -\frac{1}{1+r}\left(1-g'\left(w_{it}\right)\right) E\left[\frac{\partial C^{w}(s_{i,t+1})}{\partial s_{i,t+1}} \right] w_{i,t+1} \\
& + \frac{1}{1+r} \left(\frac{1-g'(w_{it})}{1-g'(w_{i,t+1})} \right) E\left[\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}} - C^{w}(s_{i,t+1}) \right] \\
& + \frac{1}{1+r} \left(\frac{1-g'(w_{it})}{1-g'(w_{i,t+1})} \right) E\left[\left(\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}} - C^{w}(s_{i,t+1}) \right) \sum_{j=1}^{I} \frac{\partial \theta_{ji}(s_{1,t+1}, \ldots, s_{I,t+1})}{\partial s_{i,t+1}} s_{j,t+1} \right] \\
& + \frac{1}{1+r} E\left[\sum_{j=1}^{I} \left[\left(\frac{1-g'(w_{it})}{1-g'(w_{j,t+1})} \right) \left(\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^{w}(s_{j,t+1}) \right) \left(\frac{k_i(2s_{i,t+1} - s_{j,t+1})}{x_{ij}} \right) \right] \right].
\end{aligned} \tag{17}$$

2.4. Comparing non-cooperative behavior and the socially optimal coordinated solution

Comparing the Euler equation (9) under non-cooperative behavior and the Euler equation (15) for the socially optimal coordinated solution, we see that there is an additional term on the right-hand side of equation (15) in the socially optimal coordinated solution that reflects the marginal social cost to nearby plots of land. Since the marginal social cost to nearby plots of land is an additional cost of extracting water in time *t*, the farmers behaving non-cooperatively will over-extract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches owned by different farmers. The magnitude of this externality is intuitively greater for plots j that are closer to plot i, since the distance x_{ji} to plot i is relatively smaller. Similarly, more transmissive plots, or plots j in which k_j is relatively large, are also expected to be susceptible to larger spatial externalities, since water will flow more easily into or out of the plot.

In particular, the solution to the individual dynamically optimizing farmer behaving non-cooperatively with respect to other farmers leads to greater extraction than would occur under a single owner, as long as $\theta_{ii}(\cdot) \neq 1$. The net flow rate $\theta_{ji}(\cdot)$ is the proportion of the water that starts in patch j and disperses to patch i by the next period. If all of the water that starts in i stays in i, for all i, then there is no lateral flow in the aquifer, and the derivatives $\frac{\partial \theta_{ji}(s_{1t},...,s_{It})}{\partial s_{it}}$ and $\frac{\partial \theta_{ij}(s_{1t},...,s_{It})}{\partial s_{it}}$ are equal to zero. Given stock dependent flow, an increase in the stock level at i will cause more movement out of patch i to other patches: $\frac{\partial \theta_{ij}(s_{1t},...,s_{It})}{\partial s_{it}} \geq 0$. Thus, as long as $\sum_{j \neq i} \frac{\partial \theta_{ij}(s_{1t},...,s_{It})}{\partial s_{it}} > 0$, the total amount of water withdrawn per period by the social planner will be less than the total amount of water withdrawn by all of the farmers if the individual farmers behave non-cooperatively.

2.5. Partial coordination

Partial coordination occurs if the groundwater manager only manages a subset of the all the plots of land that share the same aquifer. Let's suppose a groundwater manager manages a subset of plots $\{1,...,I'\}$, where $I' < I$. Such a groundwater manager's intertemporal choice of water extraction satisfies the following Bellman equation:

$$V_t(s_{1t},...s_{I't}) = \max_{\{\{w_{it}\}_t\}_{i=1}^{I'}} \sum_{i=1}^{I'} [R^{it}(w_{it}) - C^w(s_{it})w_{it}] + \frac{1}{1+r} EV_{t+1}(s_{1,t+1},...s_{I',t+1}), \tag{18}$$

subject to the system of equations of motion (1) for the plots of land $i \in \{1,...,I'\}$.

The Euler equation for the partially coordinated solution is then given by:

$$\begin{aligned}
&\frac{\partial R_{it}(w_{it})}{\partial w_{it}} - C^w(s_{it}) = \\
&\quad -\frac{1}{1+r}\left(1-g'\left(w_{it}\right)\right) E\left[\frac{\partial C^w(s_{i,t+1})}{\partial s_{i,t+1}}\right] w_{i,t+1} \\
&\quad +\frac{1}{1+r}\left(\frac{1-g'(w_{it})}{1-g'(w_{i,t+1})}\right) E\left[\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}} - C^w(s_{i,t+1})\right] \\
&\quad +\frac{1}{1+r}\left(\frac{1-g'(w_{it})}{1-g'(w_{i,t+1})}\right) E\left[\left(\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}} - C^w(s_{i,t+1})\right) \sum_{j=1}^{I} \frac{\partial \theta_{ji}(s_{1,t+1},...,s_{I,t+1})}{\partial s_{i,t+1}} s_{j,t+1}\right] \\
&\quad +\frac{1}{1+r} E\left[\sum_{j=1}^{I'}\left[\left(\frac{1-g'(w_{it})}{1-g'(w_{j,t+1})}\right)\left(\frac{\partial R_{j,t+1}}{\partial w_{j,t+1}} - C^w(s_{j,t+1})\right)\left(\frac{\partial \theta_{ij}(s_{1,t+1},...s_{I,t+1})}{\partial s_{i,t+1}} s_{i,t+1} + \theta_{ij}(s_{1,t+1},...s_{I,t+1})\right)\right]\right].
\end{aligned} \tag{19}$$

Comparing the Euler equation (19) under partial coordination and the Euler equation (15) for the socially optimal coordinated solution, we see that partial coordination does not account for the full social marginal cost. Thus, groundwater managers who each manage a subset of the plots of land over an aquifer and who behave non-cooperatively with respect to other groundwater managers will over-extract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches that are managed by different groundwater managers.

3. Spatial Externalities

As seen in our game theoretic framework, farmers behaving non-cooperatively will over-extract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches owned by different farmers. Similarly, groundwater managers who each manage a subset of the plots of land over an aquifer and who behave non-cooperatively will over-extract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches that are managed by different groundwater managers.

Theoretically, spatial externalities are potentially important causes of welfare loss (Dasgupta and Heal, 1979; Eswaran and Lewis, 1984; Negri, 1989; Provencher and Burt, 1993; Brozovic, Sunding and Zilberman, 2002; Rubio and Casino, 2003; Msangi, 2004; Saak and Peterson, 2007). Owing in large part to spatial externalities, the issue of managing water resource use across political boundaries is particularly important (Dinar and Dinar, 2016).

If spatial externalities in groundwater use are significant, they lend insight into the causes of resource over-exploitation. If they are not significant or are very small in magnitude, a simpler model of groundwater user behavior, where each user essentially owns his own stock, is sufficient. Both outcomes would give guidance to policy-makers, although it is important to note that the results are highly dependent on the hydrological conditions of the aquifer (Pfeiffer and Lin, 2015; Lin Lawell, 2016). To make optimal spatial management more politically feasible, Pitafi and Roumasset (2009) devise an intertemporal compensation plan that renders switching from the status quo to optimal spatial management Pareto-improving.

Pfeiffer and Lin (2012) empirically examine whether the amount of water one farmer extracts depends on how much water his neighbor extracts. Their econometric model is spatially explicit, taking advantage of detailed spatial data on groundwater pumping from the portion of western Kansas that overlies the High Plains Aquifer system. Pfeiffer and Lin (2012) is the first study to empirically measure economic relationships between groundwater users.

According to their results, Pfeiffer and Lin (2012) find evidence of a behavioral response to this movement in the agricultural region of western Kansas overlying the High Plains Aquifer. Using an instrumental variable and spatial weight matrices to overcome estimation difficulties resulting from simultaneity and spatial correlation, they find that on average, the spatial externality causes over-extraction that accounts for about 2.5 percent of total pumping. Kansas farmers would apply 2.5 percent less water in the absence of spatial externalities (Pfeiffer and Lin, 2012; Pfeiffer and Lin, 2015; Lin Lawell, 2016).

Strengthening the evidence of the behavioral response to the spatial externalities caused by the movement of groundwater is Pfeiffer and Lin's (2012) empirical result that when a farmer owns multiple wells, he does not respond to pumping at his own wells in the same manner as he responds to pumping at neighboring wells owned by others. In fact, Pfeiffer and Lin (2012) find that the response to pumping at a farmer's own wells is to marginally decrease pumping, thus trading off the decrease in water levels between spatial areas and internalizing the externality that exists between his own wells (Pfeiffer and Lin, 2012; Pfeiffer and Lin, 2015; Lin Lawell, 2016).

Aquifer heterogeneity can affect the extent of the spatial externality. Aquifers vary in rock composition, which determines the extent to which the water resource is shared. Portions of an aquifer where water moves rapidly, those with high hydraulic conductivity, as well as those that receive less yearly recharge, face a more costly common-pool problem and therefore receive higher benefits from coordinated management (Edwards, 2016). Edwards (2016) uses the introduction of management districts in Kansas to test the effect of underlying aquifer heterogeneity on changes in agricultural land value, farm size, and crop choice. A landowner in a county with hydraulic conductivity one standard deviation higher sees a relative land value increase of 5-8% when coordinated management is implemented. Counties with lower recharge also see relative increases in land value. Changes in farm size and percentage of cropland in corn are also consistent with the proposition that the effect of coordinated management is unequal and depends on properties of the physical system (Edwards, 2016; Lin Lawell, 2016).

In addition to the spatial externality, another externality that arises with groundwater extraction is that groundwater pumping from aquifers can reduce the flow of surface water in nearby streams through a process known as *stream depletion.* In the United States, recent awareness of this externality has led to intra- and inter-state conflict and rapidly-changing water management policies and institutions. Although the marginal damage of groundwater use on stream flows depends crucially on the location of pumping relative to streams, current regulations are generally uniform over space (Kuwayama and Brozovic, 2013). Kuwayama and Brozovic (2013) use a population data set of irrigation wells in the Nebraska portion of the Republican River Basin to analyze whether adopting spatially differentiated groundwater pumping regulations leads to significant reductions in farmer abatement costs and costs from damage to streams. They find that regulators can generate most of the potential savings in total social costs without accounting for spatial heterogeneity. However, if regulators need to increase the protection of streams significantly from current levels, spatially differentiated policies will yield sizable cost savings (Kuwayama and Brozovic, 2013; Lin Lawell, 2016).

4. Application to California

California has been experiencing its third-worst drought in 106 years (Howitt and Lund, 2014). From 1960 to the present, there has been significant deterioration in the groundwater level of the Central Valley of California, making current levels of groundwater use unsustainable

(Famiglietti, 2014). Figure 1 shows the decline in groundwater levels in California since 2011, by administrative basin.

Groundwater management is particularly important in California as the state produces almost 70 percent of the nation's top 25 fruit, nut and vegetable crops (Howitt and Lund, 2014). Most crops in California come from two areas: the Central Valley, including the Sacramento and San Joaquin valleys; and the coastal region, including the Salinas Valley, often known as America's "salad bowl". Farmers in both areas rely heavily on groundwater (York and Sumner, 2015). Understanding the economics of sustainable agricultural groundwater management is particularly timely and important for California as legislation allowing regulation of groundwater is being implemented gradually in California over the next several years (York and Sumner, 2015; Sears et al., 2016; Sears, Lim and Lin Lawell, 2017).

Groundwater in California constitutes approximately 38 percent of the state's total water supply during an average year. During dry years, groundwater contributes up to 46 percent (or more) of the statewide annual supply, and serves as a critical buffer against the impacts of drought and climate change. Many municipal, agricultural, and disadvantaged communities rely on groundwater for up to 100 percent of their water supply needs. Groundwater extraction in excess of natural and managed recharge has caused historically low groundwater elevations in many regions of California (California Department of Water Resources, 2017a).

Figure 2 presents a map of the principal aquifer systems in California. Groundwater in California is contained in five major aquifers, four of which consist primarily of basin-fill deposits that occupy structural depressions caused by deformation of the Earth's crust. The four basin-fill aquifers are the Basin and Range aquifers, the Central Valley aquifer system, the Coastal Basins aquifers, and the northern California basin-fill aquifers. The fifth major aquifer is the northern California volcanic-rock aquifers (U.S. Geological Survey, 1995).

The Basin and Range aquifers are located in an area that comprises most of Nevada and the southern California desert. Many of these valleys and basins are internally drained; that is, water from precipitation that falls within the basin recharges the aquifer and ultimately discharges to the land surface and evaporates within the basin. Basins might be hydraulically connected in the subsurface by fractures or solution openings in the underlying bedrock, but this is rare. Several basins or valleys may develop surface-water drainage that hydraulically connects the basins, so that groundwater flows between the basins (U.S. Geological Survey, 1995).

The Central Valley aquifer system occupies most of a large basin in central California between the Sierra Nevada and the Coast Range Mountains. The Central Valley is the single most important source of agricultural products in the United States, and groundwater for irrigation has been essential in the development of that industry. The basin contains a single, large, basin-fill aquifer system, the largest such system in the United States (U.S. Geological Survey, 1995).

The Coastal Basins aquifers occupy a number of basins in coastal areas from northern to southern California. Nearly all the large population centers in California are located in these basins. In most of the basins, however, population has grown to such an extent that local groundwater supplies are no longer adequate, and surface water must be transported from distant sources to meet demand. In nearly all basins that contain more than one aquifer, the aquifers are hydraulically connected to some degree. Interior northern California is sparsely populated, and most groundwater demand there is for agricultural irrigation (U.S. Geological Survey, 1995).

The most productive and highly-utilized aquifers in the area are the northern California basin-fill aquifers. In some basins, wells drilled into underlying volcanic rocks might produce large quantities of water (U.S. Geological Survey, 1995).

The northern California volcanic-rock aquifers consist of volcanic rocks that yield water primarily from fractures and locally from intergranular spaces in porous tuffs. Because water-yielding zones in these rocks are unevenly distributed, there are more dry holes than wells that yield water; however, in some areas, wells completed in the volcanic-rock aquifers yield large volumes of water. The northern California volcanic-rock aquifers are relatively unexplored and undeveloped (U.S. Geological Survey, 1995).

In 2015, the California Department of Water Resources developed a Strategic Plan to implement its 2014 Sustainable Groundwater Management Act (California Department of Water Resources, 2015). Each groundwater basin is to be managed at the local level by locally-controlled Groundwater Sustainability Agencies (GSAs). Each Groundwater Sustainability Agency is responsible for developing and implementing a groundwater sustainability plan. The California Department of Water Resources' primary role will be to provide guidance and technical support to local agencies (California Department of Water Resources, 2015).

In terms of the allocation of regulatory responsibility between the state and local agencies, the particular allocation for California delineated by 2014 Sustainable Groundwater Management Act and the 2015 Strategic Plan in which each local agency develops its own groundwater sustainability plan and policies, while the state agency provides guidance and technical support to the local agency, has features of reverse conjoint federalism. Under reverse conjoint federalism, the local governments each set their own regulatory standards while the central government aids the local governments in meeting the regulatory standards they each set on their own (Lin, 2010;

Lin Lawell, 2017a; Lin Lawell, 2017b). Under certain circumstances, reverse conjoint federalism may be the most efficient distribution of regulatory power (Lin, 2010; Lin Lawell, 2017a; Lin Lawell, 2017b). Thus, in terms of the distribution of regulatory authority between central and local tiers of government, the 2014 Sustainable Groundwater Management Act (SGMA) may have it at least partially right.

However, neither the 2014 Sustainable Groundwater Management Act (SGMA) nor its 2015 Strategic Plan for implementation adequately addresses spatial externalities that may lead to non-cooperative behavior among groundwater users sharing the same aquifer. As seen in our game theoretic framework, groundwater managers each managing a subset of the plots of land over an aquifer and each behaving non-cooperatively with respect to other groundwater managers will over-extract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches that are managed by different groundwater managers. Thus, in order to achieve the socially optimal coordinated solution, the jurisdictions of local agencies should be large enough to internalize all externalities, so that there are no transboundary issues between jurisdictions. This means that local agencies should each cover an entire groundwater basin, and also that a groundwater basin should not be managed by multiple Groundwater Sustainability Agencies.

Figure 3 presents a map of the jurisdictions of the Groundwater Sustainability Agencies in California. Regions managed by an exclusive Groundwater Sustainability Agency (GSA), which is a GSA that operates in an area in which no other local agency submitted a conflicting notice within 90 days, or in which previous GSA formation overlap has been resolved, are denoted in green. Exclusivity within a basin only applies to the area within a local agency's service area. Exclusive local agencies, which were created by statute to manage groundwater within their respective statutory boundaries, are denoted in yellow. These exclusive local agencies still need to decide to form a GSA and notify the California Department of Water Resources of their intent to undertake sustainable groundwater management. The local agencies involved in GSA formation overlap shall seek to reach agreement to resolve the overlap by June 30, 2017, or risk potential intervention by the State Water Resources Control Board (California Department of Water Resources, 2017b). Regions with a non-exclusive GSA or a non-exclusive GSA overlap are indicated in light blue and blue, respectively.

When comparing the jurisdictions of the Groundwater Sustainability Agencies in Figure 3 with the map of the principal aquifer systems in California in Figure 2, it is apparent that local agencies do not each cover an entire groundwater basin; on the contrary, there are many basins in which multiple Groundwater Sustainability Agencies operate. Moreover, the prevalence of regions with a non-exclusive GSA or a non-exclusive GSA overlap, as indicated in light blue and blue, respectively, in Figure 3 show that there are many regions in which multiple local agencies operate.

Thus, even if the local agencies each internalize the spatial externalities within their jurisdiction, spatial externalities still exist among local agencies that share the same groundwater basin. As a consequence, the local agencies may behave non-cooperatively, leading to over-extraction relative to the socially optimal coordinated solution.

Another spatial externality that is not internalized by either the 2014 Sustainable Groundwater Management Act (SGMA) or its 2015 Strategic Plan for implementation are transboundary issues that may arise between California and Nevada. As explained above, the Basin and Range aquifers are located in an area that comprises most of Nevada and the southern California desert, and many of the basins are hydraulically connected. Thus, groundwater managers in California and Nevada may behave non-cooperatively with each other, leading to over-extraction relative to the socially optimal coordinated solution.

5. Conclusion

When designing groundwater management policies, it is important to account for spatial considerations that may lead groundwater users to behave non-cooperatively. Spatial considerations arise because groundwater users face a common pool resource problem: because farmers are sharing the aquifer with other farmers, other farmers' pumping affects their extraction cost and the amount of water they have available to pump (Pfeiffer and Lin, 2012; Lin and Pfeiffer, 2015; Lin Lawell, 2016; Sears et al., 2016). Spatial externalities resulting from groundwater users' inability to completely capture the groundwater to which property rights are assigned can lead to over-extraction (Sears et al., 2016).

In this paper, we present a game theoretic framework for analyzing spatial groundwater management. We apply our framework to discussing spatial groundwater management in California. We find that although California's 2014 Sustainable Groundwater Management Act and 2015 Strategic Plan for implementing it may have specified the efficient allocation of regulatory responsibility between central and local tiers of government, the jurisdictions for the local agencies do not internalize all the spatial externalities. As a consequence, the local agencies may behave non-cooperatively, leading to over-extraction relative to the socially optimal coordinated solution.

Spatial groundwater management is an important component of sustainable agricultural groundwater management, which includes complete, measured, enforceable, and enforced property rights that consider the physical properties of the resource; as well as carefully designed policies that internalize any externalities, whether they are caused by the physical movement of water, by environmental damages or benefits, or by other causes (Lin Lawell, 2016).

Our research has important implications for the design of policies for sustainable agricultural groundwater management for California and globally.

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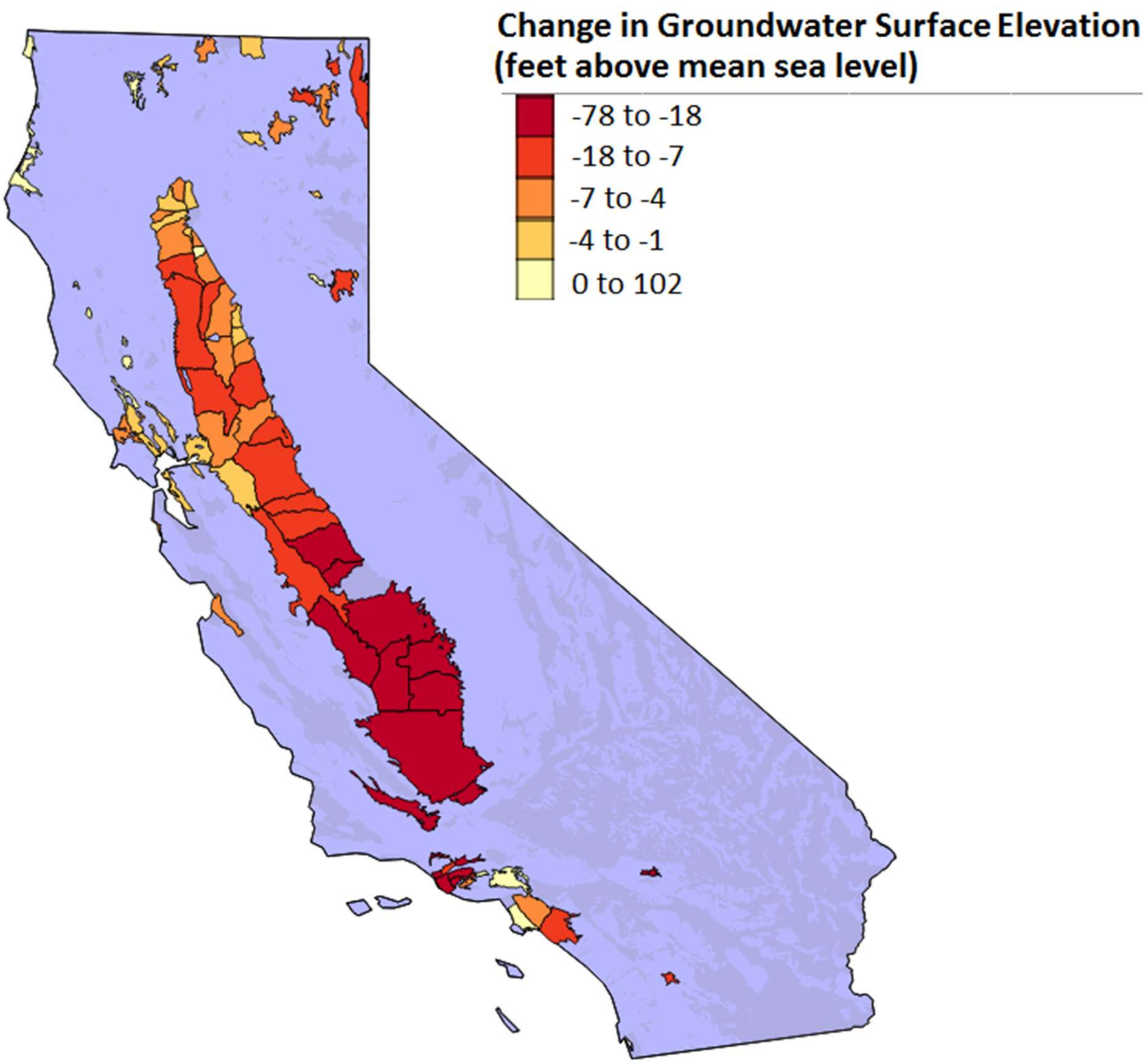
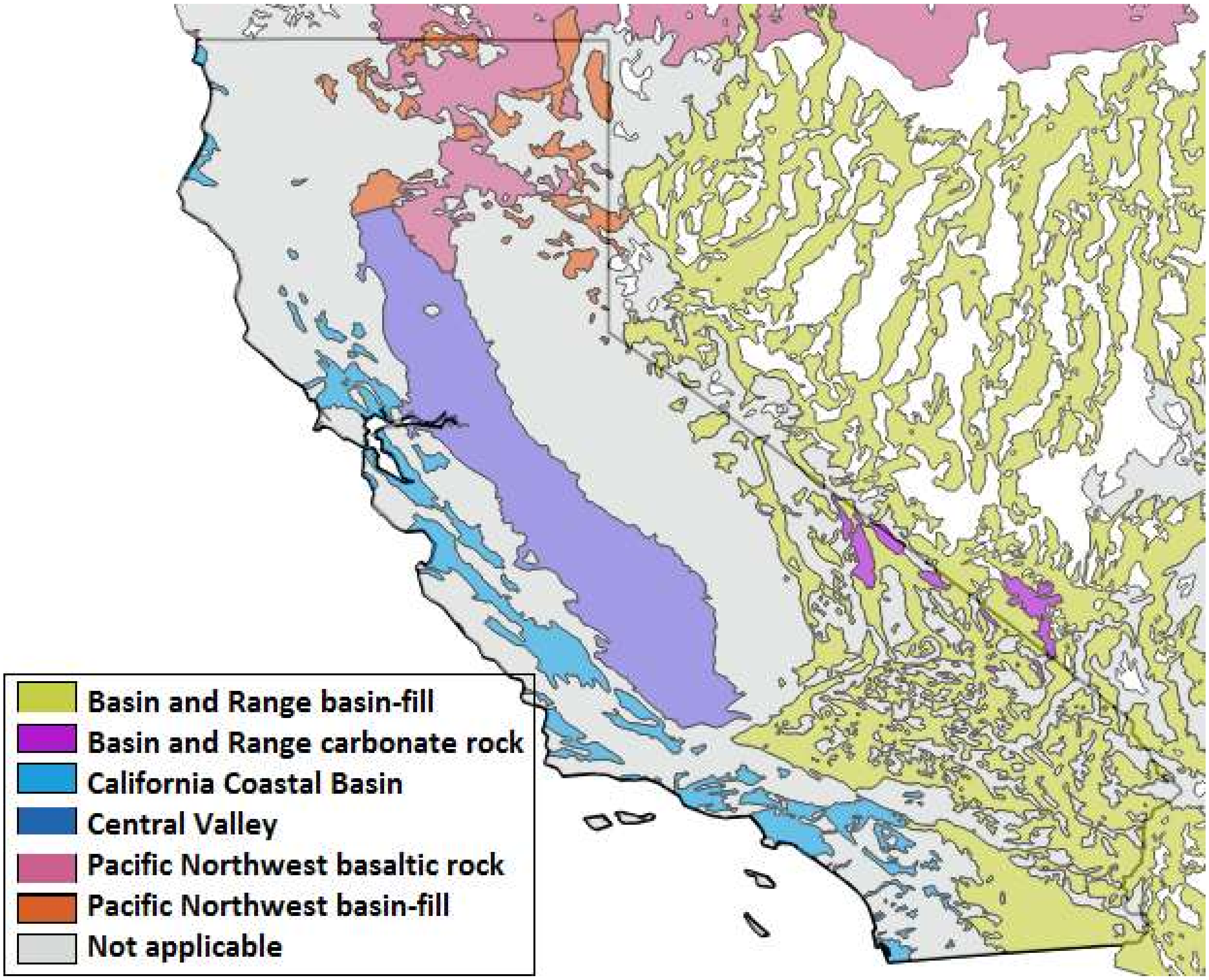
Figure 1. Decline in Groundwater Levels in California Since 2011, By Administrative Basin



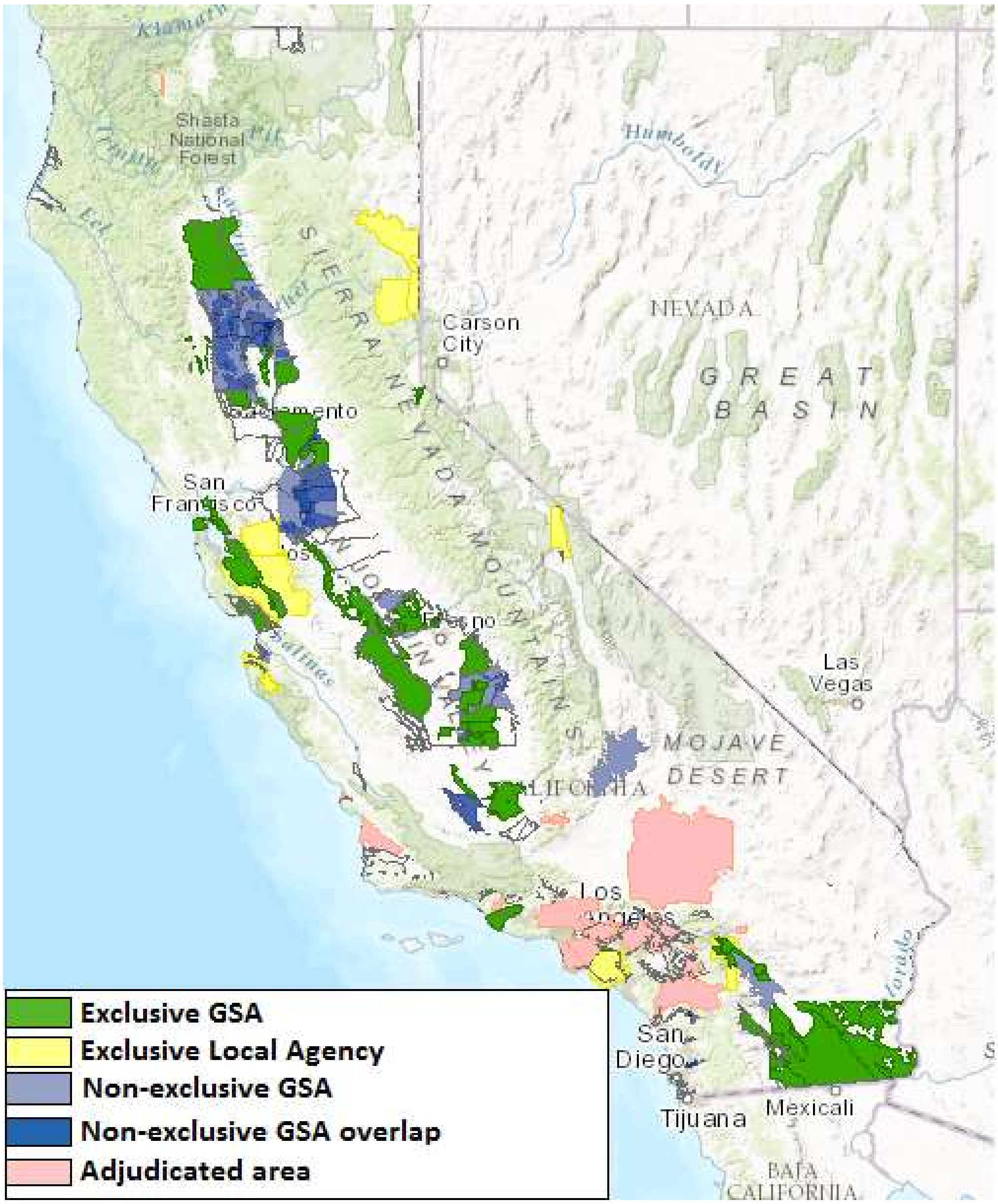
Data source: California Department of Water Resources

Figure 2. Principal Aquifer Systems in California



Data Source: U.S. Geological Survey (2003).

Figure 3. California Groundwater Sustainability Agencies (GSAs)



Data Source: California Department of Water Resources (2017b).