Essays on Economics of Groundwater Resource Management

Thesis by
Hao Zhao

In Partial Fulfillment of the Requirements for the
Degree of
Doctor of Philosophy

CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California

2019
Defended May 28, 2019

Hao Zhao
ORCID: 0000-0002-9110-589X

To Jianjun Zhao and Xiaohua Hu, who gave me life

To Yinan Liu, who gives me love

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my advisor Jean-Laurent Rosenthal. I owe an enormous intellectual debt to Jean-Laurent. My weekly meetings with him bred most of the ideas in this work. Without his help, this thesis would have been impossible.

I am also deeply indebted to John O. Ledyard. Being his TA in the environmental economics class armed me with the knowledge and techniques to develop the theory in Chapter 4.

My other committee members, Matthew Shum and Michael Ewens, also shared me with precious time and wisdom. I have benefited very much from their insightful comments.

I would especially like to thank Charles R. Plott for his boundless patience and for the wisdom he shared throughout our collaboration. My coauthorship with Charles, and other coauthors, Richard Roll and Han Seo, is delightful. I became a better researcher by learning from my coauthors.

I would also like to thank all faculty members in HSS and my fellow classmates in the HSS proseminar. Their comments were always insightful and help improve this work.

Financially, I am grateful for funding provided by the Resnick Sustainability Institute at Caltech for my research on groundwater. The institute provided me with incredible opportunities to meet with scientists out of my field. Conversations with Neil Fromer enlighted me a lot on California water issues.

Lastly, I want to thank again my parents and my girlfriend, Yinan. Their love and support is the only reason I am here.

ABSTRACT

This thesis examines groundwater management regimes in California and discusses how to implement an optimal aquifer management scheme.

Chapter 2 examines the effectiveness of adjudication, a legal settlement among groundwater pumpers, in managing groundwater basins in Southern California. As a form of self-governance, adjudication generally leads to higher water level in the adjudicated basins than the unregulated ones. However, its rigid rules impair dynamic efficiency. Compared with the competitive pumpers, pumpers in the adjudicated basins actually have a less counter-cyclical extraction pattern in response to surface water availability.

Chapter 3 examines how surface water trading intensifies groundwater depletion in California's Central Valley. A surface water market only mitigates the groundwater over-extraction problem when pumping costs are very high, while market failure arises when the pumping costs are low. I build an agricultural water use model to connect the efficacy of the surface water market with crop patterns response to surface water supply variation. The data suggest that the Central Valley is in a low pumping cost regime where the farmers pump groundwater to replace whatever surface water they sell. Therefore, the surface water trade is inefficient because it depletes groundwater resources and should be curtailed until the commons problem is addressed.

Chapter 4 studies optimal groundwater aquifer management. I solve the dynamic optimization problem for groundwater extraction by a social planner when when farmers are heterogeneous and the surface water supply is uncertain. To implement the optimal pumping plan, the farmers must be allocated pumping rights each period equal to the socially optimal extraction. An incentive compatibility issue arises if farmers have heterogeneous access to groundwater. Those who overlie the deepest part of the aquifer might delay regulation because they will get more water as others exit. A larger amount of farmers must be included in the decision set to resolve this political conflict.

CONTENTS

Acknowledgements iv
Abstract v
Contents vi
List of Figures vii
List of Tables viii
Chapter I: Introduction 1
Chapter II: Adjudication of Groundwater Rights in Southern California 3
2.1 Introduction 3
2.2 Background 5
2.3 A Model of Pumping under Uncertainty 8
2.4 Empirical Analysis 20
2.5 Conclusion 30
Chapter III: Surface Water Trading and Groundwater Depletion in California Central Valley 32
3.1 Introduction 32
3.2 Literature Review 35
3.3 Background: Water Market in the Central Valley of California 36
3.4 Theoretical Model: Depletion of Groundwater Basin with Surface Water Market 39
3.5 Empirical Analysis 56
3.6 Conclusion 79
3.A Consistency of PML Estimator 80
Chapter IV: Optimal Aquifer Management 83
4.1 Introduction 83
4.2 Social Planner's Groundwater Extraction and Crop Choice 87
4.3 Open Access to Groundwater 97
4.4 Implementation of Optimal Aquifer Management 100
4.5 Artificial Recharge 112
4.6 Conclusion 115
4.A Solution to the Dynamic Programming Problem under Extreme Weather Conditions 116
4.B Proof of Proposition 4.1 119
4.C Proof of Proposition 4.2 120
Bibliography 122

LIST OF FIGURES

Number *Page*

3.1 Change of Normalized Price of Different Types of Crops over Time 63

3.2 Density of Permanent Crops by Space and Time 65

LIST OF TABLES

Number *Page*

2.1 Representativeness of the Estimated Sample 22

2.2 Summary Statistics 24

2.3 Effect of Adjudication on Water Level Change 28

2.4 Effect of Institution on Cyclicality of Groundwater Extraction 29

3.1 Water District Summary Statistics 57

3.2 History of Crop Change 58

3.3 Plot Level Summary Statistics 60

3.4 Crop Transition Matrix 61

3.5 Moran's I in Districts without Groundwater 67

3.6 Determinants of Planting Permanent Crops 73

3.7 Determinants of Planting Annual Crops in Water Districts without Groundwater before 2004 75

3.8 Determinants of Fallowing in Districts with Groundwater 76

3.9 Robustness Check: Continuous Outcome Measure 78

3.10 Spatial Influence: PMLE at Order 1 & 3 82

Chapter 1

INTRODUCTION

Groundwater depletion has been a critical problem in dry regions like California. It leads to environmental issues such as land subsidence, seawater intrusion, degradation of water quality, etc., thus causing significant economic losses. According to a recent report[1], the cost of managing groundwater in the aquifer by recharge ranges from 90 to 1100 USD per acre-foot, far below the cost of reservoir expansion (1700 to 2700 USD per acre-foot) and seawater desalination (1900 to over 3000 USD per acre-foot). Therefore, groundwater depletion is not merely in the interest of environmentalists. Groundwater users can take action themselves to avoid the huge cost that may be incurred in the near future.

Luckily, running out of groundwater is not the destiny of California water users. The water table in Southern California basins has been stabilized in recent decades, despite a long history of decline. Most Southern California aquifers are managed through adjudication, a form of self-governance that restricts average total extraction from the aquifer not to exceed its sustainable yield.

Adjudication is expensive and slow. It can take decades for the water users to negotiate the allocation of pumping rights and other management regulations. It is also expensive to investigate the hydrology of the aquifer to determine the sustainable yield of the basin. Since water rights are usually determined based on historical use, information asymmetry about each party's past water consumption also presents. As a result, it is not surprising that adjudication mainly succeeds in Southern California, where rapid urbanization has increased the users' value of water and the willingness to pay for management.

No adjudication occurs in the Central Valley where the agricultural community consumes more than 90% of water. Due to the sparse interest among farmers, no one is willing to pay

[1] Water in the West, "Recharge: Groundwater's Second Act."

for the cost of management even though the collective action can benefit all the users. In particular, farmers do not want to bear the cost to monitor. As a consequence, groundwater basins in the Central Valley are still in open access today, and their water table keeps falling.

Without regulation, the commons problem is easily exacerbated by institutions that affect the allocation of surface water, a substitute for groundwater. The farmers not only pump for their own use. With well-defined surface water rights and a market for surface water trade, they are likely to sell their surface water rights to those without enough irrigation water and pump more groundwater to compensate the water sale. In Kern County, groundwater districts supply their surface water to districts without groundwater and pump more for their own use. The amount of extra pumping that is imputed to surface water sale accounts for about 80% of the groundwater over-extraction in the county.

The open access groundwater system suffers more than just the commons problem. It is also vulnerable to other institutional arrangements that target to improve water use efficiency. This is an example of the second-best scenario where the partially efficient water system does not generate the second-best outcome. Implementation of a surface water market should take into account its unintended consequence on groundwater aquifer. A groundwater regulation not only solves the commons problem, but also avoids the distortion caused by the surface water market.

The optimal aquifer management requires a dynamic efficient groundwater extraction plan. To implement that plan, the pumping rights and their allocation need to be carefully designed to induce the efficient extraction and be incentive-compatible. In the rest of the thesis, I will discuss the adjudication of groundwater rights in Chapter 2, the surface water market in Chapter 3, and issues with respect to the optimal groundwater management in Chapter 4.

Chapter 2

ADJUDICATION OF GROUNDWATER RIGHTS IN SOUTHERN CALIFORNIA

2.1 Introduction

Recent studies of self-governance have brought new perspectives on how to solve common pool resource (CPR) problems (Ostrom, 1990; Ostrom, 2002). A rich body of lab experiments (Messick, Allison, and Samuelson, 1988; Ostrom, Gardner, and J. Walker, 1994; J. M. Walker et al., 2000) and field case studies (Berkes, 1986; Berkes et al., 1989a; Ostrom, 1990; Blomquist, 1992; Casari, 2007[1]) have confirmed that appropriators can devise regulations among themselves to manage the common pool. Outside authorities (such as the government) and private markets, as suggested by the conventional theory of the CPR problem[2] Hardin (1968), are not the only solutions to "the tragedy of the commons" (Ostrom and J. Walker, 2000).

Despite the growing consensus on the effectiveness of self-governance (Agrawal, 2001; Rahman, Hickey, and Sarker, 2012; Atkinson et al., 2014), the literature provides little quantitative evidence of the success of private solutions (Tang, 1992; Lam, 1998[3]). For this chapter, I assemble an original dataset from Southern California groundwater basins, conduct a cross-sectional analysis and demonstrate that self-governance does improve sustainability.

Beyond sustainability, I also extend the general framework of CPR to a multi-period model with uncertainty in the availability of substitute resources. I analyze the dynamic efficiency of different institutions depending on how the agents utilize the CPR as insurance against demand and supply risk.

[1] The cases investigated in those studies include fishery (also lobster), wildlife hunting, forest management, groundwater pumping, etc.

[2] Also see M. Olson (1965) for the discussion of the more general collective action problem.

[3] There studies looked at the performance of irrigation systems governed under different groups: the government or farmers themselves.

The context for this chapter is groundwater pumping in Southern California. Groundwater contributes a significant proportion of the state's total water supply. It provides more than one-third of water used by Californians in an average year and more than one-half in a drought year when other sources (mainly surface water) are scarce[4]. In Southern California, groundwater basins account for nearly 35 percent of total water supply and almost 70 percent of the local supply[5].

Groundwater pumpers confront two layers of issues. First, in an unregulated basin, competitive pumping leads to overdrafting and irreversible destruction of the basin's storage capacity. Second, it is unclear how to make joint use of groundwater and surface water efficiently (Zilberman and Lipper, 2002). Unlike surface water, the groundwater supply is not sensitive to immediate weather condition. I argue that groundwater use is the most efficient if pumpers save water in wet years and pump more during droughts. Their doing so of course depends on incentives.

Two broad types of groundwater management exist in California. Most basins remain unregulated. Within them, anyone can drill a well and pump groundwater. Some basins are managed in a different way. They have been adjudicated, meaning that the overlying pumpers have arrived at a legal settlement to close the common pool and apportion the pumping rights among themselves. We consider adjudication as a self-governing institution since the pumpers initiate the process and design the management rules among themselves. Although the courts are involved, they are merely a third-party enforcement agency whose authority is recognized by the pumpers.

Using a theoretical model, I analyze the sustainability and dynamic efficiency of the two different institutions. I start by demonstrating that competitive pumping leads to more extraction than the socially optimal level. I hypothesize that adjudicated basins are more likely to be sustainable than the unregulated ones – in simple terms, they suffer less ground water level decline. In terms of dynamic efficiency, I argue that an optimal intertemporal

[4]See findings in the Sustainable Groundwater Management Act (SGMA) of California.

[5]See the Urban Water Management Plan (2015) of the Metropolitan Water District of Southern California.

groundwater-pumping pattern requires a certain level of counter-cyclicality[6] to offset the variation of surface water supply. Due to the saving externality, competitive pumpers do not have enough of an incentive to use the basin as a drought buffer. In my model, adjudication generates an even smaller counter-cyclical pumping pattern than the competitive case.

My empirical findings confirm the claims that self-governing institutions can solve the CPR problem. By comparing the changes of water levels of wells located in adjudicated and unadjudicated basins within the same period, I find that the self-governed systems are better at preserving water levels. The panel data analysis also shows that groundwater use in adjudicated basins is less counter-cyclical than unadjudicated ones. This result is consistent with the model, and verifies our concern that adjudication may have a problem with dynamic efficiency.

I begin with some necessary background of groundwater basins and groundwater management in California. In Section 2.3, I present the dynamic model of pumping with uncertainty. I will impose different institutions, and then solve for agents' best responses. Section 2.4 contains the empirical analysis, which tests the hypotheses developed in Section 3. Section 2.5 summarizes my conclusion and discusses the broader implications of my findings.

2.2 Background

Groundwater basin as a common pool

Groundwater is generally stored in subsurface zones of saturated sediments called aquifers. A groundwater basin is defined as an alluvial aquifer or a stacked series of alluvial aquifers with reasonably well-defined boundaries (nonwater-bearing material such as bedrock or an underground displacement of rock such as a fault or divide) in a lateral direction and a definable bottom[7]. Groundwater travels within an aquifer from areas of higher elevation towards areas of lower elevation. It may also flow into adjacent basin across underground divides, but the confining boundary makes it much harder for water to leave than flow

[6] Cyclicality in this chapter refers to surface water supply, which is high in wet years and low in dry years.
[7] The definition is from the Department of Water Resource (DWR) Bulletin 118 (2003 update).

within the aquifer (Heath, 1983). Although not completely isolated, each basin can be approximately treated as an isolated system, which is mainly affected by pumping from its own aquifers[8].

In a typical basin, groundwater is a renewable resource. As discussed in Karamouz, Ahmadi, and Akhbari (2011), water enters a groundwater basin either by percolating through the soil and overlying sediments or by flowing in from adjacent underground water systems. A certain amount of water may be "harvested" over regular intervals without impairing the resource. This is the safe yield of the basin. The "annual safe yield" of a basin is roughly its long-term average annual natural replenishment. Overdrafting in modest amount and for limited periods is unlikely to cause serious adverse consequence in most groundwater basins. Persistent over-pumping, however, can make the sediments compact. Then, the aquifer's storage capacity may dwindle or even disappear. With extensive compaction, land may subside, which causes serious problems for surface structures.

A basin satisfies the definition of CPR system as it generates finite water resources with one person's use negatively affecting others' access to water. The negative externality occurs through two channels. First, water level declines increase pumping lift and imposes greater cost on others. If the water level falls below a certain threshold, wells must be deepened or replaced, pushing out those pumpers who cannot afford the capital investment. Second, if the outflow of water is not fully compensated by recharge, the storage space of an aquifer may shrink. Water users then need to invest in expensive ground facilities such as reservoirs for water storage (Carruthers and Stoner, 1981).

Groundwater rights and management regime in California

The groundwater rights system of California recognizes two different sets of water rights. Overlying rights allow landowners to extract water from wells on their property. Appropriative rights are recognized mainly for water purveyors that deliver water to customers.

[8] Basins are not completely independent, but moving of water between basins are slow due to the confining boundaries. I assume independence in this chapter, but even though the cross-basin externality exists, it should not affect the qualitative results.

Although appropriative rights are generally subordinate to overlying rights, neither water right system specifies quantity or associated rules to prevent others from obtaining new rights (Sawyers, 2005). As a result, every pumper is an unlimited groundwater right holder, which makes it difficult to restrict extraction.

Prior to 2014 groundwater was not regulated by the State. The political power of counties and municipalities to manage groundwater is uncertain, since basins generally do not respect county or municipal boundaries. Even for matters within the jurisdiction of local political entities (regulation of well drilling), counties or municipalities rarely attempt to restrict pumping[9]. In fact, through California's history, local pumpers are always the primary decision-makers on groundwater issues. The California Legislature has repeatedly held that groundwater management should remain a local responsibility (Sax, 2002). The most recent legislation (SGMA 2014) requires basins to form their own groundwater sustainability agencies, continuing its long stand of letting the users to solve their problem locally.

In adjudication, the most prominent path to groundwater management, local pumpers turn to courts to settle disputes over how much groundwater can be extracted by each party. It starts when a suit is brought to adjudicate the basin (e.g. City of Pasadena v. City of Alhambra et al.), but usually evolves to a situation in which each defendant's answer to the complaint is treated as cross-complaints against other defendants because of the mutual prescriptive nature of water rights conflict (Blomquist, 1992). The court helps defining the limitation of resource and boundary of water rights community, but it requires the parties to negotiate agreements among themselves. Therefore, each case of adjudication is a fully decentralized bargaining process. The court judgment is in fact a private contract among the water users in the basin, with the court acting as the enforcement agency. In a typical adjudication, the court rules on several matters[10]:

[9] Some counties or cities (for example the Venura County and the city of Beverly Hills) have ordinances to regulate well permitting process or groundwater extraction. However, the regulating power is mainly on the public purveyors who have high value of water use and plenty of supplemental water resources.

[10] See the DWR report: Groundwater Management in California (1999).

1. who the extractors are;

2. how much each party can extract; and

3. who the watermaster will be to monitor and sanction the violation against the court's decree.

Adjudication is usually slow and costly due to the uncertainty about basin hydrology, the complexity of existing water right and the massive and diverse interests in the bargaining process. It took seven years to adjudicate the Raymond basin, and more than ten years passed in the first attempt for the Mojave river basins that ended in failure. Although adjudication is well understood by groundwater users in the state, it has hardly diffused to north of the Tehachapi Mountains, leaving Southern California the unique field to examine the influence of self-governance on CPR's performance.

Next, I analyze a model of groundwater pumping.

2.3 A Model of Pumping under Uncertainty

There are $N > 1$ water users overlying a basin. Denote the agents by $i = 1, \ldots, N$. For simplicity, assume the water users are identical[11]. Each agent obtains revenue $f(q)$ from "consuming" q units of water. Depending on the type of the water user, "consuming" means selling the water if the agent is a water purveyor, or watering crops if the agent is a farmer. The revenue function is increasing and concave.

There are two sources of water, surface and ground water. Surface water is available at a price that depends on current condition (high in drought, low in rainy years). Denote the severity of drought as d. The unit price of surface water $p(d)$ is an increasing function of the drought level.

[11] Heterogeneity among water users does not hurt our results when there is no regulation since agents make decisions independently. When there is regulation, for example, adjudication, water users can trade water rights. Heterogeneity to some sense is offset by the private market, so it does not affect the qualitative result if the market works.

Groundwater must be pumped. The cost of pumping has two components, the amount of extraction and the depth of the water table. When the water table falls, pumping lift in the well increases and groundwater contains a larger quantity of dissolved solids. Both will increase the pumping cost. Let the influence of water level be linear. The pumping cost takes the form: $c(e) = \bar{l}e$, where e denotes the amount of extraction and $\bar{l}$ is the average depth to the water in the well during the pumping process.

Water depth l changes with production and recharge. In the short run, natural recharge is negligible. The water level change in agent i's well is only affected by her own extraction e_i. Therefore, we have the final water depth $l_i = l_0 + \frac{e_i}{s_w}$ where l_0 denotes the water depth before extraction and s_w is the size of the well.

In the long run, water moves from high elevation to low elevation within the basin. Following previous economic studies (Gisser, 1983; Koundouri (2004)), I model the basin as a bathtub[12]. Long-term water level in the basin is determined by the total extraction $E = \sum_i e_i$ and natural recharge H during the period. According to the bathtub condition, water depth is the same across the agents in the long run: $l_1 = l_0 + \frac{E-H}{s_b}$ where s_b denotes the size of the basin.

Assume the number of the agents is linear to the size of the basin: $s_b = sN$ where s is a positive parameter. The long-term change of water depth is $l_1 - l_0 = \frac{e_i}{sN} + \frac{\sum_{j \neq i} e_i - H}{sN}$. Therefore, the larger the basin is, the less a single agent's extraction contributes to the overall water depth change.

For simplicity, I normalize $s_w = \frac{1}{2}$ and $s = 1$. Let $h = \frac{H}{N}$. As a result, the short run average water depth in agent i's well is $\bar{l} = l_0 + e_i$, and the long-term water depth in the basin is $l_1 = l_0 + \frac{\sum_i e_i}{N} - h$.

[12]In the real world, basins can have distinct slopes. Users in the upper part of the slope are more sensitive to drop of water level than those in the lower part. The CPR problem remains as long as there are enough pumpers lying in the upper part who are affected by the change of water level. Besides that, in Southern California, most groundwater pumpers are urban water agencies with a value of water much greater than the cost of pumping. Those agents will always stay in the pool and compete with each other for groundwater resource. Therefore, treating the basin as a bathtub will not affect the qualitative results.

In a static setting, agent i selects water consumption q_i and extraction e_i to maximize her payoff:

$$\max_{q_i,e_i} f(q_i) - c(e_i) - p(d)(q_i - e_i) \tag{2.1}$$

Henceforth, I only consider the solution with $q_i > e_i$. In this case, surface water is the marginal source, and agents will keep pumping until the marginal cost of groundwater equals the surface water price. This assumption is reasonable in Southern California because nearly all communities use imported surface water every year[13]. Both equilibrium water consumption and extraction depend on the price of surface water:

$$q_i = f'^{-1}(p(d)); \qquad e_i = \frac{p(d) - l_0}{2}$$

Agent i's optimal level of extraction changes with surface water price and starting level of water depth. Higher surface water price makes it more attractive to withdraw water from the basin; a larger water depth makes it more costly to pump. In the static case, individual extraction is essentially a private process since the water level only changes locally over a short period. The problems with competitive pumping arise for longer time horizons.

This chapter models the externality through increased future pumping cost. Since water moves within the basin, the starting water depth next period is $l_1 = l_0 + \frac{\sum_i e_i}{N} - h$. In a multi-period situation, every agent receives the full benefit from current extraction, but only bears part of the future increased pumping cost. As a result, individual rational choice of extraction leads to "over-pumping" of the basin.

Typically, there is another channel of externality caused by pumping. Given the finite recharge rate of the basin, any agent's extraction increases the possibility of overdrafting and shrinkage of basin storage space. As the risk is also positively correlated with overall pumping, I shut down this channel in the modeling process. However, we will keep it in mind when discussing the incentive of adjudication.

---

[13] According to the Urban Water Management Plan (2015) of the Metropolitan Water District of Southern California, about a half of total water supply in Southern California comes from imported water sources that include the State Water Project and Colorado River.

Another potential problem with competitive pumping is the failure to consider dynamic efficiency. Competitive agents have little incentive to save for future dry years since the overall over-pumping will result a high pumping cost anyway. Intuitively, in an efficient pumping scheme, users should pump less in wet years to save for dry years when the alternative surface water is very expensive. I employ a two-period model to study water users' intertemporal pumping decisions. Weather d is realized in the beginning of each period ($t = 1, 2$), as well as the surface water price $p(d)$ and natural replenishment $H(d)$ as a function of the drought level. $H'(d) < 0$ and $h(d) = \frac{H(d)}{N}$. l_0 is the water depth at the beginning of Period 1; l_1 is the water depth at the end of Period 1 and beginning of Period 2. Agents choose water consumption and extraction for each period after observing the weather condition. The discount factor is 1[14].

State of nature

The first case I will explore is the state of nature when no governing agency controls pumping. Each agent extracts based on her own cost-benefit analysis. The optimization problem is solved backwards. In Period 2, agent i's maximization problem is:

$$\max_{q_{2i}, e_{2i}} f(q_{2i}) - c(e_{2i}) - p(d_2)(q_{2i} - e_{2i}) \tag{2.2}$$

where $c(e_{2i}) = (l_1 + e_{2i})e_{2i}$. I only consider the case when parameter values yield the interior solution with positive surface water purchase. Let the value function of Period 2 be V_{2i}. The Period 1 problem is:

$$\max_{q_{1i}, e_{1i}} f(q_{1i}) - c(e_{1i}) - p(d_1)(q_{1i} - e_{1i}) + \mathbb{E}_d[V_{2i}] \tag{2.3}$$

[14]Since we are discounting the long term (Period 2) payoff, the discounting factor is generally less than 1. I set it at 1 to shut down the influence of discounting, which, if any, should only erode the dynamic efficiency because agents care even less about the future than the present.

where $c(e_{1i}) = (l_0 + e_{1i})e_{1i}$. The solution to the above two-period problem is:

$$q^n_{1i} = f'^{-1}(p(d_1)); \qquad q^n_{2i} = f'^{-1}(p(d_2))$$
$$e^n_{1i} = \frac{2Np(d_1) - h(d_1) - (2N-1)l_0 - M}{4N-1}; \qquad e^n_{2i} = \frac{p(d_2) - l_0 - \frac{E^n_1}{N} + h(d_1)}{2}$$
$$E^n_{1i} = \frac{2Np(d_1) - h(d_1) - (2N-1)l_0 - M}{4 - \frac{1}{N}}; \qquad E^n_2 = \frac{N[p(d_2) - l_0 + h(d_1)] - E^n_1}{2}$$

where $M = \mathbb{E}_d[p(d)]$.

Any reduced extraction in Period 1 will increase water level in Period 2. Due to the structure of the cost function, a dynamic efficient pumping arrangement will encourage an optimal amount of saving by each agent. However, in a competitive case, an agent bears the full cost of saving but only receives part of its benefit since raising the water table generates a positive externality to others. Therefore, in the model, lack of regulation not only leads to more pumping than is sustainable, it also fails to be dynamic efficient. I will validate this argument by a comparison with the socially optimal pumping strategy.

Social planner's problem

An opposite scenario to the competitive pumping allocates pumping decisions to a central authority. Uncertainty to weather remains, but the central planner has all the information she needs and optimizes as social planner. Again, there is a two-period problem:

$$\text{Period 1:} \qquad \max_{q_{1i}, e_{1i}, i=1,...,N} \sum_i \{f(q_{1i}) - c(e_{1i}) - p(d_1)(q_{1i} - e_{1i}) + \mathbb{E}_d[V_{2i}]\} \tag{2.4}$$
$$\text{Period 2:} \qquad \max_{q_{2i}, e_{2i}, i=1,...,N} \sum_i \{f(q_{2i}) - c(e_{2i}) - p(d_2)(q_{2i} - e_{2i})\} \tag{2.5}$$

The Period 2 social planner's problem is the same as the individual agent's problem, since any agent's extraction does not affect others' pumping cost and the world ends at the end of the period. The major distinguishing feature between the social planner and the individual pumper is in Period 1 when the social planner internalizes all the externalities in future cost of pumping. The solution to the two-period problem is:

$$q_{1i}^{sp} = f'^{-1}(p(d_1)); \qquad q_{2i}^{sp} = f'^{-1}(p(d_2))$$
$$e_{1i}^{sp} = \frac{2p(d_1) - h(d_1) - l_0 - M}{3}; \qquad e_{2i}^{sp} = \frac{p(d_2) - l_0 - \frac{E_1^{sp}}{N} + h(d_1)}{2}$$
$$E_{1i}^{sp} = \frac{N[2p(d_1) - h(d_1) - l_0 - M]}{3}; \qquad E_2^{sp} = \frac{N[p(d_2) - l_0 + h(d_1)] - E_1^{sp}}{2}$$

When N is large enough, $E_1^n > E_1^{sp}$ is approximately equivalent to $[M - p(d_1)] + [M - l_0 + 2h(d_1)] > 0$. $M - l_0 + 2h(d_1) > 0$ always holds by construction. Since $M = E_d[p(d)]$, on expectation, $M - p(d_1) = 0$. Therefore, ex ante, competitive pumping leads to a depleted basin. In the short term, it is possible for $p(d_1)$ to be very high due to extremely dry weather. A dynamic efficient pumping scheme may require the agents to pump even more than the competitive level and compensate by reduced extraction in the future. This confirms our speculation that competitive pumping does not provide agents with sufficient incentives to save water for dry years.

Adjudication

Although a social planner can achieve maximal welfare for the group of pumpers as a whole, it is not always feasible to implement an optimal scheme. In a world with heterogeneous pumpers, the central authority may not have the appropriate information to decide the pumping allocation[15]. What's more, it is not clear who can play the role of social planner in particular because of agency problems[16]. Lam (1998) has shown that government systems actually do worse than self-governing irrigation systems in Nepal. The same concern exists among Southern California pumpers (Blomquist, 1992). Adjudication, as a form of

[15]In Gordon (1954), the author mentioned the failure of the international fishery agreement between the United States and Canada that established a fixed-catch limit during the early 1930s. The limit led to a competitive race for fish and over-investment in capital. A similar problems also arose in the Canadian Atlantic Coast lobster-conservation program. To the contrary, also mentioned by the author, in a few places the fishermen have successfully reduced fishing gears and improved income by banding with each other and setting up rules regulating their own operations.

[16]According to Berkes et al. (1989a), there is also an "ideological" reason that some societies subscribe to the idea of freedom of the commons.

self-governance, may also be more acceptable to the local pumpers than the centralized regulation by the state.

Pumpers rely on adjudication to achieve two main outcomes. First, it protects the basin from overdrafting by setting the total annual pumping rights equal to the long-term safe yield of the basin. Second, it avoids competition between the pumpers by assigning an exact amount of pumping rights to each of them.

As each basin devises its own rules, the flexibility of adjudicated rights varies across adjudications. A key source of variation is the benchmark used to decide the pumping rights R. Some basins target the long-term average yield of the basin, i.e. $R = \mathbb{E}_d[H(d)]$. Others use a varying annual yield[17], the so-called operating safe yield, to determine pumping right each year, i.e. $R(d) = H(d)$. Both adjudication rules can achieve sustainability, but they have different short-term implications.

A second dimension of difference worth exploring is the option to save. Some basins allow pumpers to store any unused pumping rights and increase their future rights accordingly. Others strictly execute the assigned pumping allocation, and impose replenishment fees for over-pumping immediately. The savings option can influence agents' intertemporal pumping decisions. In my model, any adjudication achieves sustainability by assumption, but it remains uncertain how the adjudication rules affect dynamic efficiency. I will examine the two dimensions of flexibility by considering the 2×2 cases: long-term average yield versus operating safe yield, and savings versus no savings.

Long-term average yield without savings

Using long-term average yield and not allowing savings seem to be the most rigid type of adjudication. Appropriators face the same upper bound of pumping $r = \frac{R}{N}$ in each period independent of the weather[18]. In Period 2, the agent faces a constrained optimization

[17] To do so, some technical advisor estimates the yield of the basin in next water year before it starts. The estimation is taken as the operating safe yield.

[18] I assume the identical agents share the pumping rights equally. The distribution of adjudicated rights actually does not matter as long as there is a market for pumping rights with minimal friction.

problem:

$$\max_{q_{2i},e_{2i}} f(q_{2i}) - c(e_{2i}) - p(d_2)(q_{2i} - e_{2i}) \text{ s.t. } e_{2i} \le r \tag{2.6}$$

The value function of Period 2 is not smooth at the point that the constraints bind. Taking into account the expected value in Period 2, the agent solves another constrained optimization problem in Period 1:

$$\max_{q_{1i},e_{1i}} f(q_{1i}) - c(e_{1i}) - p(d_1)(q_{1i} - e_{1i}) + \mathbb{E}_d[V_{2i}] \text{ s.t. } e_{1i} \le r \tag{2.7}$$

If neither constraint binds, the problem is the same as competitive pumping. In this chapter, we are interested in cases where adjudication is not trivial. Therefore, I only consider the case where both constraints bind. This is true when natural recharge or adjudicated pumping rights is so limited that, even at the boundary, the marginal cost of pumping is too low to generate any incentive for saving. Water use and extraction in each period are:

$$\begin{aligned} q_{1i}^{l,ns} &= f'^{-1}(p(d_1)); & q_{2i}^{l,ns} &= f'^{-1}(p(d_2)) \\ e_{1i}^{l,ns} &= r; & e_{2i}^{l,ns} &= r \\ E_{1i}^{l,ns} &= R; & E_{2}^{l,ns} &= R \end{aligned}$$

Without doubt, the rigid adjudication rules lead to rigid pumping decisions. Extraction is constant in each period irrespective of surface water availability.

Operating yield without savings

A modification to the rigid allocation above is to use operating yield as the benchmark when deciding annual pumping rights. However, without savings accounts, agents still do not have an incentive to smooth pumping over time. Compared with the first case, the constraint to the maximization problem now varies according to the realized weather condition in the period:

$$\text{Period 1:} \quad \max_{q_{1i},e_{1i}} f(q_{1i}) - c(e_{1i}) - p(d_1)(q_{1i} - e_{1i}) + \mathbb{E}_d[V_{2i}] \text{ s.t. } e_{1i} \le r(d_1) \tag{2.8}$$

$$\text{Period 2:} \quad \max_{q_{2i},e_{2i}} f(q_{2i}) - c(e_{2i}) - p(d_2)(q_{2i} - e_{2i}) \text{ s.t. } e_{2i} \le r(d_2) \tag{2.9}$$

Again, I only consider the case when both constraints bind. Since the basin does not allow savings, the overall extraction only reflects the change of natural recharge. Water use and extraction in each period are:

$$
\begin{aligned}
q_{1i}^{o,ns} &= f'^{-1}(p(d_1)); \qquad & q_{2i}^{o,ns} &= f'^{-1}(p(d_2)) \\
e_{1i}^{o,ns} &= \frac{H(d_1)}{N}; \qquad & e_{2i}^{o,ns} &= \frac{H(d_2)}{N} \\
E_{1i}^{o,ns} &= H(d_1); \qquad & E_{2}^{o,ns} &= H(d_2)
\end{aligned}
$$

Although it seems more flexible, I argue that using operating yield without a savings account actually decreases the overall welfare. Since $H'(d) < 0$, indeed in the constant annual extraction program, groundwater use is less than recharge in wet year and more than recharge in dry years. With operating yield extraction, groundwater use will be less in dry years and more in wet ones. Therefore, agents actually buy more surface water in dry years when it is expensive and less in wet years when it is cheap. The pro-cyclical pattern of groundwater recharge actually undermines the basin's function as drought buffer.

So far, neither adjudication rule provides the agents with the right incentive to use groundwater as drought insurance. That is why it is important to have a savings option with adjudication.

Long-term average yield with savings

In a two-period model with savings allowed, each agent does the cost-benefit calculation with an overall budget constraint. The constrained optimization problem is:

$$
\text{Period 1:} \qquad \max_{q_{1i}, e_{1i}} f(q_{1i}) - c(e_{1i}) - p(d_1)(q_{1i} - e_{1i}) + \mathbb{E}_d[V_{2i}] \tag{2.10}
$$

$$
\text{Period 2:} \qquad \max_{q_{2i}, e_{2i}} f(q_{2i}) - c(e_{2i}) - p(d_2)(q_{2i} - e_{2i}) \;\text{ s.t. }\; e_{2i} \leq 2r - e_{1i} \tag{2.11}
$$

Since the total budget of extraction is fixed, the agent smooths her pumping over two periods such that the difference of marginal pumping cost equals to the difference of price. The solution to the two-period problem is:

$$
\begin{aligned}
q_{1i}^{l,s} &= f'^{-1}(p(d_1)); \qquad & q_{2i}^{l,s} &= f'^{-1}(p(d_2)) \\
e_{1i}^{l,s} &= \frac{N[p(d_1) - h(d_1) - M] + (4N-2)r}{3N-1}; \qquad & e_{2i}^{l,s} &= 2r - e_{1i}^{l,s} \\
E_{1i}^{l,s} &= \frac{N[p(d_1) - h(d_1) - M] + (4N-2)r}{3-1/N}; \qquad & E_{2}^{l,s} &= 2R - E_{1i}^{l,s}
\end{aligned}
$$

Given savings account, pumpers are willing to save in the first period if the price of surface water is low ($e_{1i}^{l,s}$ decreases with $p(d_1)$).

Operating yield with savings

The most flexible case is using operating safe yield as adjudicated rights and allowing savings at the same time. When pumping rights depend on realized weather condition, pumpers are assigned more pumping allocation in wet years than in dry years. The extraction budget is not fixed ex post, motivating the agent to choose the two periods' pumping in a way that not only takes into account the expected surface water price, but also the expected future pumping allocation. The constrained optimization problem is:

$$
\text{Period 1:} \qquad \max_{q_{1i}, e_{1i}} f(q_{1i}) - c(e_{1i}) - p(d_1)(q_{1i} - e_{1i}) + \mathbb{E}_d[V_{2i}] \tag{2.12}
$$

$$
\text{Period 2:} \qquad \max_{q_{2i}, e_{2i}} f(q_{2i}) - c(e_{2i}) - p(d_2)(q_{2i} - e_{2i}) \;\text{ s.t. }\; e_{2i} \le \frac{H(d_1)}{N} + \frac{H(d_2)}{N} - e_{1i} \tag{2.13}
$$

The solution to this problem is similar to the last case:

$$
\begin{aligned}
q_{1i}^{o,s} &= f'^{-1}(p(d_1)); \qquad & q_{2i}^{o,s} &= f'^{-1}(p(d_2)) \\
e_{1i}^{o,s} &= \frac{N[p(d_1) - h(d_1) - M] + (2N-1)(\frac{H(d_1)}{N} + r)}{3N-1}; \qquad & e_{2i}^{o,s} &= \frac{H(d_1)}{N} + \frac{H(d_2)}{N} - e_{1i}^{o,s} \\
E_{1i}^{o,s} &= \frac{N[p(d_1) - h(d_1) - M] + (2N-1)(\frac{H(d_1)}{N} + r)}{3-1/N}; \qquad & E_{2}^{o,s} &= H(d_1) + H(d_2) - E_{1i}^{o,s}
\end{aligned}
$$

Adjudication here also generates an incentive for saving, but when compared with the socially optimal case, the incentive is not enough. When the social planner decides pumping levels, the first derivative of Period 1 total extraction with respect to the surface water price is $\frac{\partial E_1^{sp}}{\partial p(d_1)} = \frac{2N}{3}$. That is always greater than $\frac{\partial E_1^{o,s}}{\partial p(d_1)} = \frac{N}{3-1/N}$, the derivative when pumpers are managed by adjudication with a savings account. The externality still exists since one agent's saving will raise everyone's water level in the second period. Adjudication may successfully limit the amount of extraction and keep the water level stable, but we still have an unsolved problem of how to provide agents with a strong enough incentive to save in wet periods.

Extensions

The simple two-period model has its limitations. The fact that pumping ends in Period 2 may be insufficient for a full comparison of dynamic efficiency across institutions. In the real world, savings accounts can last much longer than two periods, increasing the agents' incentive to save. In addition, the Period 2 equilibrium extraction is solved under a "use it or lose it" situation. That is not a problem when the quantity of pumping rights is specified. However, in looking at the social planner's optimum, something is lost because agents pump more in Period 2, which has an unexpected effect on their Period 1 pumping plan.

Chapter 4 extends the two-period model to an infinite horizon problem. Both sustainability and dynamic efficiency have a different implication in the infinite horizon game than the two-period model. In the steady state, the expected annual extraction from the basin should be equal to its long-term recharge rate under any institution, so sustainability is not defined based on the amount of pumping. Instead, lack of sustainability is associated with a lower steady state water level, which indicates that the basin is exposed to higher risk of depletion. Since the competitive pumpers always have larger incentive to extract than the social planner, the steady state water level under the state of nature should be lower than the socially optimal level. In addition, during adjudication pumpers can select any water level to maintain by scheduling a controlled overdraft or artificial replenishment. The steady state water level in an adjudicated basin should be close to the socially optimum to achieve larger overall benefits. Therefore, I speculate that the competitive case would have lower sustainability than other institutions in the infinite horizon model.

As for dynamic efficiency, it depends on how agents allocate the same amount of steady state extraction across different weather conditions. The social planner's incentive to save in wet years as drought insurance does not change; the agents have an incentive to save but they still suffer from the externality. The competitive case is more complicated. On one hand, pumpers react to the surface water price with little incentive to save; on the other hand, the amount of extraction depends on the water level which is much lower during a drought cycle due to lack of natural recharge. As a result, I anticipate that adjudication still have a problem with dynamic efficiency, but it remains unclear how adjudication works compared with the state of nature.

As for this chapter, I will put aside the difference between this model and an infinite horizon game. In next sub-session, I discuss the hypotheses drawn from the simple two-period model. I will test these hypotheses in the next section.

Hypotheses

Two sets of hypotheses can be drawn from the equilibrium analysis:

Hypothesis 2.1 (Sustainability) *As adjudication generally limits the maximal amount of extraction, I expect adjudicated basins to pump less than unadjudicated ones and hence are more likely to maintain groundwater resources.*

The other hypothesis is related to the dynamic efficiency. I expect the optimal mechanism to have some responsiveness to changing weather conditions. Once again, the first derivative of Period 1 total extraction to the price of surface water is a measure of dynamic efficiency[19]. It shows to what extend agents adjust their pumping plan according to the availability of supplemental water resources.

[19]Weather also affects extraction through natural recharge. Since surface water supply is more sensitive to weather condition than groundwater recharge, I ignore $H'(d)$ and only consider the influence of surface water price.

The first derivatives of Period 1 total extraction over surface water price are as follows:

$$\frac{\partial E_1^n}{\partial p(d_1)} = \frac{2N}{4 - \frac{1}{N}}; \quad \frac{\partial E_1^{sp}}{\partial p(d_1)} = \frac{2N}{3}; \quad \frac{\partial E_1^{l,ns}}{\partial p(d_1)} = \frac{\partial E_1^{o,ns}}{\partial p(d_1)} = 0; \quad \frac{\partial E_1^{l,s}}{\partial p(d_1)} = \frac{\partial E_1^{o,s}}{\partial p(d_1)} = \frac{N}{3 - \frac{1}{N}} \tag{2.14}$$

They satisfy:

$$\frac{\partial E_1^{sp}}{\partial p(d_1)} > \frac{\partial E_1^n}{\partial p(d_1)} > \frac{\partial E_1^{l,s}}{\partial p(d_1)} = \frac{\partial E_1^{o,s}}{\partial p(d_1)} > \frac{\partial E_1^{l,ns}}{\partial p(d_1)} = \frac{\partial E_1^{o,ns}}{\partial p(d_1)} \tag{2.15}$$

As a result, I argue that neither the state of nature nor adjudication generates enough counter-cyclicality of pumping. Within the adjudicated basins, adjudication without the option to save is rigid, because agents do not take into account the price of surface water at all. In the hypothesis of dynamic efficiency, I put adjudication with a savings account in one category and without in another category. Since we only observe the state of nature and adjudication in Southern California,[20] I compare the relative counter-cyclicality of those two institutions:

Hypothesis 2.2 (Dynamic efficiency) *The state of nature generates a larger counter-cyclical pumping pattern than adjudication, and among the adjudicated basins, those without a savings option do not have enough counter-cyclicality.*

2.4 Empirical Analysis

The empirical basis for this study is a collection of depth to water (henceforth well depth) data for 87 wells in 33 Southern California basins. Under the assumption that an aquifer is like a bathtub, the hydrology of a basin satisfies the formula:

$$\Delta\text{Water Level} \times \text{Size of Aquifer} = \text{Total Recharge} - \text{Total Extraction} \tag{2.16}$$

Therefore, the change in the water level in a basin is a monotonic function of recharge and extraction normalized by the size of the basin. In reality, the bathtub condition generally does not hold, so we do not have a unified measure of water level change in one basin. As

[20] In fact, we also observe a third type of institution that a central authority uses tax to regulate agents' pumping behavior (see Orange County Water District). As the tax rate is set such that overall tax revenue equals to the total cost to recharge the basin, an individual agent has the incentive to pump more than the efficient level since the replenishment cost is distributed among all the agents through the uniform tax rate. I save the discussion of that mechanism for later.

an alternative, I look at individual wells in each basin and use the change of well depth as the measure of water level change.

There is no clear geological definition for Southern California as a whole. In this study, I follow the classifications of the DWR's Southern Region Office and include three hydrological regions: South Coast, South Lahontan, and Colorado River. Selection of those regions is reasonable since all adjudicated basins, except for some coastal ones, are in this area[21]. DWR identifies 214 basins or subbasins in Southern California, among which I only select the 59 basins that produce more than 3000 Acre-feet (AF) groundwater per year[22]. The largest basin produces as much as 342,000 AF of groundwater each year, so the lower limit excludes a large number of extremely small basins where a single dominant agent may bear the cost of collective action.

Because of data limitations[23], the period of study is 2000 to 2015. Not all wells have 16 years of well depth readings. For each basin, I only pick the wells with 14 or more years' observation from 2000 to 2015. I keep at most 3 wells for one basin if that basin has more than 3 wells satisfying our requirement. We end up with 33 basins and 87 wells in our sample. Most basins have 2 or 3 wells.

Table 2.1 illustrates the representativeness of our sample. According to the p-values from the t-tests, our sample does not have a statistical significant difference from other large basins ($>$ 3000 AFY) in terms of size, share of agricultural land and population density. It does include more adjudicated basins, consistent with the fact that adjudicated basins are more likely to monitor their water levels. The comparison of the sample basins and the excluded small basins imply that the basins with less than 3000 AFY have significantly different basin characteristics. In particular, they are smaller and less populated, confirming

[21] Coastal basins have a different incentive to adjudicate than inland ones. They are more likely to be threatened by seawater intrusion instead of increasing pumping cost.

[22] The estimates are from DWR California Groundwater Update 2013.

[23] Monitoring effect of water level varies across different agencies. The United State Geological Survey started a comprehensive monitoring program only after 2006. DWR requires local groundwater pumping agencies to submit their well depth data to its database. However, most local agencies read their well depth in very low frequency (annually or biannually) and keep few records for the years before 2000.

our concern that those basins may have a smaller group of pumpers and thus a different groundwater use situation.

	Basins in the Sample	Other >=3000 AFY			Other South Cal. Basins		
Number	33	26			181		
	Mean	Mean	Mean difference	p-value	Mean	Mean difference	p-value
Fraction of adjudication before 2000	0.52	0.23	-0.28	0.03	0.06	-0.45	0.00
Basin size (acres)	135545.27	149605.15	14059.88	0.78	87051.51	-48493.76	0.10
Fraction of ag. land	0.18	0.10	-0.08	0.18	0.03	-0.15	0.00
Population density (per acre)	3.30	2.27	-1.03	0.33	1.05	-2.25	0.00

Table 2.1: Representativeness of the Estimated Sample

Well depth change is our outcome variable and the two main equations we want to estimate are:

$$y_{jit} = \alpha_1 + \beta_1 A_i + \theta_1 \boldsymbol{z_i} + \sigma_{1t} + \epsilon_{1jit} \quad (2.17)$$

$$y_{jit} = \alpha_2 + \beta_2 \boldsymbol{A_i} + \gamma D_t + \delta \boldsymbol{A_i} \times D_t + \theta_2 \boldsymbol{z_i} + \sigma_{2t} + \epsilon_{2jit} \quad (2.18)$$

y_{jit} is change of well depth for well j in basin i at period t. A_i is a dummy which equals to 1 if the basin is adjudicated before 2000 and 0 otherwise. $\boldsymbol{A_i}$ is a vector of institution dummies, which equals to $(1, 0)$ if the basin is adjudicated before 2000 with a savings account, $(0, 1)$ if the basin is adjudicated before 2000 without a savings account, and $(0, 0)$ if it has not been adjudicated before 2000. D_t is a weather dummy which equals to 1 if the period t is a dry period, and 0 otherwise. $\boldsymbol{A_i} \times D_t$ is the cross-term to test the marginal effect of institutions on water level changes during different weather cycles (dynamic efficiency); $\boldsymbol{z_i}$ is a vector of control variables including relevant basin characteristics; σ_t is the time fixed effect; and ϵ_{jit} is the error term. Because error terms for wells from the same basin are generally correlated, they are clustered at the basin level in the regression analysis.

As for the institution variable, the DWR has established the Adjudicated Basins Annual Reporting System where we can find the names of the adjudicated basins and the terms of adjudication. There were 27 court adjudications in California through 2015. Twenty of them occurred in Southern California, and they cover 30 basins. According to Table 2.2, 17 of them have enough well data to be included in our sample. 14 adjudications occurred before 2000 and three afterwards. To avoid the identification problem that arises in our sample because a basin may be unadjudicated before a certain year and then adjudicated afterwards, and to eliminate the immediate effect of adjudication, I use a dummy variable indicating whether a basin is adjudicated before 2000 as our main institution variable[24]. Through the division of basins according to their institution choice at 2000, I compare those basins that are always adjudicated in our sample period with the rest.

For each adjudicated basin, I use the adjudication documents to identify the specific rules adopted by that basin. Some adjudicated basins allow carry-over of unexercised pumping rights while some do not give credit for that. I code the basin as adjudicated with a savings account if its adjudication rule allows for storage of unused pumping rights; otherwise, I code the basin as adjudicated without a savings account. Twelve out of 17 adjudicated basins allow savings.

The primary source of well depth data is California Statewide Groundwater Elevation Monitoring Program; the Water Data Library of DWR also provides well depth observations. I also ask water agencies directly for well monitoring data if CASGEM contained less than three qualified wells in their basin. For each well in our sample, we have scattered readings of water level on dates casually drawn from the 16-year period. Difference between any two readings is one observation of water level change[25]. For instance, the water level on January 1st, 2005 minus the water level on January 1st, 2004 is an observation of one-year water level change. A positive water level change reflects an increase of water table and a negative water level change a decline. In the tests, I only use water level changes over one, two, three or four full years to get rid of seasonality.

The unit of observation in the regression analysis is an individual well. We have a panel dataset since in principle we can observe water level changes of all wells on any time

[24] In our sample, all adjudicated basins were adjudicated before 2000 except for one in 2015. Even if we use the exact treatment (adjudicated or not), our empirical results will not change too much.

[25] Water level change is the same concept as water depth change. A higher water level corresponds to a smaller water depth. So water level changes in the opposite direction to water depth, but in the same scale.

interval between 2000 and 2015. For instance, there should be 365×15[26] observations of 1-year water level change for each well during our sample period. Unfortunately, water level observations occur at low frequency, and we do not always have two readings at a distance of 1 year. We end up with fewer observations than the theoretical number, even when I relax the definition of 1-year water level change to the change between 12 ± 1 months[27].

Table 2.2 presents the summary statistics of the outcome variables that I use in the regression analysis. We have 9172 observations of 1-year well level change in our regression. Among them, nearly a half are from the adjudicated basins, which is close to the fraction of adjudication basins over all sample basins. I also compute 2-year, 3-year and 4-year water level changes. The sample is quite balanced since there are always more than 45% observations from the adjudicated basins.

		Adjudicated before 2000		Not Adjudicated before 2000		Total		Mean(not adj.) - Mean(adj.)	p-value
		Number	Mean	Number	Mean	Total	Mean		
Basin		17		16		33			
Well		45		42		87			
Change of water level (feet)	1-Y	4314	-0.52	4858	-1.87	9172	-1.23	-1.35	0.00
	2-Y	3916	-0.24	4540	-4.15	8456	-2.34	-3.91	0.00
	3-Y	3562	-0.74	4228	-5.81	7790	-3.50	-5.07	0.00
	4-Y	3221	0.65	3927	-7.52	7148	-3.84	-8.18	0.00
Population density (per acre)		4769	3.02	5153	2.67	9922	2.84	-0.35	0.00
Fraction of ag. land		4769	0.04	5153	0.48	9922	0.27	0.44	0.00
Drought index		4769	-1.86	5153	-1.90	9922	-1.88	-0.04	0.59
Precipitation (inches)		4749	0.68	4986	1.01	9735	0.85	0.32	0.00

Note: The unit of observation is well*date.

Table 2.2: Summary Statistics

P-values from the t-tests of water level changes in the adjudicated and unadjudicated basins indicate that for all time intervals I examine, the adjudicated basins have experienced smaller water level decreases compared with unadjudicated ones. This suggests that adjudication does lead to improvement in sustainability. For example, the mean differences imply that the water level drops in the adjudicated basins is on average 1.4 feet less in 1-year interval, 3.9 feet less in 2-year interval and 8.2 feet less in 4-year interval[28]. The difference is

[26]The water level readings are at the daily level. From 2000 to 2015, we can find 365×15 pairs of dates that are at a distance of 1 year. The difference of water levels between each pair of dates is one observation of one year water level change.

[27]I also allow 30-day flexibility for two-, three- and four-year intervals.

[28]The change is not linear because water moves within the basin. The difference between short-term and long-term changes reflects the shape of aquifer and the speed of water movement.

significant both statistically and economically. On average, well levels drop 1.9 feet in the unadjudicated basins each year, while the wells in the adjudicated basins drop 62% less. If we look at 4-year intervals, well levels in the unadjudicated basins on average drops 7.5 feet within 4 years, while they actually increase 0.7 feet in the adjudicated basins.

Table 2.2 also reports the mean of population density, fraction of agricultural land, Palmer drought severity index (PDSI) and monthly precipitation for all observations. The first two variables are at the basin level. DWR divides California into Detailed Analysis Units (DAU) by which it estimates population and size of agricultural land annually. For the purpose of our study, I match DAUs to each basin. There are cases that one basin overlies several DAUs or several basins overlie the same DAU. For each basin, I add up estimates from all DAUs it overlies. Then I calculate the annual growth rate of population and agricultural land using the sums. As I obtain 2010 population and agricultural land size for each basin from another data source (DWR 2013 Update), I apply the growth rate to the 2010 data, and get an annual measure of population and agricultural land size for each basin. The unit of population density is person/acre. As the data shows, on average, the adjudicated basins are more populated and have a smaller proportion of land in agriculture.

The last two variables concern the weather. PDSI is an index that uses temperature and precipitation data to estimate relative dryness. It is at monthly level and only published for two broad regions: Colorado River/South Lahontan and South Coast. As a result, there is very little variation of PDSI across the basins. Therefore, I merely use it to define drought and wet cycles over Southern California. I employ monthly precipitation data at the basin level to control for basin specific weather conditions. The PDSI data I use in the study comes from the National Centers for Environmental Information, and the precipitation data mainly comes from the California Irrigation Management Information System (CIMIS). CIMIS has monthly-accumulated precipitation information for various stations. I associate each basin with the closest station and assign the precipitation figure from that station to the basin. A complementary source comes from the California Data Exchange Center, which has similar monthly precipitation data for different stations. Since the precipitation record may not start until after 2000, we have fewer observations with precipitation data than with other control variables. In general, the drought index does not show any difference between adjudicated and unadjudicated areas, but the more detailed precipitation data shows that on average the adjudicated basins have less rain than the unadjudicated ones.

Two coefficients from the two estimation equations are of particular interest for this research. β_1 measures the average effect of adjudication over the changes of water level across wells from different basins and across different dates. According to Hypothesis 2.1, β_1 should be positive since the adjudicated basins should have greater water level changes due to their limits on extraction.

The other coefficient we care about is $\delta = (\delta_1, \delta_2)$. As the coefficients of the cross-terms of institution and drought dummy, δ_1 and δ_2 measure the effect of institution over the dry-wet year difference of water level changes. The benchmark for the difference-in-difference analysis is counter-cyclicality of the unadjudicated basins, where the agents only react to surface water price. According to Hypothesis 2.2, adjudication with a savings account should be less counter-cyclical than the competitive case, or in other words, it should have a greater dry-wet year difference of water level changes. Furthermore, adjudication without a savings account is expected to result a flat extraction pattern, with an even greater dry-wet year difference. As a result, δ_1 should be positive and δ_2 should be greater than δ_1.

There is a potential problem with endogeneity because basins with severe overdraft might be forced to adjudicate. Even when we choose the institution variable so that the treatment happens before the sample period, we cannot ensure the underlying conditions causing the overdraft do not persist. Omitted variables such as precipitation and urbanization rate might, for example, cause the selection bias in our estimation. A basin with less rain usually has less natural recharge to the aquifer, but it is also more likely to experience drought and then adjudicate. Similarly, a more urbanized basin will have an easier time transferring the adjudication cost to water users, and the urbanized area also has different water demand and natural recharge rate compared with agricultural area.

I use accumulated precipitation, growth of population density and growth of agricultural land ratio to account for the potential effects of weather and human activity. The selection bias may still exist even after controlling for those three variables. However, since a basin with higher propensity to be adjudicated is also more likely to suffer from the factors that cause water level decline, the selection effect, if any, should only bias our estimation results downwards. Therefore, I can safely draw conclusions from the estimated coefficients despite of the endogeneity issue.

In Table 2.3, I test the effect of adjudication over water level changes. Control variables for the basin-level characteristics are included. The effect of adjudication becomes larger than indicated by the summary statistics in all time intervals after adding the controls. For instance, the adjudicated basins now on average experience 0.7 feet increase of water level in one year compared with 1.9 feet drop in the unadjudicated basins. Precipitation has a positive effect in that 1 inch more precipitation in a year raises the water level up about 0.48 feet.

Both population density and agricultural land ratio growth lead to lower water level, implying both urban and rural water use have a negative effect on water level compared with places with less human activities. In 1 year, a one standard-deviation increase of population density growth leads to 0.75 feet decline of water level; a one standard-deviation increase of the change of agricultural land ratio leads to 1.3 feet fall of groundwater. Both effects are significant in magnitude. One may worry that population density and the change in the agricultural land ratio work in opposite directions. I also run regressions with only one of the two variables. The coefficients only change little, implying collinearity is not a concern.

The test of sustainability confirms the effectiveness of adjudication. Even without a central planner or privatization, the agents within a basin can effectively regulate themselves and protect the basin from overdrafting. The role of self-governance on sustainability is crucial. Without adjudication, basins on average experience decline of water level, while those adjudicated basins actually experience rise of water table.

Water level change	(1) 1-year	(2) 2-year	(3) 3-year	(4) 4-year
Adjudication before 2000	2.621**	7.533***	9.445***	14.43***
	(1.098)	(2.119)	(3.012)	(3.800)
Precipitation	0.482*	0.564**	0.523**	0.502***
	(0.249)	(0.231)	(0.204)	(0.181)
Population density change	-19.79***	-20.42**	-10.02	1.315
	(7.210)	(8.154)	(7.880)	(8.960)
Agricultural land change	-139.2**	-37.71	-196.6***	-83.74
	(58.150)	(35.620)	(52.250)	(79.860)
Constant	-6.581**	-15.99***	-22.53***	-30.33***
	(2.879)	(5.489)	(7.656)	(9.297)
Observations	8,771	8,036	7,364	6,729
R-squared	8.5%	14.5%	16.7%	16.9%

Note: Robust standard errors in parentheses are clustered at basin level.
*** p<0.01, ** p<0.05, * p<0.1

Table 2.3: Effect of Adjudication on Water Level Change

Another hypothesis that I test is the dynamic efficiency of the adjudication rules. Since the cyclicality of pumping results from the intertemporal decisions of the agents, we do not want to disturb the estimation by including periods with overlapping dates. Instead, I divide the whole sample period into 3 drought cycles (2001-2004, 2007-2009 and 2012-2015) and two wet cycles (2005-2006 and 2010-2011)[29]. I run panel analysis on the five cycles to check the marginal effect of institution on water level change under different weather conditions.

Since there are not too many variations of adjudication rules in terms of savings account, in the first two columns of Table 2.4, I pool the adjudicated basins as one category. The

[29]According to definition of the National Centers for Environmental Information, a year is in drought if the average monthly PDSI is below -2. I define a period is a drought cycle if it consists of consecutive drought years. Our identification of drought cycles are consistent with other sources such as the United States Department of Agriculture and Taeb et al. (2016).

	(1)	(2)	(3)	(4)
Depend Variable: water level change during hydrological cycles				
Adjudication before 2000	3.785***	2.507**		
	(1.187)	(1.164)		
Adjudication before 2000 & Savings			4.168***	3.503***
			(1.215)	(1.183)
Adjudication before 2000 & No Savings			8.321***	8.563***
			(1.265)	(1.228)
Dummy for drought cycle	-0.727	-13.01***	0.581	-11.24***
	(2.181)	(2.371)	(2.152)	(2.328)
Adjudication before 2000 X Dummy for drought cycle	8.911***	7.868***		
	(1.751)	(1.702)		
Adjudication&Savings X Dummy for drought cycle			2.699	-0.0889
			(2.348)	(2.282)
Adjudication&NoSavings X Dummy for drought cycle			4.461***	0.989
			(1.382)	(1.361)
Length of the cycle	-13.34***	-2.411	-11.47***	-0.555
	(1.461)	(1.642)	(1.454)	(1.633)
Precipitation	0.333***	0.230***	0.336***	0.244***
	(0.0250)	(0.0254)	(0.0256)	(0.0257)
Population density change	12.31***	8.229**	7.923*	2.356
	(4.219)	(4.098)	(4.310)	(4.199)
Agricultural land change	153.5***	13.37	102.6***	-43.82
	(34.64)	(35.18)	(32.99)	(33.77)
Constant	21.31***	4.479	16.02***	-1.305
	(2.923)	(3.207)	(2.799)	-3.085
Cycle fixed effect	N	Y	N	Y
Observations	2,404	2,404	2,404	2,404
R-squared	16.3%	21.9%	16.2%	21.8%

Note: Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.4: Effect of Institution on Cyclicality of Groundwater Extraction

effect of institution persists. Adjudication before 2000 results in higher water level. The estimated coefficient for the cross term is positive, indicating that the difference of water level change between dry and wet cycles is 6.7 feet larger in the adjudicated basins compared with the unadjudicated basins. So, the adjudicated basins do have a less counter-cyclical groundwater use pattern than the unregulated ones.

Column 3 and 4 present the estimation by dividing the adjudicated basins into those with a savings account and those without. The effect of adjudication remains. The sign of cross terms are as expected. In the regression without cycle fixed effect, the marginal effect of adjudication without a savings account is statistically significant. The coefficient for the cross term of adjudication with a savings account is smaller than the coefficient for the cross term of adjudication without a savings account, indicating that adjudication rules with a savings option generate greater counter-cyclicality than the rigid rules.

Several issues remain unsolved for Table 2.4. Both the population density change and agricultural land ratio change have signs that are the opposite of our expectation. Also, after clustering the error term at the basin level, we lose all significance. A better specification of the estimation model is needed to address those issues.

2.5 Conclusion

A rich body of literature has documented self-organized governance on CPR systems around the world. In this chapter, I analyze groundwater management in Southern California and confirm the effectiveness of self-governing institutions in solving the CPR problem. Through adjudication, pumpers in the same basin arrive at a contract that specifies the exact amount each pumper can extract from the basin, as well as rules to monitor and sanction the violations. By looking at water depth of wells located in different basins, I show that the adjudicated basins have greater water level increase or smaller water level decrease than those unregulated ones within the same time period.

My findings have significant real-world implications. Since Elinor Ostrom's pioneering work (Ostrom, 1990; Ostrom, 2002), adjudication of groundwater rights has been considered as a major solution to CPR problem in groundwater basins. In the important case of California, however, this institution rarely diffused to the north of the state. The reason may be more complicated stakes in water rights (for instance in the Central Valley). If so, then my quantitative measure of the effect of adjudication can resolve the uncertainty that the agents face weighing between the *status quo* and the legal settlement. The evidences found in this chapter will help the advocates of self-governance and accelerate institutional change.

In the economic literature on common rights, this work is the first one to evaluate the self-governing institutions in terms of the dynamic efficiency of the CPR system. One concern raised by this chapter is that adjudication does not necessarily enhance the dynamic efficiency of groundwater use. Allowing flexibility in adjudication rules can provide an incentive for the agents to save water in wet years, but adjudication in general generates smaller counter-cyclical pumping pattern than the unregulated state. The fact that individuals governing the CPR may not have enough of an incentive to develop an efficient intertemporal appropriating plan suggests it is worth weighing the trade-off between self-governance and other type of institutions more carefully. Moreover, institutional designers may need to think about the proper mechanism if dynamic efficiency matters a lot for welfare of the community.

A problem remains open: why is adjudication so slow to diffuse. Since the first adjudication (Raymond Basin 1944), only 30 out of 214 basins have adjudicated in Southern California and less than a handfull elsewhere in the State. Given the large benefit it brings, it is urgent to figure out why pumpers in some basins organize themselves and why they fail to do so in other place. The study has to go back to the early stage when the adjudications actually occurred. Work by Ostrom and Blomquist has conducted case studies over several large basins. A further step we can make is to find quantitative evidence for the reasons behind adjudication.

Chapter 3

SURFACE WATER TRADING AND GROUNDWATER DEPLETION IN CALIFORNIA CENTRAL VALLEY

3.1 Introduction

Economists have long argued that markets allocate resources efficiently (A. Smith, 1776; Walras, 1874; Marshall, 1895; Coase, 1960). For example, water markets have been established in many places around the world to cope with water scarcity (Bjornlund, 2003; Bithas, 2008). In California, the property rights that allowed private capture of water from streams to support mining and farming, laid the foundation of water trade (G. D. Libecap, 2007). Moreover, a surface water market should help address the mismatch of historical water rights allocation and current demand within and beyond agriculture. Yet there remain strong reservations in the agricultural community, principally because of fears that water will be "stolen" by urban communities (G. D. Libecap, 2008). Meanwhile, there are also concerns that trading surface water accelerates aquifer depletion since surface water is a substitute for groundwater (Hanak, 2005). These are the focus of this chapter.

How can the surface water market affect the performance of groundwater basins? The answer depends on the severity of common-pool resource (CPR) problem confronting the groundwater system. This chapter investigates this issue using data from agricultural output and water supply in the Central Valley of California. I build a model to establish the implications of surface water trade in a variety of property rights settings for groundwater. I then test which of these conditions apply to California. My analysis shows that the evolution of crop patterns over space and time are consistent with the assumptions that surface and ground water are perfect substitutes in the economy and the groundwater basin is in open access. I then demonstrate that the private trade between agricultural water districts leads to both lower overall social efficiency and unsustainability of the groundwater basin.

For most aquifers, scholars and policy makers only have access to data on surface water consumption at the district level. In particular, all estimates of groundwater consumption are obtained as a residual difference between expected water consumption by activity and realized surface water application. One reason for this is that, as is the case in the Central Valley, most wells are unmetered. To offset this lack of data, I develop a theoretical model that details how crops respond to different property rights regimes. I evaluate the social welfare change when the agricultural economy moves from autarky to water markets, and compare the two regimes with the social planer's optimal allocation. The efficacy of market depends on the marginal cost of groundwater use.

With a high enough pumping cost, the marginal cost of using groundwater equals its marginal return in the economy (henceforth this case will be referred to as the water constraint binds). In this case, if only the high-value users pump groundwater, the surface water market reduces overall reliance on groundwater because low-value farmers will sell their surface water to high-value users and will not pump groundwater to replace the surface water they sold. If the low-value farmers also use groundwater, as long as the water constraint binds, the overall extraction in the economy remains unchanged after reallocating surface water from low-value to high-value users. Under both circumstances, the surface water market is efficient in reallocating resource while not causing extra depletion of the aquifer.

With a low enough pumping cost, the low-value farmers find it still profitable to use groundwater until all their land has been farmed (henceforth this case will be referred to as the land constraint binds). With a surface water market, farmers who have access to groundwater will sell their surface water to farmers who do not and then pump the amount sold off to continue their low-value farming. The rise of a surface water market thus speeds up the depletion of groundwater aquifer and is not necessarily efficient.

The theoretical model establishes the link between market efficiency and the underlying condition of the economy. It is important to note that in this chapter the effectiveness of market solution, or the "social welfare," only depends on whether the water or land constraint binds in the economy. A recent law in California (SGMA 2014) defines the "social optimum" as maintaining the sustainability of the basin (average extraction equals recharge). My model is consistent with the legislation as it accounts for the difference of groundwater depletion rate under different institutions. When a market is inefficient in allocating resources, it leads to lower social welfare because it accelerates the depletion of the aquifer.

I use a micro-level crop choice data published by Kern County Department of Agriculture to test the hypotheses derived from the theoretical model. The dataset includes geocoded crop choice for each plot of farmland in Kern County from 1999 to 2016. Combining the crop choices with water supply data that I collected from various sources allows me to estimate the reaction of individual crop choice to changes of water supply, hence identifying whether the water or land constraint binds in the Central Valley.

The key empirical finding is that fallowing[1] is invariant to surface water supply. It does not change with annual surface water delivery or the extent of water sales. This fundamental invariance implies that whenever the low-value users sell more surface water to high-value users without access to groundwater, they pump more groundwater to satisfy the water demand of their crops. This is consistent with the theoretical predictions of the model only when the land constraint binds and is not consistent with its prediction when the water constraint binds. Therefore, the surface water market in the Central Valley is not efficient in reallocating resource, and it has a negative impact for the sustainability of the basin.

This chapter offers a telling example of the classical theory of the second best (Lipsey and Lancaster, 1956): Without an integrated market for surface and ground water upon the cap-and-trade practice, it would be better to postpone the implementation of a surface water market if the groundwater basin is unregulated. This conceptual framework can extend to any situation where a market is put in place for a private resource that is a substitute to a

[1] There are other reasons why farmers fallow their land. Sometimes a farmer fallows her land for a period as part of crop rotation in order to restore fertility. This chapter concerns fallowing that results from water scarcity. As will shown by the plot-level data, most of the fallowing in the data persists over time, implying that the farmland is no longer actively farmed.

CPR. For example in fisheries, a transferable quota system for certain species will cause less efficient fishermen to sell their quota and transit to technologies that help to catch the non-targeted species, leading to depletion of those species that remain in open access (Squires et al., 1998). The emission trading system also has an unintended substitute effect that exacerbates air pollution. As documented by Martin et al. (2014), firms tend to sell their emission quota and reallocate to regions with less strict environmental restrictions after the implementation of the European Union Emissions Trading System. This results in worse pollution in those unregulated regions and a potential higher global leakage.

The chapter is structured as follows. Section 3.2 reviews the literature on the subject. Section 3.3 provides some necessary background on water markets in the Central Valley of California. Section 3.4 presents the model that illustrates how a surface water market affects the depletion of a groundwater basin. Section 3.5 presents the empirical analysis including the tests on the model implications. The final section concludes.

3.2 Literature Review

This chapter contributes to the literature on water market by revealing the unintended consequence of a surface water market on an open access groundwater system. Brozovic, Carey, and D. L. Sunding (2002), Chong and D. Sunding (2006), Grafton et al. (2012) and many others have written about the efficiency gain from a surface water market without considering its consequences on aquifers. Srivastava, Kumar, and Singh (2009) examined groundwater market in India, noting that it leads to depletion of groundwater tables although it helps small and marginal farmers realize better yields. In response to the 2014 legislation, scholars have been evaluating the cap-and-trade regime of groundwater (Nylen et al., 2017; Bruno 2017[2], 2018[3]; Duym 2018[4]). Culp, Glennon, and G. Libecap (2014) expressed the same concern on restricting groundwater pumping when implementing a water market.

[2] Ellen M. Bruno, “California’s New Groundwater Law and the Implications for Groundwater Markets.” 2017. ARE Update 20.4:1-4. University of California Giannini Foundation of Agricultural Economics.

[3] Ellen M. Bruno, “The Economic Impacts of Agricultural Groundwater Markets.” 2018. ARE Update 21.6: 9-11. University of California Giannini Foundation of Agricultural Economics.

[4] Dirk van Duym, “Water Policy and the Common Pool: Examining Crop Choice in California” 2018

Findings in this chapter echoes Ostrom's exploration of common property management institutions (Ostrom, 1990; Ostrom, Gardner, and J. Walker, 1994; Ostrom and J. Walker, 2000; Ostrom, 2002). According to Ostrom, managing a commons requires defining clear group boundaries, which is also necessary for a market solution to work.

The two closest papers to this one are probably R. E. Howitt (1994) and Knapp, Weinberg, et al. (2003). Those studies focused on California's first public water market in 1990s and reached a similar conclusion that a surface water market accelerates the decline of the water table and the source region only benefits from the market if the groundwater basin is depleted at an efficient rate. This early work mostly depended on county or district level data, and calculated aggregate water demand elasticity to estimate the difference of groundwater extraction under different regimes. My empirical analysis based on micro level crop choice data shows that such estimation is inaccurate as the calculation of aggregate elasticity does not condition on other factors. Instead, I find that crop acreage is actually not sensitive to water supply changes, and the transition of crops is mainly driven by price and spatial influences.

Moreover, previous work generally relied on the accounting model to calculate groundwater extraction (residual of aggregate crop demand minus surface water supply), and requires a strict bathtub assumption for estimation of groundwater depletion rate. My work is based on a theoretical model that lays out how an individual farmer reacts as water supply conditions change and my empirical analysis examines the individual groundwater use decision without relying on the accounting model and the bathtub condition, both of which have been criticized for their inaccuracy.

3.3 Background: Water Market in the Central Valley of California

In 2012, California produced nearly $45 billion in agricultural products, or about one-tenth of the total for the entire nation (Cooley, Gleick, and Wilkinson, 2014). The Central Valley is the center of the state's agricultural production. It consumes around 70% of the state's total water use. How institutions manage that water is critical for the state's future. It also forms a valuable laboratory to understand the interaction between surface and ground water. The marginal value of water use varies dramatically across regions with different types of crops, as well as between agricultural and urban users. Given agriculture's share in total water use and frequent water shortage in the state, economists are promoting water markets to allocate water in a more efficient manner (Murphy et al., 2000; Culp, Glennon, and G. Libecap, 2014).

California's first public water market took off in the early 1990s as an outcome of a prolonged drought. The state's Department of Water Resource (DWR) and the federal Bureau of Reclamation (USBR) conducted a series of dry-year water trade programs, including the California Drought Water Bank examined in R. E. Howitt (1994). According to that paper, about 17% of water purchased by the Bank came from north of the state where surface water was in excess supply, about a half came from farmers who fallowed their low-value crops and a third came from farmers who then increased their groundwater extraction.

Despite the increased overall income and employment documented by Howitt, communities in the source regions have raised concerns about the potential adverse effect of the water market on local economy and groundwater aquifer (Hanak, 2005). By 2002, 22 of the state's 58 counties had issued ordinances that required a permit to export groundwater or to extract groundwater used in substitution for exported surface water (Hanak, 2003). As a result, trade in water across counties may be coming to a standstill.

The resistance to a large-scale water market by agricultural communities continues to this day. California water authorities have still not established a statewide water exchange. However, as the sources of most surface water supply, the state water project (SWP) and central valley project (CVP) actually allow water transfer between their contractors. Local surface water rights owners, for example the City of Bakersfield who owns the primary Kern River water rights, have also been involved in transfer contracts to supply surplus water to their neighbors. Brewer et al. (2008) and R. Howitt and Hanak (2005) report consistent water transfers in California from 1980s to 2000s.

Under the *de facto* loose control, a private water market has emerged as a natural adaptation to water supply imbalance across agricultural water districts. Private water transfers between agricultural districts have increased in response to the decline in surface water delivery. On one hand, districts without groundwater demand additional irrigation water; on the other hand, faced with high prices, districts with groundwater are now willing to sell their surface water entitlement and turn to the alternative water source. The water sold off could be temporary surface water delivery from SWP or CVP, or storage of water that the districts put in the water bank during water surplus period[5].

Water districts with access to groundwater sell tens of thousands of acre feet of surface water to districts without groundwater every year and, as I will show, farmers then extract additional groundwater to replace what they sold off. As a result, the overall farming acreage in the Central Valley has not changed in the last twenty years despite frequent droughts and a large drop in surface water delivery. The overall demand for irrigation water has grown and become less flexible due to a rapid rise in permanent crop acreage. Permanent crops are more water intensive and require irrigation every year. Not surprisingly, the groundwater basins are in critical overdraft across the Central Valley.

In next section, I derive a theoretical framework of how a surface water market affects the groundwater basin's depletion and social welfare. A market can lead to higher social welfare or not, depending on whether it successfully reallocates resource from low-value to high-value users without speeding up the depletion of CPR system. The model is designed to analyze agricultural water use in California Central Valley, and it is easily to be applied to the case including both agricultural and urban users, as well as other situations where a market is put in place for a private resource that is a perfect substitute to a common pool resource.

[5] According to the board meeting memo of Berrenda Mesa Water District in November 5, 2015, its neighboring district, Buena Vista Water Storage District (BVWSD) has offered to sell its 21,000 AF of banked water through a co-managed water bank. Based on an interview with the engineer in BVWSD, it has also sold surface water supply to its neighboring districts in 2014 and pumped water that year to replace the water sold off.

3.4 Theoretical Model: Depletion of Groundwater Basin with Surface Water Market

The decision maker is called a "farmer." It refers to whomever (owner-operator, tenant or landlord) makes the key decisions. In the Valley, due to frequent drought and upstream environmental concerns in recent decades, surface water supplies are highly uncertain. Farmers' residual demands for irrigation water are satisfied by pumping from the Valley's aquifer. The model examines how farmers choose what crops to grow and how much water to pump based on water supply conditions and the suitability of their land to different crops. I use the analysis to compare aggregate extraction under different institutional regimes.

Water supply

I consider a two-period, no-discounting, agricultural economy where water is the key input in production. For simplicity, all farms are of equal size, D[6], and both annual and permanent crops require 1 unit of water. Therefore, every farmer demands D units of water to fully irrigate her land. A farmer may use water from up to two sources: surface and ground water. The two are perfect substitutes to each other. I assume a farmer always has unsatisfied water demand after using up her own surface water supply.

I assume that surface water (W^s) is delivered each period by an outside agency in equal quantity to each farm[7]. That amount depends on the realized state s. $s \in \{H, L\}$ where H denotes a wet year and L denotes a dry year. The realized state in each period is i.i.d. from a binary distribution: $\Pr(W^s = W^L) = q$ and $\Pr(W^s = W^H) = 1 - q$. As surface water is generally cheaper than groundwater, I normalize the cost of surface water to 0.

[6]The model ignores any effect of the size of farm or identity of farmer. Tests of the theory are also robust at farm, plot or acre level despite different degrees of measurement error. Although big farms might enjoy an advantage in capital investments or in moving water around, the organization of water districts mitigates this advantage to a large extent. In particular surface water allocation is per acre based so that farms of various sizes have equal rights to water. See the empirical analysis later for more evidence.

[7]Surface water delivery per acre actually varies across water districts as their water rights per acre differ. As I will show in the model results, the spatial variation of surface water supply does not affect the equilibrium outcome in the regime with a social planner or a surface water market since surface water will always be reallocated to high-value farmers. In the autarky equilibrium, farmer with more surface water rights can plant more permanents. Both model implications are further confirmed by the empirical tests.

Groundwater is pumped from the aquifer at a per unit cost $c^g > 0$[8]. It is a CPR, so in the absence of regulation, everyone with access to groundwater can extract as much as they want up to their well's capacity (we assume that well capacity does not bind). Because of the externalities of CPR use, extraction has a social cost as well. The social cost includes future increased pumping lift and associated energy consumption due to a lower water table. It also includes the cost of drilling deeper wells as groundwater may become unreachable with current wells. There are also important environmental impacts from rapid depletion of the aquifer like land subsidence and increased water salinity. For now, I model all these costs in a reduced form. I assume the social cost is paid each period as a function of that period's aggregate extraction and is shared equally per acre. The overall extraction E produces a social cost $g(E)$ with $g'(E) \geq 0$ and $g''(E) \geq 0$. As $g(.)$ is a monotonic function of E, I make no specific assumption about $g(.)$. Instead, I use E to measure the social cost.

Farmers (and farms) can be divided into two subgroups: those who only use surface water as F^s and those who have access to groundwater as F^g.

Crop choice

In each period, each farmer decides between an annual crop (a) and a permanent crop (p). The permanent crop requires a one-time fixed cost c^o to plant, which captures the investment needed before a harvest can be brought in[9], and pays back $r^p \in (\frac{1}{2}c^o, c^o)$ every period. The annual crop requires no fixed cost to grow and pays back r^a each period. The permanent crop needs to be irrigated in both periods to have a return in the second period (otherwise the crop dies and must be replanted).

The return of annuals (r^a) and the fixed cost of planting permanent crops (c^o) do not vary across space or time, while the return of permanent crops differs over space. r_i^p reflects the heterogeneity of land quality across farms. I relabel the agents such that $r_i^p > r_j^p$ if

[8] Pumping depth varies across the basin, so does the pumping cost. I leave this aside because how the individual pumping cost varies only affects the identify of the marginal groundwater user. It has no influences on the comparison of different regimes in the model.

[9] It takes 7-10 years for pistachio trees to reach significant production; almonds start to bear in the third year and reach full production after 5-6 years.

$i < j$ (farmer i has a farm that is more productive in permanent crops than farmer j if $i < j$). I assume that there is a farmer i^*, such that for all $i > i^*$, the average two-period return of permanent crops is lower than the return of annuals: $r_i^p - \frac{1}{2}c^o < r^a$ and for all $i \leq i^*$: $r_i^p - \frac{1}{2}c^o > r^a$. I also assume $c^g < r^a$, therefore it is profitable for all farmers to use groundwater[10].

I denote those with index $i > i^*$ as group F^a since they always prefer annual to permanent crops. For those $i \leq i^*$, they belong to group F^p since they prefer permanents to annuals if they receive enough water supply.

Recall that the farmers also differ by their access to groundwater. The land quality and water supply conditions produce four types of farmers (by slightly abuse of the notation, F also denote the farmland by the farmers):

1. F^{sa}: annual crop farmers restricted to surface water. $F^{sa} = F^s \cap F^a$;
2. F^{sp}: permanent crop farmers restricted to surface water. $F^{sp} = F^s \cap F^p$;
3. F^{ga}: annual crop farmers with access to groundwater. $F^{ga} = F^g \cap F^a$;
4. F^{gp}: permanent crop farmers with access to groundwater. $F^{gp} = F^g \cap F^p$.

There are m^{sa}, m^{sp}, m^{ga} and m^{gp} farmers in each group. I assume the number of groundwater users $m^g = m^{ga} + m^{gp}$ is large, so the classic CPR problem arises.

Surface water market

The surface water market allows agents to exchange surface water. As there is no product differentiation, I assume the sellers are involved in Bertrand competition, and water's transfer price thus equals the opportunity cost for sellers. If the sellers only use surface

[10] A farm with land quality low enough ($\max\{r^a, r_i^p - \frac{1}{2}c^o\} < c^g$) can only operate in the autarky regime. With an opportunity to trade, the farm should sell its surface water rights and exit since overall surface water is in shortage. To keep a consistent count of farmland, my model only considers active farmland with high enough quality that using groundwater is profitable in some situation. Adding low-quality land in my model will increase the efficiency gain from a surface water market.

water, the price of water equals the return of using water on their own land. If the sellers pump groundwater, the price equals the pumping cost c^g plus whatever social cost they individually have to bear.

Timing

In each period, events unfold as follows: First, every farmer observes the realized state of surface water supply. Each farmer then decides what to plant. For permanent crops, in Period 1, she decides what acreage to plant and in Period 2, she determines the fraction of existing crops to irrigate. For annual crops, she decides what acreage to plant for the current period. Second, if there is a water market, farmers can trade for surface water. Third, farmers may pump groundwater to irrigate her crops after using up their surface water supply. Finally, every groundwater user pays an equal share of the social cost.

I examine three regimes in this model. In the first regime, a social planner runs all the farmland together. He decides the overall extraction and crop choice to maximize the total social welfare. The second regime is autarky. Each farmer has her own water supply, and water trade is prohibited. In the third regime, I introduce a market where farmers can trade their surface water. Groundwater remains open access in all cases.

I start with the social planner:

Social Planner

The social planner (SP) runs all farmland together. He can allocate the surface water wherever he wants, although the groundwater can only be applied locally[11]. His endowment is therefore $\mathbf{D} = mD$ of farmland and surface water supply $\mathbf{W}^s = mW^s$.

Social welfare in this model is defined as the total profit from the crops minus the cost of

[11] In a world where the supply of surface water is higher than the demand from regions without access to groundwater, optimality achieves if the social planner moves water to irrigate all high-quality land. This is not necessarily true when surface water supply is low relative to the demand of farmland without groundwater. Some high-quality land might remain fallowed even when all surface water is supplied to no groundwater area (efficiency will require moving some groundwater as well). The Central Valley is the former case.

extraction. At period t, it is:

$$R_t = r_t^p N_t^p + r^a N_t^a - g(E_t) - c^g E_t \tag{3.1}$$

where r_t^p is the average return on permanent crop land that sums up to N_t^p. In each period t, SP chooses a portfolio (N_t^a, N_t^p) of annual and permanent crops subject to the land constraint $N_t^a + N_t^p \leq \mathbf{D}$. Because it is lower cost, SP will always use all the surface water before pumping groundwater. Extraction of groundwater equals the residual demand for water: $E_t = N_t^a + N_t^p - \mathbf{W}_t^s$.

I solve the SP's problem backward. In Period 2, SP maximizes social welfare by choosing N_2^a and N_2^p:

$$\text{Period 2:} \quad \max_{N_2^a, N_2^p} R_2 = r_2^p N_2^p + r^a N_2^a - g(E_2) - c^g E_2 \tag{3.2}$$

with $E_2 = N_2^a + N_2^p - \mathbf{W}_2^s$.

Since it does not pay to grow new permanent crops in Period 2 ($r_i^p < c^o$), Period 2's permanent crop is subject to a resource constraint: $N_2^p \leq N_1^p$. Meanwhile, since permanent crop land F^p yields higher return than annual crop land F^a, SP always irrigates the existing permanent crops first: $N_2^P = N_1^P$ whenever $N_2^a > 0$.

SP's crop choice problem is equivalent to an optimal extraction problem. He faces two sets of constraints when choosing how much groundwater to extract. Extraction has an upper bound from the land constraint:

$$\text{Land Constraint:} \quad E_2 \leq \mathbf{D}^s = \mathbf{D} - \mathbf{W}_2^s \tag{3.3}$$

There is also a water constraint that SP will not pump at a higher cost than the return to groundwater. Depending on the marginal use of water, it needs to either satisfy a water constraint (3.4) or equalize marginal cost and marginal return (3.5):

$$c^g + g'(E_2) \leq r^a \qquad \text{when} \quad N_2^a > 0 \tag{3.4}$$

$$or \quad c^g + g'(E_2) = r_2^p > r^a \quad \text{when} \quad N_2^a = 0 \tag{3.5}$$

Three cases arise in Period 2:

1. If surface water satisfies the demand from permanent crops, SP will pump to irrigate annuals.

2. If surface water is not enough for all permanents but c^g is low enough that it pays to plant annuals with groundwater, SP will irrigate all permanents first and then apply groundwater on the annuals.

3. If surface water is not enough for all permanents and c^g is large enough that it does not pay to plant annuals with groundwater, SP will irrigate permanent crops with groundwater until the marginal cost equals the marginal return.

For the first two cases, the marginal crop is annuals. The water constraint (3.4) matters so that the marginal cost of using groundwater is equal to or below the marginal return of annuals. For the third case, the marginal crop is permanents. Constraint (3.5) matters: the marginal cost of using groundwater equals the marginal return on farmland i after all land with quality higher than i is irrigated.

The model also has implications for the SP's decisions given that surface water supply varies. Indeed if groundwater is cheap SP grows annuals in both wet and dry years. But if groundwater is expensive to pump SP may decide to grow annuals only in wet years or even to never grow annuals. As we will see in the empirical section, in the Central Valley, substantial vegetables and field crops are harvested every year. That implies that annuals are always the marginal crop, and henceforth I focus on that case.

When annual crops are at the margin ($N_2^a > 0$), either the land (equation 3.3) or water constraint (equation 3.4) binds in equilibrium. When groundwater is cheap, the land constraint binds. In other words, the social planner farms all land because the basin's sustainability is not a concern. In a water deficit state like California, fallowing is observed constantly in the Valley. Therefore, I consider the solution with a binding water constraint and leave the land constraint case to further discussion.

In Period 2, as the water constraint always binds, groundwater extraction is the same in dry and wet years: $E_2 = g'^{-1}(r^a - c^g)$. All permanent crops are irrigated, and therefore the size of permanent crops remains unchanged: $N_2^p = N_1^p$. Any residual water goes to annuals: $N_2^a = W_2^s + E_2 - N_2^p$. For a given acreage of farmland, marginal cost of pumping is higher in dry years than wet years because of lower surface water supply. As a result, some annual crop land that is actively farmed in wet years will turn to fallowing in dry years.

In Period 1, SP expects to irrigate all permanent crops in Period 2. He chooses N_1^p and N_2^p to maximize the expected two-period sum of social welfare:

$$\text{Period 1:} \quad \max_{N_1^a, N_1^p} R_1 + \mathbb{E}(R_2) = (2r_1^p - c^o)N_1^p + r^a(N_1^a + \mathbb{E}(N_2^a)) - 2g(E) - 2c^g E \qquad (3.6)$$

Given that all permanent crops will be irrigated in Period 2, SP grows permanents on all F^p land since the average return is higher than annuals ($r_1^p - \frac{1}{2}c^o > r^a$): $N_1^p = m^g D$. Water constraint always binds so pumping is constant: $E = E_1 = E_2 = g'^{-1}(r^a - c^g)$. Residual water after satisfying demand of permanents goes to annual crops: $N_1^a = W_1^s + E - N_1^p$.

Only annual crop land is fallowed in either period. Since permanent crops are more valuable than annual crops, the social planner reallocates some surface water from F^a to F^{sp} to ensure irrigation of the high-value crops. F^{sa} land is fallowed, some of the F^{ga} land is also fallowed because the marginal cost of pumping has already reached the marginal return of annual crops (water constraint binds).

In summary, the overall extraction, crop acreage and social welfare in the social planner's case are:

$$E^{SP} = g'^{-1}(r^a - c^g) \qquad (3.7)$$

$$N_t^{p,SP} = m^p D \qquad (3.8)$$

$$N_t^{a,SP} = W_t^s + E^{SP} - N_t^p \qquad (3.9)$$

$$R_t^{SP} = \sum_{i \in F^p} r_i^p D + r^a N_t^{a,SP} - c^o N_t^{p,SP} \mathbb{1}\{t = 1\} - g(E^{SP}) - c^g E^{SP} \qquad (3.10)$$

Autarky

Under autarky, farmers choose a crop depending on their water supply and land quality. Therefore, I characterize the strategy of the four types of farmers separately.

Surface water only annual crop farmer: F^{sa}

F^{sa} only uses surface water and prefers annual crops. For annuals, the farmer's decision is independent in each period. As the return of the annual crop is positive, F^{sa} grows annual crops up to her surface water supply each period:

$$\text{For farmer } i \in F^{sa}: \quad n_{ti}^{p,A} = 0; \quad n_{ti}^{a,A} = W_t^s \tag{3.11}$$

Surface water only permanent crop farmer: F^{sp}

F^{sp} prefers permanent crops over annuals if there is enough water to secure the second period irrigation. Since she has no access to groundwater and the surface water supply varies over time, the farmer has to choose a portfolio of crops that deals with the supply risk of irrigation water.

There is a risk-free acreage of permanent crops, W^L, that the farmer can always irrigate. If $W_1^s = W^L$, she can plant at most W^L permanents, and there is no irrigation water risk because $W_2^s \geq W^L$. If $W_1^s = W^H$, she chooses the amount of permanents crops $n_{1i}^p \in [W^L, W^H]$ to maximize her expected two-period payoff:

$$\max_{n_{1i}^p} n_{1i}^p(r_i^p - c^o) + (W^H - n_{1i}^p)r^a + qW^L r_i^p + (1-q)[n_{1i}^p r_i^p + (W^H - n_{1i}^p)r^a] \tag{3.12}$$

Note that, the maximal amount of permanent crops the farmer can irrigate in Period 2 when the state is low is W^L.

The problem takes one of the two corner solutions:

$$n_{1i}^p = \quad W^H \quad \text{if } (2-q)(r_i^p - r^a) - c^o > 0 \tag{3.13}$$

$$n_{1i}^p = \quad W^L \quad \text{if } (2-q)(r_i^p - r^a) - c^o < 0 \tag{3.14}$$

When the chance of low water supply, q, is large enough: $q > 2 - \frac{c^o}{r_i^p - r^a}$, the expected future return is so low that the farmer prefers the risk-free solution $n_{1i}^p = W^L$. When $q < 2 - \frac{c^o}{r_i^p - r^a}$, the expected future return is large enough that she is willing to bear the risk $n_{1i}^p = W^H$.

It is reasonable to assume $q > 2 - \frac{c^o}{r_1^p - r^a}$ in this model – at least for California, where droughts hit frequently. More generally, if we consider the second period as a longer horizon representing the lifetime of a real permanent crop, it is likely that q has a high value. As a result, every permanent crop farmer i^{sp} chooses to grow W^L acreage of permanents in Period 1, and uses extra water to grow annuals whenever it is available:

$$\text{For farmer } i \in F^{sp}: \quad n_{ti}^{p,A} = W^L; \;\; n_{ti}^{a,A} = W_t^s - W^L \tag{3.15}$$

Groundwater users: F^{ga} ***and*** F^{gp}

Groundwater users are considered together since they affect each other through the negative externality of extraction. As the cost of pumping c^g is uniform for all pumpers and every groundwater user takes the same fraction $\frac{1}{m^g}$ of the social cost, the marginal cost of using groundwater is the same across all agents. In equilibrium, the aggregate extraction E_t^A in period t is where the lowest marginal return of the pumpers equals the marginal cost of using groundwater at that level.

The farmer's extraction decision depends on the social cost. Three cases arise:

If the social cost shared by each farmer is negligible: $\frac{1}{m^g} g'(m^g(D - W^s)) < r^a - c^g$, every groundwater user pumps. The land constraint binds for all groundwater users, and the equilibrium outcome in the economy is that:

$$\text{For farmer } i \in F^{gp}: \quad n_{ti}^p = D; \;\; n_{ti}^a = 0; \;\; e_{ti} = D - W_t^s \tag{3.16}$$

$$\text{For farmer } i \in F^{ga}: \quad n_{ti}^p = 0; \;\; n_{ti}^a = D; \;\; e_{ti} = D - W_t^s \tag{3.17}$$

If the social cost taken by each individual is moderate: $\frac{1}{m^g} g'(m^{gp}(D - W^L)) < r^a - c^g < \frac{1}{m^g} g'(m^g(D - W^s))$, it is profitable for all permanent crop farmers to use groundwater but only a fraction of annual crop farmers find it worth pumping. The water constraint binds. The marginal groundwater user is always an annual crop farmer, therefore the equilibrium aggregate extraction in the economy is constant: $E^A = g'(m^g(r^a - c^g))$. Permanent crop farmers F^{gp} pump to irrigate all their land and annual crop farmers F^{ga} pump extra water as well. Without loss of generality, I assume smaller i pumps first if several agents have the same marginal return[12]. Then there are two marginal annual crop farmers i^L and i^H that $c^g + \frac{1}{m^g} g'(\sum_{i \in F^g, i \leq i^L}(D - W^L)) = r^a$ and $c^g + \frac{1}{m^g} g'(\sum_{i \in F^g, i \leq i^H}(D - W^H)) = r^a$, who correspond to the highest i who pumps in dry and wet years respectively. The equilibrium outcome of the economy is that:

$$\text{For farmer } i \in F^{gp}: \quad n^p_{ti} = D; \; n^a_{ti} = 0; \; e_{ti} = D - W^s_t \tag{3.18}$$

$$\text{For farmer } i \in F^{ga} \quad n^p_{ti} = 0 \text{ and for} \tag{3.19}$$

$$i \leq i^L: \quad n^a_{ti} = D; \; e_{ti} = D - W^s_t \tag{3.20}$$

$$i^L < i \leq i^H: \quad \begin{cases} n^a_{ti} = D; \; e_{ti} = D - W^H_t & \text{if } W^s_t = W^H_t \\ n^a_{ti} = W^s_t; \; e_{ti} = 0 & \text{if } W^s_t = W^L_t \end{cases} \tag{3.21}$$

$$i > i^H: \quad n^a_{ti} = W^s_t; \; e_{ti} = 0 \tag{3.22}$$

In this case, the marginal groundwater user farms annual crops. But which farmer is marginal changes due to the variation in surface water supply. Given the acreage to irrigate, the marginal cost of using groundwater is lower in wet years than dry years thanks to more surface water supply. Therefore, more annual crop farmers can use groundwater in wet years: $i^H > i^L$ and less need to fallow their land.

If the social cost is sufficiently large: $\frac{1}{m^g} g'(m^{gp}(D - W^L)) > r^a - c^g$, only permanent crop farmers use groundwater. Similar to when the marginal pumper is an annual crop farmer, there will be a marginal groundwater user who always grow permanents on all her land,

[12]Since annual crop farmers are assumed to have the same marginal return, it could also be the situation that they all use some groundwater and fallow a fraction of crops. How groundwater extraction is allocated among the annual crop farmers does not affect the outcome of the model as we only care about the aggregate volume.

and farmers with lower quality land fallow part of their land just like the surface water only farmers. I will discuss this case in detail when introducing the surface water market.

I mainly consider the first two cases when the marginal groundwater user is an annual crop farmer because, for the last half century at least, a large fraction of annual crops in the Central Valley are irrigated using groundwater.

The extent of fallowing in the autarky case depends on each farmer's water supply condition. For F^s, $D - W^H$ acres of land are never used due to lack of water. They grow $W^H - W^L$ more acres of annuals in wet years and fallow that land in dry years. F^{gp} farmers never fallow because the permanent crops make pumping worthwhile. If the social cost is negligible, F^{ga} farmers do not fallow since the pumping cost c^g is smaller than the return of annuals r^a. When the social cost is large enough, some F^{ga} farmers find using groundwater too expensive. They only use surface water to irrigate their crops and fallow their surplus land as the surface water only farmers.

When the social cost is negligible (land constraint binds), the overall extraction, crop acreage and social welfare in the economy are:

$$E_t^A = m^g(D - W_t^s) \tag{3.23}$$

$$N_t^{p,A} = m^{sp}W^L + m^{gp}D \tag{3.24}$$

$$N_t^{a,A} = m^{sa}W_t^s + m^{sp}(W_t^s - W^L) + m^{ga}D \tag{3.25}$$

$$R_t^A = \sum_{i \in F^{sp}} r_i^p W^L + \sum_{i \in F^{gp}} r_i^p D - c^o N_t^{p,A} \mathbb{1}\{t = 1\} + r^a N_t^{a,A} - g(E_t^A) - c^g E_t^A \tag{3.26}$$

When the marginal groundwater user is always an annual crop farmer (water constraint binds), the overall extraction, crop acreage and social welfare in the economy are:

$$E^A = g'^{-1}(m^g(r^a - c^g)) \tag{3.27}$$

$$N_t^{p,A} = m^{sp}W^L + m^{gp}D \tag{3.28}$$

$$N_t^{a,A} = m^a W_t^s + m^{sp}(W_t^s - W^L) + E^A - m^{gp}(D - W_t^s) \tag{3.29}$$

$$R_t^A = \sum_{i\in F^{sp}} r_i^p W^L + \sum_{i\in F^{gp}} r_i^p D - c^o N_t^{p,A}\mathbb{1}\{t=1\} + r^a N_t^{a,A} - g(E^A) - c^g E^A \tag{3.30}$$

We now compare the autarky and the social planner's outcomes to see where the inefficiency comes from.

Autarky vs. Social planner

The social optimal extraction is[13] $E^{SP} = g'^{-1}(r^a - c^g)$. Most farmers in the Central Valley have access to groundwater, so the overall extraction under autarky exceeds the social optimum ($E^A > E^{SP}$) when either the land or water constraint binds[14]. Under both situations, all permanent crop farmers with access to groundwater F^{gp} will pump and fully irrigate their land and annual crop farmers F^{ga} pump the extra water until the corresponding constraint binds.

The acreage of permanents under autarky is $N_t^{p,A} = m^{sp}W^L + m^{gp}D$, which is smaller than the social planner's case: $N_t^{p,SP} = m^p D$. On the other hand, the acreage of annuals is larger than in the social planner's case since the overall water use is higher: $N_t^{a,A} = E^A + W_t^s - N_t^{p,A} > E^{SP} + W_t^s - N_t^{p,SP} = N_t^{a,SP}$.

The overall crop choice and groundwater extraction under autarky both deviate from the social optimum. Autarky's inefficiency has two sources. One is the CPR problem: ground-

[13]Recall section 4.1. This is the outcome when the water constraint binds in the social planner's case. If the social planner's land constraint binds, the socially optimal extraction will be larger than groundwater demanded by all groundwater users in the autarky regime: $E^{SP} > m^g(D - W^s) = E^A$. Thus, sustainability of the basin is not a concern and inefficiency of the autarky regime comes from the rigidity to move water around.

[14]When the water constraint binds, the overall extraction under autarky satisfies: $c^g + \frac{1}{m^g}g'(E^A) = r^a$. The overall extraction with the social planner satisfies: $c^g + g'(E^{SP}) = r^a$. Since $g''(.) > 0$ and $m^g \gg 1$, we have $E^A > E^{SP}$. As for the case when land constraint binds, it is possible that $E^{SP} > E^A$ if the social cost is low and the size of land without access to groundwater is large. Neither is true in the Central Valley.

water users only bear a fraction of social cost, leading to a higher level of extraction than the social optimum. The other comes from the resource misallocation in the economy: some farmers with low productivity r^a are able to produce using surface water, while some farmers with high productivity $r_i^p > r^a$ can not fully utilize their land because they have no access to groundwater. I calculate the inefficiency of autarky in this case:

$$\begin{aligned} R^{SP} - R^A = \quad & g(E^A) - g(E^{SP}) - (E^A - E^{SP})(r^a - c^g) + \\ & \sum_{i \in F^s \cap F^p} (D - W^L)(r_i^p - r^a) \end{aligned} \tag{3.31}$$

The first line in the RHS measures the distortion from the common pool (the increased social cost minus the return of using the extra water to grow annuals). The second line in the RHS measures the distortion from resource misallocation, which is the gain that would arise if water in the annual crop land was used to grow more permanents. Next, I introduce a surface market in the autarky model and examine how it affects social welfare.

A market in surface water

With the market, farmers can trade in surface water. The opportunity cost of selling one's surface water allocation is the return from farmland or the cost of pumping groundwater. The market's efficiency depends on the identity of marginal groundwater user.

If the marginal groundwater user is a permanent crop farmer, annual crop farmers do not pump and are willing to sell their surface water. Indeed, permanent crop farmers are willing to pay more than the return of annuals: $p^w > r^a$. Moreover, permanent crop farmers with lower return than the marginal farmer will also sell their surface water, since their marginal return from water is lower than the marginal cost of using groundwater. Permanent crop farmers with high value are potential buyers of the surface water. In equilibrium, the price for surface water equals to the marginal cost of using groundwater, and the marginal permanent crop farmer's return is such that: $r_i^p = c^g + \frac{1}{m^g} g'(iD - W^s)$.

In this case, the water market leads to less groundwater extraction than autarky. Under autarky F^{gp} farmers can only use their own surface water and must pump groundwater, while with a market they buy the cheaper surface water and pump less. When the cost of using groundwater is high enough, the surface water market is both efficient and preserves sustainability of the common-pool system. Unfortunately, it does not seem this case has ever held in California. Instead, the Central Valley suggests that the marginal groundwater user is always an annual crop farmer.

Water constraint binds

If the water constraint binds, the opportunity cost of using groundwater equals the return to planting annuals (r^a). At a price of r^a, F^{sp} farmers will use the market to make up for any deficiency in surface water. The sellers are all annual crop farmers (both F^{sa} and F^{ga}). Because the water constraint binds, the cost of pumping water is higher than r^a, thus annual crop farmers will not pump groundwater to replace surface water they sell. Instead they will fallow.

In equilibrium, extraction E^M remains the same as under autarky. Buyers of water now have a secured water supply, so they will grow permanents on all their land. The overall extraction and crop acreage in the economy are:

$$E^M = g'^{-1}(m^g(r^a - c^g)) \tag{3.32}$$

$$N_t^{p,M} = m^p D \tag{3.33}$$

$$N_t^{a,M} = mW_t^s + E^M - m^p D \tag{3.34}$$

I calculate the welfare gain with surface water market at Period 2 (Period 1 is similar except for an extra term of the fixed cost in planting permanent crops):

$$R^M - R^A = \sum_{i \in F^{sp}} (D - W^L)(r_i^p - r^a) > 0 \tag{3.35}$$

As a result, the surface water market improves social welfare since it reallocates water from low to high value users. If I compare the market with the social planner's case, the acreage of permanent crops is the same but more groundwater is used on annual crop land. In this case, the market solves the reallocation problem, but it does nothing to attack the CPR problem if it arises under autarky.

The size of fallowing in the economy changes with surface water delivery in this case:

$$N_t^{f,M} = mD - mW_t^s - E^M \tag{3.36}$$

Permanent crop farmers purchase surface water to irrigate their crops; therefore, the size of permanent crop land is not sensitive to the realized surface water supply. However, annual crop farmers who sell water to the permanent crop farmers fallow more land in dry years since they receive less surface water supply and sell more water.

Land constraint binds

If the land constraint binds under autarky, the marginal cost of using groundwater water is $c^g + \frac{1}{m^g} g'(E^A) < r^a$. The cost of pumping is less than the opportunity cost of surface water users who plant annual crops. F^g farmers who sell their surface water, pump extra water to replace it. Without loss of generality, I assume the land constraint still binds after the water trade. Therefore, water is only sold out by groundwater users, and the price out of a Bertrand competition is below r^a.

Farmers without groundwater have an opportunity cost equal to or above r^a and are unwilling to sell at the prevailing price. In fact, all surface-water-only farmers are potential buyers of water. Since water price $p^w < r^a$, F^{sp} farmers purchase water to secure irrigation of their permanent crops, and F^{sa} farmers purchase water to grow annuals.

The surface water market leads to higher extraction, since more farmland will receive irrigation. The overall extraction and crop acreage in the economy are:

$$E_t^M = m(D - W_t^s) \tag{3.37}$$

$$N_t^{p,M} = m^p D \tag{3.38}$$

$$N_t^{a,M} = m^a D \tag{3.39}$$

Without loss of generality, I calculate the welfare change with surface water market at Period 2 when a drought hits:

$$R^M - R^A = g(E^A) - g(E^M) + \sum_{i \in F^{sp}} (D - W^L)(r_i^p - c^g) + \sum_{i \in F^{sa}} (D - W^L)(r^a - c^g) \quad (3.40)$$

Although the surface water market does induce trade from low-cost pumpers to high-value users, the efficiency gain from water reallocation is not realized since the sellers just pump more groundwater. If the increased social cost with a surface water market $|g(E^A) - g(E^M)|$ is larger than the return of extra crops grown by the surface-water-only farmers (the last two terms in Equation (3.40)), the distortion from CPR problem dominates, and the market produces an outcome worse than autarky.

By assumption, the marginal social cost of extraction is higher than the net return of annuals: $g'(E^M) > g'(E^A) > g'(E^{SP}) = r^a - c^g$. Unless the return to permanent crops is so high that irrigating more permanent crops using groundwater is socially beneficial, Equation (4.18) will be negative since the increased social cost is more than the value of the extra acreage of permanents. In this case, although the surface water market has solved the resource misallocation problem (as all F^p land is irrigated), it exaggerates the CPR problem by inducing a lager extraction than the autarky case.

No fallowing occurs in this case:

$$N_t^{f,M} = 0 \quad (3.41)$$

In summary, when the marginal groundwater user is an annual crop farmer, the efficiency of surface water market depends on the condition of the groundwater basin and the severity of the CPR problem[15]. If the social cost of extraction borne by individual pumper is large

[15] Note that discussion in this section is based on the assumption that land constraint does not bind in the social planner's case. If the land constraint binds, there is no CPR problem. Overall extraction from the basin is below the social optimum even when all land is farmed. Extraction under autarky is at an inefficient level since some farmers have no access to groundwater and have to fallow part of their land, while surface water market will lead to the same level of efficiency as the social planner since it grants all farmland irrigation water through surface water reallocation.

enough, overall extraction from the basin is limited by the marginal return of annuals. Introducing a surface water market will not result in more extraction but only reallocate water efficiently. However, if the social cost borne by each farmer is small, the surface water market lets F^s farmers irrigate their crops using groundwater through the nominal surface water trade, leading to a higher level of extraction from the aquifer.

Hypotheses

The theoretical model generates two sets of hypotheses. One set summarizes how crop choices react to water supply changes. The other set describes how the underlying condition of the economy and the effectiveness of surface water market affect fallowing decisions.

Hypothesis 3.1 *In area with frequent drought, the size of permanent crops does not respond to changes in surface water delivery.*

Hypothesis 3.2 *In surface-water-only districts, without surface water trade, the size of annual crops increases with surface water delivery.*

Whether the water or land constriant binds in the economy has different implications on the efficacy of water market. Although I lack direct observation on the cost and payoff structure of each farmer, and cannot directly decide which constraint binds, the model makes different predictions at the fallow decisions of water sellers under the two situations:

Hypothesis 3.3 *If the surface water market is efficient, annual crop farmers fallow less land when surface water supply is high.*

Hypothesis 3.4 *If the surface water market is inefficient, fallow acreage is not correlated with surface water supply.*

3.5 Empirical Analysis

To test the hypotheses, I focus on Kern County in the Central Valley because its Department of Agriculture has published crop choice data for each plot of farmland since 1997. I match the crop data to local water supply conditions.

In Kern County, surface irrigation water is supplied by 21 water districts who hold contracts for delivery of surface water from the State Water Project (SWP), Central Valley Project (CVP) and Kern River. Some water districts also drill wells and deliver groundwater to their clients together with surface water. Most districts charge a uniform basic price for the water they deliver. The on-site price may include a varying surcharge based on the distance between the water user and the water delivery facilities.

There are also some farms in the county that do not belong to any water districts and rely on private wells for irrigation. Within the water districts, many farmers have also drilled private wells and pump groundwater to supplement what they receive from the district. Because private wells are not metered, the actual water used by individual farmers is unknown. In most water districts, every acre has an equal and proportional right to surface water, so I assume each acre receives the total district water supply divided by acres farmed.

Table 3.1 reports the summary statistics for each water district over the period 1999-2016. There are four districts without access to groundwater (henceforth referred as surface-water-only–SWO–districts). They cover 13% of the farmland in Kern County. The SWO districts use 22% of all surface water delivered to the county, implying that they hold more long-term surface water rights than the water districts with groundwater (henceforth referred as groundwater–G–districts). Nevertheless, surface water supply for these four districts only accounts for 60% of their total water demand, and they also purchase short-term water delivery from other agencies.

These SWO districts choose different crops than the rest of the valley. They grow 19% of the permanents in the whole county but only 6% of the annuals. They fallow more farmland (26%) than G districts (18%). The large fraction of fallowing in SWO districts reflects

Water District	Farmland	Annuals	Permanents	Fallowing	Water Demand	Surface Water Delivery
Without access to groundwater						
Belridge Water Storage District	52,110	12,003	32,111	7,997	132,761	74,187
Berrenda Mesa Water District	37,720	6,427	23,814	7,478	92,274	56,537
Lost Hills Water District	62,664	11,859	28,059	22,747	119,436	72,723
Tejon - Castac Water District	2,005	-	10	1,995	33	1,926
Total	154,500	30,289	83,994	40,217	344,504	205,374
With access to groundwater						
Arvin - Edison Water Storage District	157,854	78,472	49,463	29,919	354,461	86,879
Buena Vista Water Storage District	48,351	37,377	5,313	5,661	110,444	13,005
Cawelo Water District	42,158	1,911	35,809	4,439	119,365	23,323
Delano - Earlimart Irrigation District	8,191	150	7,358	683	23,921	112,141
Henry Miller Water District	39,668	19,233	158	20,276	48,590	21,675
Kern - Tulare Water District	15,484	1,551	11,064	2,869	39,282	43,697
Kern County Water Agency	7,123	4,149	16	2,957	10,425	24,752
Kern Delta Water District	160,409	115,395	10,444	34,570	321,908	15,671
North Kern Water Storage District	75,596	20,313	46,984	8,300	201,129	7,854
Rag Gulch Water District	450	5	124	321	409	4,138
Rosedale - Rio Bravo Water Storage District	40,102	24,090	11,048	4,964	95,578	27,411
Semitropic Water Service District	160,289	86,825	55,509	17,956	394,689	95,916
Shafter - Wasco Irrigation District	35,519	13,071	19,754	2,694	95,890	47,993
Southern San Joaquin Municipal Utility District	50,968	8,359	39,727	2,882	148,024	87,719
Tehachapi - Cummings County Water District	17,292	7,268	317	9,707	19,184	2,625
West Kern Water District	4,114	1,541	829	1,743	6,508	3,969
Wheeler Ridge - Maricopa Water Storage District	128,970	44,158	57,724	27,089	295,111	120,333
Unserved area	65,576	38,634	10,195	16,747	129,209	-
Total	1,058,115	502,502	361,835	193,778	2,414,127	739,100

Summary statistics for the Kern County water districts, averaged over the period 1999-2016. The crop data is from Kern County Spatial Data. The water supply data is from SWP and CVP websites. The units on land are acres and the units on water are acre-feets.

Table 3.1: Water District Summary Statistics

water scarcity due to lack of groundwater access. Surprisingly, those districts are devoting a larger fraction of farmland to permanent crops than the G districts. For farmers in SWO areas, surface water imports are thus essential.

In Table 3.2, I report the history of crop change by water district type and surface water delivery. The major crop in Kern County has moved from annuals to permanents over the sample period. Surface water delivery for all the water districts has been very variable, which is not surprising given that California has multi-year wet-dry cycles. Moreover, there is a general declining trend due to delivery reductions associated with increasingly stringent environmental regulations.

In G districts, acreage of annuals has dropped by 20%. Fallowed acres have also fallen despite the reduction in surface water supply. Permanent crop acreage has grown rapidly, driving up total agricultural water demand. The water demand unsatisfied by surface water

Year	*Surface water only districts* Fallowing	Annuals	Permanents	Annual Crop Water Demand	Permanent Crop Water Demand	Total Water demand	Surface Water Delivery
1999	6,406	80,973	61,889	202,433	198,044	400,477	333,218
2000	8,233	73,892	67,143	184,731	214,857	399,588	302,846
2001	9,650	70,991	68,627	177,476	219,607	397,084	131,233
2002	35,457	48,135	65,676	120,336	210,164	330,500	235,547
2003	30,498	51,830	66,940	129,576	214,207	343,783	302,846
2004	48,016	30,478	70,774	76,194	226,478	302,673	218,722
2005	42,263	21,682	85,323	54,205	273,035	327,240	302,846
2006	27,101	31,118	91,049	77,796	291,356	369,152	336,496
2007	28,230	24,305	96,732	60,763	309,543	370,306	201,898
2008	35,654	21,126	92,488	52,815	295,960	348,775	117,774
2009	49,169	10,108	89,991	25,270	287,971	313,241	134,598
2010	42,795	14,236	92,237	35,590	295,159	330,749	168,248
2011	42,146	18,320	88,802	45,799	284,167	329,966	269,197
2012	40,813	15,143	93,311	37,858	298,596	336,454	218,722
2013	40,686	11,414	97,168	28,535	310,937	339,471	117,774
2014	52,043	5,832	91,393	14,581	292,457	307,037	33,650
2015	49,705	3,309	96,254	8,272	308,014	316,286	67,299
2016	40,874	12,303	96,091	30,757	307,492	338,249	201,898

Year	*Groundwater districts* Fallowing	Annuals	Permanents	Annual Crop Water Demand	Permanent Crop Water Demand	Total Water demand	Surface Water Delivery
1999	172,047	499,624	276,477	1,249,061	884,727	2,133,788	1,003,912
2000	153,961	501,006	293,182	1,252,515	938,182	2,190,696	1,017,148
2001	174,219	491,289	282,641	1,228,223	904,450	2,132,673	534,894
2002	170,124	493,556	284,469	1,233,890	910,300	2,144,190	780,341
2003	166,716	497,259	284,173	1,243,148	909,353	2,152,501	949,094
2004	176,226	481,332	290,591	1,203,330	929,890	2,133,220	713,229
2005	146,709	486,356	315,084	1,215,890	1,008,268	2,224,158	1,222,790
2006	147,277	460,955	339,917	1,152,387	1,087,733	2,240,120	1,144,164
2007	133,756	466,100	348,293	1,165,250	1,114,538	2,279,787	612,675
2008	106,552	480,579	361,017	1,201,447	1,155,256	2,356,702	569,138
2009	138,345	447,867	361,937	1,119,668	1,158,198	2,277,865	664,697
2010	138,605	441,759	367,784	1,104,398	1,176,909	2,281,307	909,563
2011	124,680	441,784	381,685	1,104,460	1,221,391	2,325,852	1,086,108
2012	89,078	466,651	392,420	1,166,628	1,255,743	2,422,370	640,610
2013	93,508	440,957	413,684	1,102,392	1,323,788	2,426,180	456,750
2014	100,090	424,746	423,313	1,061,865	1,354,600	2,416,465	157,180
2015	76,999	423,879	447,270	1,059,698	1,431,265	2,490,964	155,595
2016	79,541	403,886	464,721	1,009,715	1,487,107	2,496,822	656,949

The units on land are acres and the units on water are acre-feets.

Table 3.2: History of Crop Change

is met by groundwater extraction. As a result, the changing crop pattern is accelerating the basin's depletion.

In SWO districts, the acreage of annual crops has dropped dramatically (85%). Half of the decline goes to fallowing and half of the land transits to permanent crops. Depletion of the basin has also increased because of SWO districts' increasing demand for water import. It peaked at 2014 when nearly 90% of irrigation water had to be imported from outside the districts. In 2016, SWO districts still purchased about 130,000 acre-feed of extra water.

That accounts for 40% of water consumption within those districts.

The theoretical model predicts that the water transferred from G districts to SWO districts has two possible implications: (1) more fallowing or (2) more groundwater pumping. That overall the number of fallowed acres does not increase over time rules out the first possibility. Moreover, the change of relative product price that favors permanent crops seems to push against fallowing land and instead toward pumping groundwater. To confirm the aggregate crop pattern, we examine the farmland transition matrix using plot-level crop choice data. These data help clarify how much of the transition is caused by water sales and how much is due to a price effect that favors permanents.

Crop transition at plot level

To start, we must construct a plot-crop data set from the Kern County Spatial Database. In practice plots vary in shape over time, making it difficult to track the evolution of crops. Instead of plots, I study the observed crop at 12102 fixed points on the map over time. Doing so creates a spatially consistent data set where each dot stands for a square of 61.8 acres. The number of dots with active farming information is similar to the number of registered plots in the original data.

Table 3.3 reports summary statistics of the reconstructed dot-level crop choice data. On average, 35% of dots are used for annual crops, 39% are used for permanents and 26% are fallowed. The number is close to the acreage data in Table 1 although the size of annuals is reported larger in acreage because there might be multiple harvest of annual crops within a year. In addition, the dot-level data picks up more fallowed land due to the ability to track changes in consistent locations while in the acreage data sometimes the fallowed land is not reported. The trends of declining annuals and rising permanents persist at the dot level. While for fallowing, the dot data shows that it stabilized at around 28% after 2003 both in SWO and G districts. This implies that neither the water market nor the price effect plays an important role on fallowing in the recent decade, and crop transition mainly happened between annual and permanent crops.

	Annuals	Permanents	Fallowing	Fallowing (SWO)	Fallowing (G)
Aggregate:					
12102	35%	39%	26%	32%	25%
By year:					
1999	49%	32%	19%	2%	17%
2000	47%	33%	20%	3%	17%
2001	46%	33%	20%	2%	18%
2002	43%	32%	25%	4%	21%
2003	43%	31%	26%	5%	21%
2004	39%	32%	29%	6%	23%
2005	37%	35%	28%	6%	22%
2006	35%	38%	27%	4%	22%
2007	33%	40%	27%	5%	23%
2008	32%	41%	27%	5%	23%
2009	30%	41%	29%	6%	23%
2010	31%	41%	28%	5%	22%
2011	30%	42%	28%	5%	23%
2012	29%	44%	27%	5%	22%
2013	27%	46%	27%	5%	22%
2014	25%	47%	28%	6%	22%
2015	24%	48%	29%	6%	22%
2016	23%	49%	28%	6%	22%

Table 3.3: Plot Level Summary Statistics

SWO and G districts have different dynamics. As shown by Table 3.4, in SWO districts, fallowing increases by 150%, compared with a 30% increase in G districts. Fallowing mainly comes from a reduction in annual crops. In SWO districts, only 7% of annuals in 1999 remain annual crop in 2016 and more than half are fallowed. While in G districts, over 50% of annuals remain and only a quarter are fallowed. The large fraction of fallowing in SWO districts confirms that they are water scarce.

Despite that scarcity, the number of dots with permanent crops in SWO districts grows over time. Permanent crops' share increases from 40% in 1999 to more than 50% in 2016, even larger than the fraction in G districts. This is due to a substantial fraction of annual acreage transitioning to permanents.

Panel A: All districts

			crop choice in 1999		
			annual	permanent	fallow
		Total	5,916	3,871	2,315
crop choice in 2016	annual	2,777	2,095	192	490
	permanent	5,968	2,123	3,213	632
	fallow	3,357	1,698	466	1,193

Panel B: Districts without groundwater

			crop choice in 1999		
			annual	permanent	fallow
		Total	829	711	267
crop choice in 2016	annual	116	60	15	41
	permanent	1,014	331	607	76
	fallow	677	438	89	150

Panel C: Districts with groundwater

			crop choice in 1999		
			annual	permanent	fallow
		Total	5,087	3,160	2,048
crop choice in 2016	annual	2,661	2,035	177	449
	permanent	4,954	1,792	2,606	556
	fallow	2,680	1,260	377	1,043

Table 3.4: Crop Transition Matrix

The big increase in permanent crops is consistent with a transition from autarky equilibrium to market equilibrium in the model due to the introduction of private water trade. Under autarky, SWO farmers could not expand permanents acreage in wet years since they would not have enough water in the next drought. Instead, they grew some annuals and fallowed annual crop land in dry years to water their permanent crops[16]. When it became feasible to buy surface water, SWO farmers expanded their permanent acreage. The decline of annual

[16]In fact, Berrenda Mesa Water District has water allocation rule that permanent crop land is served first whenever there is shortage in water supply.

acreage is also predicted by the model.

Empirical methods

The crop transition at dot level show that the water market influenced crop choice in those water districts without groundwater. Permanent crop acreage increased as a result of water trade, which is consistent with the model prediction that water market reallocates surface water from groundwater users to high-value users who have no access to groundwater. At the same time, efficiency of water market is challenged by the fact that fallowing does not rise in SWO districts as an outcome of water transfer from SWO to G districts. To confirm those implications, I estimate crop choice at the plot level.

According to the hypotheses (3.3 and 3.4) developed in Section 4.4, the main outcome of interest is how much annual crops are fallowed. Since annual crops are the marginal crops that may be sensitive to water supply variations, I infer the underlying state of the economy from the impact of water supply changes on the farmers' fallowing decision. I also test the impact of surface water supply to permanent crops (Hypothesis 1) and to annual crops in surface water only districts (Hypothesis 2) to check the model predictions on permanent crops and crop pattern in autarky equilibrium. The outcome variables could be a binary choice such as whether a certain type of crop is planted on a certain plot or not, or a continuous measure such as the fraction of a certain type of crop within a certain area.

Water supply is the main influence on crop choice as discussed in the model. Three different variables are used to measure variation in water supply across space and time. *SWP allocation* is a percentage of the full entitlement of SWP water the water district receives in a given year. It is the main explanatory variable of interest as it measures the change of surface water supply for the same land over time. It is highly correlated with a drought index [see Chapter 2]. *Surface water rights* is the ratio of long-term surface water supply over total crop water demand. It captures the spatial variation between different water districts due to their different endowment of surface water. *Groundwater access* captures the difference between surface water only and groundwater districts. It varies over space, but not time.

Additional control variables include:

Land quality: I acquire a cropland suitability index (CSI) for vegetables (*CSI Potato*) and field crops (*CSI wheat*) from Food and Agriculture Organization (FAO) of the United Nations. I do not include FAO's land suitability index for permanent crops because it does not vary across the region examined.

Relative crop price: I compute the *price ratio* of permanent to field crops each year. A common view on the cause of transition from annual to permanent crops is that price changes favor permanent crops. Figure 3.1 shows that it is not always the case. In fact, the price of vegetables has been rising even faster than the price of permanent crops, reflecting the increase in labor cost because vegetables are much more labor-intensive than the tree crops. Nevertheless, as the acreage of vegetables is relatively stable and the transition mainly happens from field crops to permanent crops, I use the relative price of permanent to field crops to control the price effect on crop decisions.

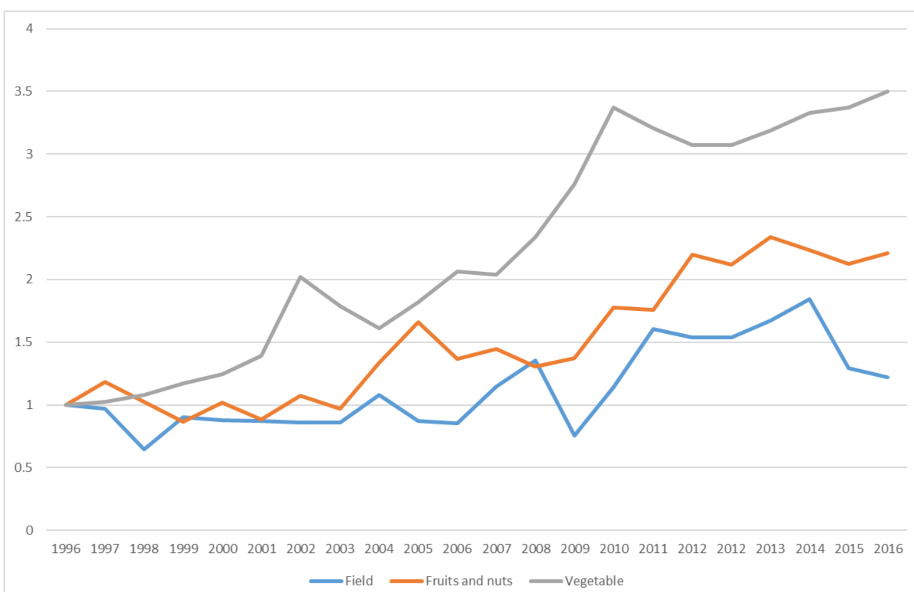


Figure 3.1: Change of Normalized Price of Different Types of Crops over Time

Agriculture capacity: Local density of agriculture matters as it affects the local investment of infrastructure or knowledge spillover. I measure the local *agriculture capacity* as the number of dots that are actively farmed within one mile circle of the observation point.

Lagged crop choice: The *lagged crop choice* measures the influence of crop decision in the past. Serial correlation arises for different reasons. For permanent crops, it is mainly due to the fixed cost on planting trees. For annuals, it could be the special knowledge the farmers gained before growing the crop, or special tools they purchased, or some unobserved factors of the land that make growing a certain type of crops more profitable.

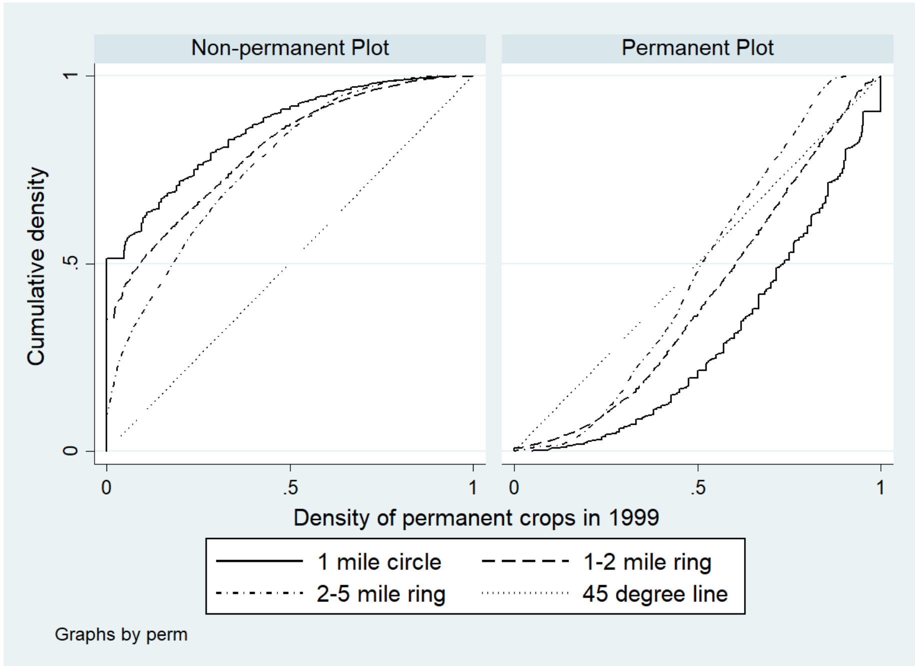
Network influence: The *network influence* measures how a farmer's crop choice is affected by the decisions of her neighbors. For each observation point, network influence is calculated as the density of the same type of crops within its one mile circle (number of dots with the same type of crops divided by total number of dots). I use the lagged value of the density to avoid simultaneous influences between farmers' crop decisions.

In spatial analysis, individual observations usually correlate with each other based on their geological closeness. Beyond the network influence, which is a special form of spatial interdependence, spatial econometricians have developed econometric models dealing with the issue of spatial autocorrelation between control variables or error terms. I take one of the model that is appropriate to the water market context and the spatial autocorrelation in my data.

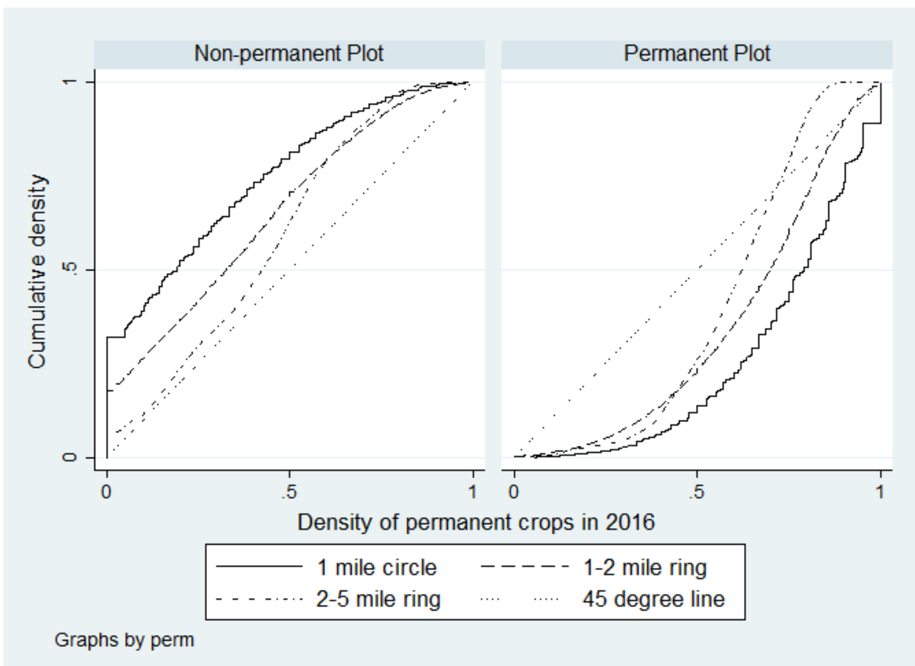
Evidence of spatial autocorrelation

To evaluate spatial autocorrelation, I divide the dot sample into those dots with permanent crops and those with other uses. If there is no spatial autocorrelation among the observations, the crop choice should be random across locations, and the distributions of neighboring density of permanent crops in the two subsamples should be similar. If there is positive spatial autocorrelation, neighboring areas around the dots with permanent crops should also have higher density of permanents.

Figure 3.2 displays the cumulative density distribution of the permanent density in the



(a) Distribution of permanent density in 1999



(b) Distribution of permanent density in 2016

Figure 3.2: Density of Permanent Crops by Space and Time

neighboring area of the two subsamples. In the upper panel, I calculate the density of permanent crops in 1999, and the results for 2016 is presented in the lower panel.

Difference in distribution of permanent crop density between the two subsamples are striking both in 1999 and 2016. Taking the one-mile circle (solid line) around the dots as an example, at the 50% threshold, the density in the permanent crop dot subsample is around 0.7, while in the other subsample is about 0.1.

Spatial autocorrelation generally decreases with distance. The cumulative density distribution line approaches to the 45-degree line (dot line) when it moves from one-mile circle to one-to-two mile ring (dash line) and then to two-to-five mile ring (dash/dot line) around the dots.

I also check the difference over time. Due to the increase of relative price of permanents a large fraction of farmland transits to permanent crops through the sample period; thus, I expect the distribution of permanent crop density to increase over time, and the distributions of the two samples to become more similar. Comparison between the left and right panel confirms my expectation. In fact, in the two-to-five-mile ring area, the two distributions are quite similar in 2016 as both of them become close to the 45-degree line.

Moran (1950) developed a formal measure of spatial dependence called Moran's I, which is defined as:

$$I = \frac{N}{\mathbb{W}} \frac{\sum_i \sum_j w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2} \tag{3.42}$$

where N is the number of observations, x is the variable of interest, w_{ij} is the spatial weight between observation i and j and $\mathbb{W}$ is the sum of w_{ij}.

If there is no spatial autocorrelation, the expectation of I is $E(I) = \frac{-1}{N-1}$, which converges to 0 in a large sample. On the other hand, if there is spatial autocorrelation, the value of I varies from -1 to $+1$ with negative value implying negative spatial autocorrelation and positive value corresponding to positive spatial autocorrelation.

I calculate the Moran's I for water districts without groundwater. As presented by Table 3.5, the value is positive and statistically significantly different from $E(I)$ in both 1999 and 2016. It confirms that there is spatial autocorrelation in the data and the specification of econometric model should account for it. Moreover, comparison between the two years is consistent with our observation from the figure that due to the increased popularity of permanent crops, the distribution of crops around different dots becomes close. Therefore, the Moran's I is smaller in 2016 than in the first year of the sample period.

	I	E(I)	sd(I)	z	p-value*
1999	0.166	-0.001	0.001	155.605	0
2016	0.126	-0.001	0.001	118.889	0

*1-tail test

Table 3.5: Moran's I in Districts without Groundwater

The econometric model

Outcome variables in the empirical analysis could be either a binary crop choice $d \in \{0, 1\}$ that $d = 1$ if a certain type of crop is planted at a given plot and $d = 0$ otherwise, or a continuous variable $d \in [0, 1]$ that d measures the density of a certain type of crop within a certain area. Without loss of generality, I derive the econometric model based on the binary crop choice of planting a permanent crop. The models for other binary choices follow directly. Estimation using the continuous outcome variables are conducted as robustness checks. The estimation technique is less complicated and standard in literature (Yu, Jong, and L.-f. Lee, 2008; L.-f. Lee and Yu, 2010).

Whether to grow a permanent crop at dot i in year t is determined by the latent profit y_{it}. The farmer compares y_{it} with other options, including growing annuals and fallowing in current period. I pool other options as an outside option, and normalize the value of the outside option to 0. Therefore, the relationship between the normalized profit and crop choice is:

$$d_{it} = \begin{cases} 1, & \text{if } y_{it} > 0; \\ 0, & \text{otherwise} \end{cases} \tag{3.43}$$

Farmer of dot i chooses $d_{it} = 1$ if and only if the latent profit $y_{it} > 0$.

In a standard discrete choice model, the latent profit function can be written as:

$$y_{it} = x_{it}\beta + \varepsilon_{it} \tag{3.44}$$

where x_{it} is a vector of explanatory variables and ε_{it} is individual-time specific error term. In the absence of spatial autocorrelation (or more accurately ε_{it} is i.i.d.), probit or logit regression could be applied to estimate the vector of coefficients β. However, because of spatial interdependence, the standard probit/logit estimation results are no longer efficient and may not be consistent.

There is a rich literature discussing the spatial autocorrelation in the land use problem (Li, Wu, and Deng, 2013). The issue becomes complicated with a discrete choice model since the usual differencing method can not be applied here. In addition, due to the heteroskedasticity among the error terms, the standard maximum likelihood estimation is infeasible as it requires n-dimensional integration where n is the size of the sample. Below, I discuss specific forms of spatial autocorrelation that may exist in my data and provide solutions to each.

In general, the crop choice data features two sorts of spatial autocorrelation. Factors that are fixed over time but correlated over space cause permanent spatial interdependence. Most geological features such as access to groundwater and surface water river or land quality belong to this category. For this type of spatial autocorrelation, it is included in the explanatory vector x_{it} if it is observed; for example, the land suitability to specific crops (Holmes and S. Lee, 2012). Otherwise, it contributes to an intercorrelated component in the error term. Below is the vector of individual errors at period t:

$$\varepsilon_t = e + u_t \tag{3.45}$$

where e is the vector of unobserved individual feature. $e = \rho We + v$ due to spatial interdependence where W is the weight matrix depending on the distance between observations, ρ measures the level of spatial autocorrelation and v is a time-invariant individual shock.

Note that, if the dependent variable is continuous, the fixed spatial autocorrelation could be easily resolved by taking difference across time:

$$y_t - y_{t-1} = (x_t - x_{t-1})\beta + (u_t - u_{t-1}) \tag{3.46}$$

Although we can not estimate the scale of spatial autocorrelation ρ, the estimator for explanatory variables β is unbiased, efficient and consistent.

For the discrete choice model, Pinkse and Slade (1998) provide a GMM method to estimate the discrete choice model with spatial dependent error terms.

A second type of spatial autocorrelation arises when the dependence between farmers' crop choices evolves over time. Different economic explanations could be applied to explain the transitory spatial interdependence.

The first channel I consider is when a farmer's crop choice is affected directly by others' choices. For example, the economies of scale arises from having other land nearby planted with the same crop, which may help lower costs by adding to the pool of labor with special skill or allowing share of special tools (Holmes and S. Lee, 2012). Higher crop density may also encourage local government/agency to invest in infrastructure that is more helpful for that crop. For instance, agglomeration of water-intensive crops may encourage local water suppliers to dig more wells. Finally, there is knowledge spillover from neighbors' crop choices (Munshi, 2004). Since the crop choices are observable, the latent profit function includes the choices on other dots as in Mohammadian and Kanaroglou (2003):

$$y_t = x_t\beta + \rho W d_t + \varepsilon_t \tag{3.47}$$

Standard profit/logit estimation could be applied to estimate the model parameters.

When profitability is locally correlated, the second channel of transitory spatial autocorrelation arises. This differs from the first channel as it involves forward looking behavior where farmers are influenced by the additional value created by increasing a particular crop's local density. In this situation, farmers expect that high value of the latent variable will lead to growing permanent crops by other farmers, which in turn lowers costs and introduces network effects. The specification of latent profit function in this channel is:

$$y_t = \rho W y_t + x_t\beta + \varepsilon_t \tag{3.48}$$

In the literature, such specification is often referred to as a spatial lag model. The latent profit can be written as:

$$y_t = (I - \rho W)^{-1} x_t\beta + (I - \rho W)^{-1}\varepsilon_t \tag{3.49}$$

Smirnov (2010) proposes a Pseudo maximum likelihood estimator to estimate the above model with an additional assumption that individuals disregard shocks on others. Klier and McMillen (2008) extend the Pinkse and Slade (1998) GMM method to this setting.

The last channel of time-variant spatial autocorrelation involves situations when farmers' decision are driven by unobservables that are correlated over space. The transitory case of interdependent error term is an extension of the permanent spatial autocorrelation we examined before, except that the error term now is written as:

$$\varepsilon_t = \rho W\varepsilon_t + u_t = (I - \rho W)^{-1} u_t \tag{3.50}$$

This model is often referred to as spatial error model. In the literature, econometricians rarely distinguish the transitory and permanent cases, since the GMM estimator could be applied in both situations. The latent profit function can be written as:

$$y_t = x_t\beta + (I - \rho W)^{-1}\varepsilon_t \tag{3.51}$$

As shown in Anselin and Florax (2012), the spatial lag model and spatial error model are special case of each other with additional assumption on the parameters. Influence from both channels exist in the farming decision. A farmer grows a certain type of crop on a given dot based on her expectation of her neighbors' choices. At the same time, neighboring farmers profits are affected by similar local geological and water conditions.

In the Central Valley, the major factor that drives the crop pattern change over the sample period is the relative price of permanent to field crops. Since crop price affects the farmers' choice through their profit function, I consider the influence from latent profits of neighboring land as the main channel through which farmland correlates with each other. At the same time, most of local unobserved geological connections should be captured when we include land quality, water supply and agriculture capacity in the latent profit function. Therefore, I adopt the spatial lag model and conduct the pseudo maximum likelihood (PML) estimation to examine the crop choice with spatial autocorrelation.

Derivation of PML estimator

The pseudo maximum likelihood estimator I use is a simplification of Smirnov (2010) that facilitates computation with a large dataset. For the spatial lag specification, the latent profit function is (the subscript for time is ignored):

$$y = Ax\beta + A\varepsilon \tag{3.52}$$

where $A = (I - \rho W)^{-1}$ is the spatial multiplier matrix. A could be expanded as the limit form:

$$A = \lim_{n\to\infty} I + \rho W + \rho^2 W^2 + \ldots + \rho^n W^n \tag{3.53}$$

Denote by D the $n \times n$ matrix composed of the diagonal elements of the matrix A. D indicates private effects of random shocks on the individual profits. As shown by Equation 3.53, these effects are the sum of direct non-spatial effects and aggregate spatial effects.

The conditional choice probability for the individual i to plant permanent crops is:

$$P_i = \Pr(d_i = 1 | \{\varepsilon_j, j \neq i\}, \beta) \tag{3.54}$$

Rewrite the latent profit function as:

$$y = Ax\beta + (A - D)\varepsilon + D\varepsilon \tag{3.55}$$

Note that the diagonal elements in the matrix $A - D$ are zero, thus the conditional choice probability is:

$$P = \Pr(\varepsilon < \frac{Ax\beta + (A-D)\varepsilon}{D}) \tag{3.56}$$

Therefore, the individual conditional probability is:

$$P_i = \frac{1}{1 + \exp(-\frac{g_i}{d_{ii}})} \tag{3.57}$$

where $g_i = \sum_{j=1}^{n} a_{ij} x_j \beta + \sum_{j=1}^{n} (a_{ij} - d_{ij})\varepsilon_j$.

Notice that the random components ε_j in g_i are i.i.d. with mean 0; therefore, they have no systematic effect on the conditional choice probability P_i. Suppose individuals focus only on spatial effects that systematically affect their conditional choice probability and disregard all other effects. Then private shock $a_{ii} = d_{ii}$ always affects the conditional choice probability while a_{ij} with $j \neq i$ has no expected effect. The simplified closed form for the conditional probability is:

$$\hat{P}_i = \frac{1}{1 + \exp(-\frac{\sum_{j=1}^{n} a_{ij} x_j \beta}{d_{ii}})} \tag{3.58}$$

Estimation for such specification is equivalent to the spatial discrete choice model with spatial random profit:

$$\tilde{y}_i = Ax\beta + D\varepsilon_i \tag{3.59}$$

The pseudo maximum likelihood estimator for the original model is the maximum likelihood of this model. As the computation involves inversion of the spatial weight matrix A, which is difficult with a sample size n over $10,000$, I simplify the spatial weight matrix by assuming away the spatial effects of order larger than three:

$$A \approx \tilde{A} = I + \rho W + \rho^2 W^2 \tag{3.60}$$

and denote the matrix of diagonal elements of $\tilde{A}$ as $\tilde{D}$. In the end, it is easy to find the maximum likelihood estimator for:

$$\tilde{y}_i = \tilde{A}x\beta + \tilde{D}\varepsilon_i \tag{3.61}$$

This is the PML estimator I will present in the estimation results.

Estimation results

Table 3.6 reports the tests of Hypothesis 3.1: permanent crops are not correlated with water supply changes over time. The coefficient of SWP allocation is negative and statistically significant in column (1), implying that in years with less surface water supply, there is more transition to permanent crops. This is consistent with the introduction of water trade in later periods when the surface water supply was low. Such effect disappears in the other three columns where lagged crop choice or time trend is added to control for long run changes in crop choice. That SWP allocation does not matter is consistent with Hypothesis 3.1 that permanent crops are not subjected to water supply variations.

	(1)	(2)	(3)	(4)
VARIABLES		Logit		PML
SWP allocation	-1.110***	-0.202	0.0991	-0.159
	(0.22)	(0.23)	(0.08)	(0.19)
Surface water rights	-0.559	0.115	-0.561	0.0823
	(1.09)	(0.24)	(1.09)	(0.20)
Groundwater access	-1.087***	-0.491***	-1.090***	-0.399***
	(0.37)	(0.13)	(0.38)	(0.11)
CSI (Potato)	0.232	0.19	0.233	0.163
	(0.37)	(0.15)	(0.37)	(0.13)
CSI (Wheat)	-0.051	0.0564	-0.0516	0.0497
	(0.26)	(0.08)	(0.26)	(0.07)
Price ratio (p/a)	0.971***	0.868***	-0.113	0.705***
	(0.18)	(0.24)	(0.07)	(0.20)
Agricultural capacity	0.178***	0.125***	0.179***	0.103***
	(0.02)	(0.02)	(0.02)	(0.01)
Lagged crop choice		6.284***		6.659***
		(0.11)		(0.13)
Network influence		1.705***		
		(0.18)		
Time trend			0.0725***	
			(0.01)	
Spatial correlation				0.150***
				(0.03)
Constant	-3.628**	-7.777***	-148.5***	-7.526***
	(1.43)	(0.74)	(29.50)	(0.54)
Observations	108,918	108,918	108,918	108,918

Note: 1. Standard errors in parentheses and clustered at water district level.
2. All even years are included.
3. Spatial weight matrix: Neighbors within 1 mile circle.

Table 3.6: Determinants of Planting Permanent Crops

Variation of surface water rights has no influence on the likelihood of growing permanents. This is consistent with the idea that water scarcity is mitigated by surface water trade. The positive coefficient of groundwater access implies that SWO districts grow more permanents than G districts. This is also supported by water trade.

FAO measures of land quality have no impact on the permanent crop decisions. The price effect is as expected (except for column (3) where the time trend that absorbs the price effect) that higher relative price of permanent to field crops leads to more transition to the permanents.

Influences from related agricultural decisions all have expected sign. A plot in a region with denser agriculture, planted with permanent crops in the past, or in a neighborhood with larger density of permanent crops is more likely to have a permanent crop. The spatial correlation parameter estimated in PML estimation (column (4)) is also positive and statistically significant, confirming the existence of spatial interdependence of crop choices.

Table 3.7 presents tests of Hypothesis 3.2. Although private water trade was always allowed during the sample period, in the early years, water districts without groundwater had not transited to permanent crops in large scale and surface water delivery was high, so there was no need for private water trade and the economy was in the autarky equilibrium. The year 2004 is chosen as the cutoff because in surface-water-only districts, the acreage of permanent crop suddenly jumped 20% from 2004 to 2005 after a long period of slow growth.

To confirm the model's autarky predictions, I estimate the correlation between annual crop decision and water supply conditions in water districts without groundwater before 2004. Coefficients for SWP allocation are positive across all specifications and statistically significant in the subsample with high fallow density (column (4) and (6)). This implies that on farmland with relatively low quality, the annual crop farmers pay attention to surface water supply and fallow the land if water supply is low, consistent with the autarky equilibrium that annual crops are sensitive to short-term surface water supply variation.

VARIABLES	(1)	(2) Logit & all data	(3)	(4) High fallow density	(5) PML	(6) PML& High fallow density
SWP allocation	0.372	0.576	0.72	2.506**	0.405	2.205**
	(0.29)	(1.35)	(1.45)	(1.09)	(0.99)	(0.95)
Surface water rights	-6.154***	5.983***	6.148***	12.49*	1.193	-7.309**
	(0.79)	(1.72)	(1.88)	(7.00)	(3.45)	(3.62)
CSI (Potato)	-0.0772	-0.570***	-0.569***	-5.698	-0.426***	-1.2
	(0.15)	(0.06)	(0.06)	(4.59)	(0.10)	(1.22)
CSI (Wheat)	-1.178*	-0.0718	-0.0524	0.229	-0.111	-0.0156
	(0.67)	(0.23)	(0.26)	(0.56)	(0.22)	(0.30)
Price ratio (p/a)	-3.191**	-5.182*	-5.867	-7.327*	-3.839*	-3.908**
	(1.31)	(3.06)	(3.71)	(3.91)	(2.29)	(1.76)
Agricultural capacity	0.0824	0.158***	0.160***	0.241***	0.114***	0.173***
	(0.06)	(0.03)	(0.03)	(0.07)	(0.03)	(0.05)
Lagged crop choice		1.935***	2.010***	3.175**	3.625***	3.058***
		(0.40)	(0.52)	(1.57)	(0.85)	(0.80)
Network influence		3.029***	3.028***	1.650**		
		(0.77)	(0.77)	(0.83)		
Time trend			0.0802			
			(0.15)			
Spatial correlation					0.385***	0.898**
					(0.04)	(0.38)
Constant	12.33***	0.858	-159.2	28.47	2.965	11.98***
	(4.66)	(4.19)	(298.50)	(19.81)	(4.80)	(3.31)
Observations	9,035	9,035	9,035	1,432	9,035	1,432

Note: 1. Standard errors in parentheses and clustered at water district level.
2. Years before 2004 are included.
3. Spatial weight matrix: Neighbors within 1 mile circle.

Table 3.7: Determinants of Planting Annual Crops in Water Districts without Groundwater before 2004

As for other control variables, the effect of surface water rights is mixed. Districts with more surface water allocation may grow more annuals or transit to more permanents. Land quality has a negative sign, implying that high-quality land is more likely to be planted with permanents when there is water scarcity. Other variables all have expected sign. The price effect and spatial autocorrelation are both consistent with findings in Table 3.6.

The main results of this chapter are shown in Table 3.8. The two competing Hypotheses 3.3 and 3.4 provide different predictions about water market efficiency and fallowing decision. I look at whether the likelihood of fallowing is affected by surface water supply conditions or not. Column (1) and (2) report the logit regression results using all G districts, column (3) reports logit regression results using only the regions with high density of fallowing, column (4) reports logit regression results using only farmland that is never planted with permanent crops and the last two columns report the PML estimation results based on all water districts.

VARIABLES	(1) Logit & all data	(2)	(3) High fallow density	(4) Non-permanent	(5) PMLE	(6)
SWP allocation	0.118	0.0895	-0.282	0.0583	0.259	0.0385
	(0.13)	(0.06)	(0.25)	(0.28)	(0.30)	(0.04)
Surface water rights	0.870***	0.199	1.665***	0.433*	0.856**	0.345
	(0.29)	(0.17)	(0.33)	(0.24)	(0.33)	(0.21)
CSI (Potato)	-0.244**	-0.133	-0.173	-0.235***	-0.299*	-0.142*
	(0.12)	(0.09)	(0.14)	(0.09)	(0.17)	(0.08)
CSI (Wheat)	-0.000554	-0.0523	0.0288	-0.0235	-0.138	0.018
	(0.11)	(0.07)	(0.20)	(0.14)	(0.13)	(0.08)
Price ratio (p/a)	-0.232*	-0.140**	0.194	-0.219	-0.482	-0.0517*
	(0.13)	(0.07)	(0.24)	(0.29)	(0.34)	(0.03)
Agricultural capacity	-0.359***	-0.199***	-0.422***	-0.236***	-0.430***	-0.212***
	(0.02)	(0.02)	(0.03)	(0.02)	(0.03)	(0.01)
Lagged crop choice	5.273***		3.395***	3.756***	5.263***	
	(0.23)		(0.48)	(0.32)	(0.27)	
Network influence	-4.272***	2.310***				
	(0.50)	(0.35)				
Spatial correlation					-0.416***	0.398***
					(0.02)	(0.13)
Constant	3.882***	1.910**	1.237	2.252**	4.292***	2.517***
	(0.984)	(0.890)	(1.324)	(0.982)	(1.42)	(0.76)
Observations	72,065	72,065	11,160	32,186	72,065	72,065

Note: 1. Standard errors in parentheses and clustered at water district level.
2. Year 2004, 2006, 2008, 2010, 2012, 2014 and 2016 are included.
3. Spatial weight matrix: Neighbors within 1 mile circle.

Table 3.8: Determinants of Fallowing in Districts with Groundwater

The key variable of interest is SWP allocation. None of the estimated coefficients for SWP allocation are statistically significant, suggesting that fallowing is not sensitive to surface water supply. Therefore, when a low-value farmer sells her surface water to high-value users, she does not fallow her land. Instead, the farmer likely pumps more groundwater to supplement irrigation water for her crops. This contradicts Hypothesis 3.3 and is consistent with Hypothesis 3.4 that the market does not efficiently reallocate water from low-value to high-value users; instead, it just provides high-value users with water.

Surface water rights have a positive and statistically significant influence on fallowing decision. Such effect goes away when lagged crop choice is not controlled, implying that places with less surface water rights fallow earlier than area with more surface water rights. This is consistent with the lack of pumping capacity in early years of the sample period.

Land quality has a negative effect on fallowing as expected, although the coefficient is only statistically significant under some specifications. The relative price of permanent crops to fields reduces fallowing. But the effect becomes smaller and even goes away when we restrict the sample size or control for spatial autocorrelation, consistent with the findings at aggregate level that price effect is not a main driver for fallowing.

The lagged crop choice and network influence have the expected sign. As the two are usually highly correlated, the effect of network influence is absorbed by the lagged crop choice (column (1)). This is confirmed by the coefficient of spatial correlation term in the column (5) and (6). When I include the lagged crop choice in the regression with spatial autocorrelation under control, the estimated measure of spatial correlation is negative. This is because the lagged crop choice has already captured most of what determines whether a plot will be fallowed or not. In fact, in column (6) where I do not include lagged crop choice in the regression, the measure of spatial autocorrelation is positive and statistically significant, suggesting that dots where neighborhood fallow rate is high are also more likely to be fallowed.

Robustness check

To booster confidence in the earlier results, I conduct a robustness check by replacing the binary outcome variable with a continuous variable that measures the density of different types of crops. I first divide the Kern County into blocks of 1914 acres, which is the average size of farms in the data. Then, I calculate the fraction of fallowing, permanent crop and annual crop within each block as the continuous outcome variables.

I rerun the previous three tests using both OLS and MLE estimation of the SAR specification. The results are shown in Table 3.9. Column (1) - (4) test the permanent crop decisions. Column (5) and (6) explore the influencing factors for annual crop decision in SWO districts before 2004. Column (7) and (8) evaluate fallowing decisions in G districts.

The estimated coefficients are consistent with the former results. For permanent crop

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Permenant				Annual w/o groundwater before 2004		Fallow with groundwater	
	OLS		SAR model: MLE		OLS	SAR model: MLE	OLS	SAR model: MLE
SWP allocation	-0.180***	-0.0031	-0.0133**	0.0285***	0.0262	0.00434	0.00686	-0.00377
	(0.01)	(0.00)	(0.01)	(0.00)	(0.05)	(0.03)	(0.01)	(0.01)
Surface water/ total demand	-0.146***	-0.00706*	-0.117***	-0.0108**	-0.0513	-0.194	0.0465***	0.234***
	(0.02)	(0.00)	(0.04)	(0.00)	(0.07)	(0.23)	(0.01)	(0.03)
Groundwater access	-0.202***	-0.0107***	-0.156***	-0.00835***				
	(0.01)	(0.00)	(0.02)	(0.00)				
CSI (Potato)	-0.0107*	-0.00119	-0.0268*	-0.00339*	-0.0245	0.0536	-0.0111***	-0.0530***
	(0.01)	(0.00)	(0.02)	(0.00)	(0.02)	(0.06)	(0.00)	(0.01)
CSI (Wheat)	-0.000718	0.00132	0.0125	0.00521***	-0.00455	-0.0439	0.00667	-0.0235
	(0.01)	(0.00)	(0.02)	(0.00)	(0.02)	(0.05)	(0.00)	(0.02)
Price ratio	0.160***	0.0198***	0.00855	-0.00966**	-0.653***	0.0955	-0.0240***	0.000658
	(0.01)	(0.00)	(0.01)	(0.00)	(0.10)	(0.08)	(0.01)	(0.01)
Agricultural capacity	0.0300***	0.00250***	0.0221***	0.00258***	0.0102***	0.0432***	-0.0163***	-0.0540***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Lagged crop choice		0.953***		0.924***	0.676***	0.0726***	0.675***	0.287***
		(0.00)		(0.00)	(0.02)	(0.03)	(0.01)	(0.01)
Spatial correlation			0.976***	0.221***		0.601***		0.848***
			(0.01)	(0.02)		(0.08)		(0.05)
Constant	0.263***	-0.0115	0.0777	-0.0663***	0.955***	-0.354	0.296***	0.809***
	(0.04)	(0.01)	(0.09)	(0.01)	(0.19)	(0.49)	(0.03)	(0.08)
Observations	9,414	9,414	9,414	9,414	815	815	6,181	6,181
R2̂	29%	94%	11%	94%	59%	14%	79%	66%

Note: 1. Standard errors in parentheses and clustered at water district level.
2. Spatial weight matrix: Inverse distance.

Table 3.9: Robustness Check: Continuous Outcome Measure

decisions, a negative and statistically significant coefficient for SWP allocation is found in column (1) and (3) and such effect goes away when lagged crop choice is put in control. This is consistent with the results in Table 3.6.

Column (5) and (6) imply a positive although not statistically significant effect of SWP allocation on annual crop planting decisions in SWO districts before 2004. This is consistent with the findings in Table 3.7. We are not able to restrict the sample into a subsample with only high fallow density, since the sample size shrinks dramatically. Nevertheless, having not found a significant effect at farm level implies that fallowing annuals in dry years is not a common action in response to drought. Instead, large farms can maintain production and only small farms with low profitability fallow.

Column (7) and (8) are test results of our main focus. Consistent with Table 3.8, the coefficient of SWP allocation on fallow decisions is not statistically significant. It implies that farmers do not fallow land when surface water supply is low, confirming Hypothesis 3.4 that the surface water market is inefficient.

3.6 Conclusion

Water sales from groundwater districts to surface-water-only districts are likely to continue in the Central Valley over next few years. These sales are driven both by droughts and by the increased demand for permanent crops. Beyond California, markets are likely to become popular in the era of global warming and the increasing shortage of surface water supply. The consequence of establishing a surface water market varies depending on the underlying economic and hydrological condition of the region. This chapter shows that a surface water market can cause harm when groundwater extraction is unregulated. Since the marginal cost of pumping groundwater is low, farmers simply replace any water they have sold by pumping more groundwater. The overall impact of the water market is to grant more farmers access to groundwater, making the CPR problem even worse.

In the Central Valley, the surface water market neither reallocates resources nor sustains the aquifer. The scale of increased extraction to replace the surface water sold off is large. On average, the import demand from surface water-only-districts is about 140,000 AF per year. If all import comes from the groundwater districts, extra groundwater extraction to replace the surface water sold off accounts for 8% of all groundwater use by all the water districts. What's worse, the surface-water-only districts are at the boundary or out of the groundwater aquifer; therefore, the water transferred to that area eventually runs off instead of percolating back to the groundwater system as a source of natural recharge.

According to the USGS report (2009)[17], the long-term average groundwater pumpage in the Central Valley as a whole is about 8.6 million acre-feet (MAF) per year while the annual recharge is only 7.7 MAF. Kern County agriculture alone consumes 20% of total groundwater extraction in the Valley. Moreover, if we apply the same ratio of extraction to safe yield in the whole Valley to Kern County, over-extraction above the safe yield in Kern County is about 174,000 AF per year, more than 80% of which could be blamed to the surface water trade!

[17] Groundwater Availability of the Central Valley Aquifer, California.

This chapter's conclusions have implications for all aquifers in arid or semi-arid regions – places where the land constraint rather than the water constraint binds in agricultural activity. Some argue that depletion of aquifer is caused by excessive transition from annual to permanent crops, which increase water demand and makes it more inelastic. Others argue that a water market reallocates water efficiently so that the overall reliance on groundwater basin will decline. Findings of this study suggest that neither the transition to permanents or lack of water market are to blame for depletion. Rather, it is the common pool. As long as the groundwater basin is unregulated, low-value farmers have no incentive to stop growing annual crops or to halt their surface water sales, and their extraction from the groundwater aquifer will not stop. Therefore, the very first step to solve the sustainability and efficiency problem of water use is to define groundwater rights and stop unlimited pumping. It is only after closing the common pool that a water market can work as expected to reallocate resource toward higher efficiency.

The argument presented here is not specific to water. The effectiveness of market is rarely guaranteed when it involves a common property. As the CPR problem origins from the users' unlimited use of the resource, market sometimes introduces demand that leads to even higher depletion of the common pool. Fur-bearing animals went nearly extinct in the early nineteenth century as an outcome of the North American fur trade (Berkes et al. (1989b)). Today, the water users in the Central Valley of California are risking the future of the valley on excessive pumping caused by private water trade. The market cannot be assumed to be helpful to solving the resource depletion problem. If we want a market to work efficiently while not depleting the resource that is traded, we must define the boundary of the resource system properly.

3.A Consistency of PML Estimator

When deriving the PML estimator, I make a simplification of the weight matrix by assuming away the spatial effects of orders larger than three:

$$A \approx \tilde{A} = I + \rho W + \rho W \tag{3.62}$$

Below, I show how the estimator will behave if I use a full Taylor expansion of A instead of taking the approximation.

Take the observation j as an example. Let i_K denotes its order K neighbor. The influence coefficient from its first-order (direct) neighbor is:

$$I_1 = \frac{1}{n_j} d_{ji_1} \tag{3.63}$$

where n_j is the number of j's neighbors and d_{1i_1} is a neighbor indicator that equals to 1 if observation j and i_1 are neighbors and 0 otherwise. Influence on observation j from its first order neighbors is thus:

$$x_j^1 = \rho \sum_{i_1} I_1 x_{i_1} \tag{3.64}$$

Similarly, the influence coefficient from j's second-order neighbor is:

$$I_2 = \sum_{i_1} I_1 \frac{1}{n_{i_1}} d_{i_1 i_2} \tag{3.65}$$

Influence on observation j from its second order neighbors is thus:

$$x_j^2 = \rho^2 \sum_{i_2} I_2 x_{i_2} \tag{3.66}$$

Following the same procedure, the influence coefficient from j's order-K neighbor is:

$$I_K = \sum_{i_{K-1}} I_{K-1} \frac{1}{n_{i_{K-1}}} d_{i_{K-1} i_K} \tag{3.67}$$

Influence on observation j from its order-K neighbors is thus:

$$x_j^K = \rho^n \sum_{i_K} I_K x_{i_K} \tag{3.68}$$

By definition, the sum of j's order-1 influence coefficients is $\sum_{i_1} I_1 = 1$. Apply this to I_2, I_3,..., we have $\sum_{i_K} I_K = 1$. If the independent variable x's are of the same order across the observations, the order-K spatial influence on j is of order ρ^K. Since $|\rho| \in [0, 1]$, the higher the order of spatial influence included in the estimation process, or the smaller the spatial autocorrelation coefficient ρ, the larger consistency of the estimated coefficients we get. Nevertheless, to show the robustness of the tests, I present the PML estimation results including order-1 and order-3 spatial influence in the Appendix Table 1.

As shown below, the estimated coefficients from order-1 and order-3 spatial influence are very similar and do not deviate too much from the order-2 PML estimation results we present in the main tables. Therefore, taking the approximation of the weight matrix helps simplify the estimation process while not causing the estimated outcome vary too much.

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Permenant		Annual w/o groundwater before 2004		Fallow with groundwater	
	Order 1	Order 3	Order 1	Order 3	Order 1	Order 3
SWP allocation	-0.17	-0.199	0.459	0.413	0.896	1.312
	(0.20)	(0.20)	(1.11)	(0.97)	(0.87)	(1.01)
Surface water/ total demand	0.0764	0.0583	1.278	1.526	1.164***	0.822**
	(0.21)	(0.21)	(3.83)	(3.60)	(0.43)	(0.42)
Groundwater access	-0.414***	-0.432***				
	(0.11)	(0.11)				
CSI (Potato)	0.168	0.172	-0.473***	-0.420***	-0.523	-0.272
	(0.13)	(0.13)	(0.09)	(0.10)	(0.35)	(0.37)
CSI (Wheat)	0.0488	0.0472	-0.129	-0.149	-0.252	-0.372
	(0.07)	(0.07)	(0.24)	(0.23)	(0.27)	(0.33)
Price ratio	0.730***	0.754***	-4.344*	-3.933*	-1.553	-2.370**
	(0.20)	(0.20)	(2.61)	(2.11)	(1.03)	(0.97)
Agricultural capacity	0.105***	0.109***	0.126***	0.119***	-1.990*	-2.836***
	(0.01)	(0.01)	(0.03)	(0.04)	(1.09)	(0.24)
Lagged crop choice	6.790***	6.667***	4.045***	3.645***	7.627***	8.579***
	(0.16)	(0.13)	(0.87)	(0.88)	(0.97)	(0.39)
Network influence						
Spatial correlation	0.251***	0.183***	0.534***	0.297***	-0.738***	-0.884***
	(0.03)	(0.02)	(0.10)	(0.08)	(0.10)	(0.01)
Constant	-6.613***	-6.621***	3.452	2.955	18.80**	24.43***
	(0.65)	(0.67)	(5.27)	(4.78)	(8.86)	(2.28)
Observations	108,918	108,918	9,035	9,035	72,065	72,065

Note: 1. Standard errors in parentheses and clustered at water district level.
2. Spatial weight matrix: Neighbors within 1 mile circle.

Table 3.10: Spatial Influence: PMLE at Order 1 & 3

Chapter 4

OPTIMAL AQUIFER MANAGEMENT

4.1 Introduction

Groundwater pumping in the United States increased substantially after WWII as the post-war technical developments enabled farmers to extract groundwater at greater depth and on a much larger scale (Dale, French, and Wilson, 1964; Hornbeck and Keskin, 2014). Due to the open access nature of groundwater, aquifer depletion has been observed widely throughout the US west (Ostrom, 1990; Blomquist, 1992) , raising interest in studies of optimal groundwater management. Among them, a famous paradox was raised by Gisser and Sanchez (1980) that the benefit from managing groundwater extraction is actually very low although serious depletion of the aquifers has been a major concern in dry regions all over the world for several decades. To understand the puzzle, researchers vary the baseline settings in Gisser-Sanchez model. Tsur and Graham-Tomasi (1991) found that aquifers have significant buffer value against surface water supply risk, but Knapp and L. J. Olson (1995) concluded the gains from optimal management are relatively small after considering deliberate recharge from the stochastic surface water flow. Knapp, Weinberg, et al. (2003) replaced the stochastic surface water supply with out-of-basin surface water trade and still did not find large gains from optimal control. Koundouri (2000) and Laukkanen and Koundouri (2006) documented significant gain from management for small aquifers where water scarcity is a severe issue. It is puzzling that the economic models do not predict the increasing demand for groundwater management in large basins like the Central Valley of California.

This chapter returns to this problem but takes a different tack by considering the important heterogeneity among groundwater users' willingness to pay for water. In the Central Valley of California, two broad types of crops are planted, annuals and permanents. Annual crops (alfalfa, wheat, cotton, etc.) are planted and harvested each year, so they are easy to fallow in dry years. On the other hand, permanent crops (almonds, citrus, grapes, etc.) take several years to mature and then yield fruit for decades. The total cost before a tree starts to produce can be large, including the waiting time, maintenance cost and the risk of death. Therefore, permanent crops are long-term investments and require a regular supply of water. Not surprisingly, the return from permanent cropland is much larger than the return from annual cropland[1].

The sharp differences between annual and permanent crops create an incentive to close the common pool and put the basin into proper management. With the high return from permanent crops as the benchmark of the value of groundwater stock, growing annual crops becomes no longer socially efficient when the water table is deep enough. Conflicts of interests arise because the annual crop farmers want to continue irrigating their fields with groundwater while the permanent crop farmers wish to save the water for future use. The social planner agrees with the high-value users. Therefore, a regulation that limits groundwater extraction by annual crop farmers is needed, and leads to substantial efficiency gain.

According to my theoretical model, the heterogeneity among agents divides the optimal groundwater pumping path into two stages. At the early stage, when water is near the surface, both annual and permanent crops use groundwater; at the late stage, only permanent crops consume groundwater. The major efficiency gain from management comes from the transition period of the two stages. Under open access, the farmers are only restricted by the pumping cost, so the annual crop farmers stop extraction when the pumping cost equals the return their crop, which is much later than under the socially optimal plan. A proper management plan not only delays depletion of the aquifer, but also saves some water from annual crops to irrigate more valuable permanent crops.

Not accounting for heterogeneity may be the reason that earlier papers found little efficiency gain from optimal management. Previous models of optimal groundwater pumping usually

[1] According to Kern County Crop Report (2016) the value generated per acre of fruits and nuts is about eight times the value generated per acre of field crops.

assume the demand function of water is continuous and elastic. When the data contain both annual and permanent crops, the standard model's demand function describes only the early stage when the water table is high enough that both annual and permanent crops use groundwater. Therefore, it loses the main source of demand elasticity to water table change that occurs when the economy transits between stages. Once we take in permanents, the slope of water demand is much steeper than one might observe in the early stage data.

Using the heterogeneous agent model, I find the optimal groundwater extraction and the value of artificial recharge, and then discuss how to implement such a plan. To begin, it is clear that a market for water will be needed at some point to transfer water from annual farmers to permanent farmers. Then, I first show that plans that assign individual rights to the groundwater stock at once will not produce the socially optimal groundwater extraction path. In this case, individual farmers still want to pump more than the socially optimal level because saving unused water rights in the aquifer creates positive externality by raising the water table. Unlike the stock rights, assigning operational pumping rights equal to the socially optimal extraction per period results in the efficient extraction path when there is no friction in the water market.

Besides being efficient, the optimal pumping plan must also be incentive compatible. Rationing the pumping rights proportional to the size of farmland seems to be a fair arrangement. However, the permanent crop farmers are likely to vote against such regulation because they might have to pay a higher cost to purchase water rights from the annual crop farmers than their gain from the optimal management. Because of the difference in return, annual crop farmers will stop pumping groundwater when the water table falls below a certain level. Below that level only the permanent crop farmers will use groundwater. If pumping rights are equally shared by the farmers, the permanent crop farmers will have to purchase the rights from the annual crop farmers and thus share their profits with them. Considering the cost of buying water rights, the permanent crop farmers may prefer the open access regime where the annual crop farmers leave by themselves.

The incentive compatibility problem worsens if the aquifer does not meet the bathtub assumption. Under that assumption, the aquifer is such that all pumpers have equal access. While in most real cases, aquifer's geology actually determines who are going to use groundwater as the water table declines because some parts are shallower than others (Guilfoos et al., 2013). Like the annual crop farmers, farmers over the shallow part of the aquifer will have to stop extracting when water table falls enough. Then, only the farmers overlying the deep part of the aquifer have access to the resource. They may vote against the *pro rata* rationing and wait for other agents to abandon their wells.

This chapter then looks at policy outcomes under different political decision rules. If the permanent crop farmers in the deep part of the aquifer are pivotal, delay of groundwater management could occur since those farmers would like to wait for others to leave so they can claim the residual water by themselves. Farmers in the shallow part of the aquifer bear the loss of social welfare from uncontrolled extraction, so they want to implement the optimal management early and equally share groundwater rights. To become pivotal, the shallow farmers may want to include landowners who do not use groundwater and share water rights with then to form a winning coalition.

I also examine artificial recharge as a potential way to enhance groundwater use efficiency. Results in this chapter are consistent with Knapp and L. J. Olson (1995). Artificial recharge is part of optimal aquifer management only when water table is very high or very low. When the water table is close enough to the surface, artificial recharge pays because the saved pumping cost for extracting the rest of water is large (because there are relatively many users). When the water table is very low, it pays to save water to grow more permanent crops.

The rest of this chapter is organized as follows. Section 4.2 will discuss the optimal groundwater extraction and crop decision in social planner's case. Section 4.3 will compare the socially optimal path with the path under open access. Section 4.4 considers the implementation of optimal aquifer management, including the regulation specifying pumping rights and the rules to assign the rights. Section 4.5 will discuss the option of artificial recharge. In Section 4.6, I will conclude.

4.2 Social Planner's Groundwater Extraction and Crop Choice

The Model

I consider irrigated agriculture in a region that overlies a groundwater aquifer. Surface water supply is S^H in a wet year ($\mathcal{W}$) and S^L in a dry year ($\mathcal{D}$). Each period denotes a wet-dry cycle where the uncertainty of surface water supply comes from the number of wet and dry years during each cycle. In this chapter, I consider a simple model where each wet-dry cycle begins with a pair of wet dry yeras but I build uncertainty into when the drought ends. With a probability μ it enters the second dry year after which a wet year occurs and a new cycle begins. With a probability $1 - \mu$ it enters a wet year and a new cycle begins immediately. Denote the event that the second dry year happens as d. d is a binary variable that $\Pr(d = 1) = \mu$. This setup can be generalized to a model with a Poisson Process characterizing the upcoming dry years after the first dry year. After a dry year, the probability of another dry year is μ and the probability of a wet year hence entering a new cycle is $1 - \mu$. A more general setting of the stochastic surface water supply can be found in Knapp and Olson (1995). Given our setup, the realized weather would run from $\mathcal{WDWDWDWD}$... (the extreme wet history) to $\mathcal{WDDWDDWDDWDD}$... (the extreme dry history) or anything in the middle. Denote the wet history as $\mathcal{H}^W$ and the dry history as $\mathcal{H}^D$.

In theory, there are various types of recharges, including rainfall, percolation of irrigation water and percolation during surface water conveyance. They are all positively correlated with surface water supply. For simplicity, I normalize natural recharge in dry years to be 0 and only count the recharge in the wet year, which I denote by R. The impact of artificial recharge will be discussed in Section 4.5.

Denote extraction from the aquifer by G, and the depth to water in the aquifer at the beginning of period t by H_t.The per unit pumping cost is $z(H_t)$ at period t. $z'(H) > 0$, namely the pumping cost increases as the water table falls. In this model, we take a specific form $z(H) = \alpha H$. One can think about the pumping cost as the energy consumption to lift groundwater to the surface which is approximately a linear function of water depth. Although depth to water changes within period due to extraction and recharge, I simplify the cost function to ignore the short-term change of water level and only reflect the changes between periods.

Water is used to produce two types of crops, annuals and permanents. It takes a unit of water to produce a unit of annual or permanent crop. By assumption annual crops have no cost and return r^a per year. Denote the annual acreage as K^a. Permanent crops cost C^k to plant and return r^p per year, and die at a rate δ between periods. One can think of the permanent crops as a capital investment that depreciates at rate δ. Without loss of generality, I assume permanent crops are planted in a wet year. Denote the period t stock of permanent crops as K_t, and the period t newly planted crops I_t. New permanent crops planted in period t produce fruit in period $t + 1$.

To capture the conflict of interest between annual and permanent crop farmers, I consider them as separate types. Annual crop farmers are Type-A and they control land that is best suited for annual crop (or their human capital is constrained to annual crops); permanent crop farmers are Type-P and they can grow both kinds of crops. Assume Type-A farmers' land is L^a and Type-P farmers' land is L^p. The number of annual and permanent crops are bounded by the land capacity L and L^p. In theory, farmland or farmers could transit between Type-A and Type-P. One can think that there is some cost of transition so that in equilibrium we observe both annual and permanent crop farmers. This model takes the proportion of annual and permanent cropland as fixed. Normalize total farmland L to be 1: $L^a + L^p = L = 1$.

The social planner's profit each year depends on the type of marginal crop that consumes groundwater. I consider the case where the return of permanent crops r^p is much larger than that of annual crops r^a. So whenever there is a secure water supply, it will be used for permanent crops. The aquifer's large stock of water provides a secure supply, while surface water supply is insecure as it varies between wet and dry year. Consequently, groundwater generates a higher value for permanent crops, so it is always applied to the permanent crops first.

Annual crops at the margin

When annual crops consume groundwater, the social profit in a wet year is:

$$Y^{w}(L^{p}, H) = r^{p} L^{p} + r^{a}(S^{H} + G^{H} - L^{p}) - z(H) G^{H} - C^{k} I, \tag{4.1}$$

All permanent land is used. As surface water is cheaper than groundwater, the social planner will always use all surface water before pumping groundwater. The surplus surface water and the groundwater goes to annual cropland. Some new permanent crops are planted in the wet year.

Similarly, the profit in the first dry year is:

$$Y^{d}_{1}(L^{p}, H) = r^{p} L^{p} + r^{a}(S^{L} + G^{L}_{1} - L^{p}) - z(H) G^{L}_{1} \tag{4.2}$$

and the profit in the second dry year is:

$$Y^{d}_{2}(L^{p}, H) = r^{p} L^{p} + r^{a}(S^{L} + G^{L}_{2} - L^{p}) - z(H) G^{L}_{2} \tag{4.3}$$

Total social profit at period t is:

$$Y(L^{p}, H_t, d_t) = Y^{w}(L^{p}, H_t) + Y^{d}_{1}(L^{p}, H_t) + Y^{d}_{2}(L^{p}, H_t)\mathbb{1}\{d = 1\} \tag{4.4}$$

The stock of permanent crops K_t and water depth H_t are state variables. Their laws of motion are:

$$\begin{aligned} K_{t+1} &= K_t = L^{p} && (4.5)\\ H_{t+1,1} &= H_t - R + G^{H} + G^{L}_{1} \quad \text{when } d_t = 0 && (4.6)\\ H_{t+1,2} &= H_t - R + G^{H} + G^{L}_{1} + G^{L}_{2} \quad \text{when } d_t = 1 && (4.7) \end{aligned}$$

In the analysis of optimal groundwater use, I assume the aquifer satisfies the bathtub assumption under which water flows instantaneously within the aquifer. Therefore, the changes of water stock, R and G, affect the water table equally no matter where the extraction of recharge is taken place. Further, by assumption, depth to water and maximum water depth are the same at every location. Since the size of aquifer is normalized to 1, a change in R or G are equal to a change in water depth. Long-term changes in water depth depends on the length of the drought.

Permanent crops at the margin

Similar as above, if only the permanent crops consume groundwater, the social profit in the wet year is:

$$Y^w(K,H) = r^p K + r^a(S^H - K) - C^k I, \tag{4.8}$$

the profit in the next two dry years are:

$$Y_1^d(K,H) = Y_2^d(K,H) = r^p K - z(H)(K - S^L) \tag{4.9}$$

Here, we consider the case when total permanent cropland $L^p \in (S^L, S^H)$. There is enough surface water to irrigate all permanents in a wet year, but not in a dry year. The equilibrium acreage of permanent crops K will also be in the interval (S^L, S^H). It is socially optimal to grow more permanent crops than S^L because recharge to the aquifer in the wet year provides extra secured irrigation supply. When only permanent crops consume groundwater, the social planner use the surplus water to grow annuals in the wet year and pump groundwater to irrigate all the permanents in the dry year.

Groundwater extraction G always takes a corner solution $G = K - S^L$ when permanent crops are marginal. Theoretically, the farmers could choose to only irrigate a fraction of the permanent cropland and let the rest of trees die (G takes an interior solution). This happens if the cost of using extra groundwater exceeds the present value of the future returns by the permanent crop. If this is true, the farmers are unlikely to plant the new permanent crops at the beginning, so I will take a corner solution $I = 0$.[2] In this model, I consider that the increased pumping cost due to the realization of second dry year is smaller than the fixed cost of planting permanent crops so whenever I takes positive value, G will take a corner solution.

Total social profit at period t is:

$$Y(K_t, H_t, d_t) = Y^w(K_t, H_t) + Y_1^d(K_t, H_t) + Y_2^d(K_t, H_t)\mathbb{1}\{d_t = 1\} \tag{4.10}$$

The law of motion of permanent crop stock and water depth are:

$$K_{t+1} = K_t(1-\delta) + I \tag{4.11}$$

$$H_{t+1,1} = H_t - R + K_t - S^L \qquad \text{when } d_t = 0 \tag{4.12}$$

$$H_{t+1,2} = H_t - R + 2(K_t - S^L) \qquad \text{when } d_t = 1 \tag{4.13}$$

The social planner wants to maximize the present value of social profits:

$$\sum_{t=0}^{\infty} \rho^t Y(K_t, H_t, d_t) \tag{4.14}$$

where ρ is the discount factors and $0 < \rho \leq 1$. The optimal control problem is to choose the path of $\{G_t, I_t\}_{t=0}^{\infty}$ that maximizes the expected value of (4.14) subject to the corresponding profit function and transition equations at period t. The permanent crop planting decision I_t is made in the wet year, so when deciding I_t, the social planner takes an expectation over the severity of drought at period t and all periods after.

Socially optimal pumping plan

Intuitively, the transition path of $\{H_t, K_t\}$ under optimal management includes two stages depending on the type of marginal crop that uses groundwater. At Stage 1, water depth H is small enough so it is profitable to irrigate the annual crops with groundwater. Given the constant return of annual crops and the falling water table, all land will be farmed since if

[2] An exception is when μ is very small and the variation of surface water supply is huge, so the farmers will plant permanent crops at the wet year and let them die if the second dry year happens.

it is profitable to irrigate the annual crop with groundwater at next period, it pays to grow more now and to plant all the permanents possible.

At Stage 2, water depth has increased to the point that it is no longer profitable to use groundwater for annuals but it is still profitable for permanent crops. Assume $L^p > S^L + R$ so that the water table keeps falling if all permanent cropland is farmed. Finally when the water table falls below the level defined by H^i, permanent crop acreage will fall below L^p as the pumping cost is so high that it is not profitable to deplete the aquifer further. There will be an upper bound of water depth H^s at which the permanent crop stock $K^s = \frac{R}{2} + S^L$ so that even when two droughts ($d = 1$) occur in a row, the water table will not fall below H^s. At H^s, if a normal drought occurs ($d = 0$), the water table will recover, so will the permanent crop stock. Water depth and permanent crop stock converges to H^s and K^s when severe droughts (two consecutive dry years) occur again.

Proposition 3 in Knapp and L. J. Olson (1995) guarantees the convergence of groundwater stock to a invariant distribution. In this model, I solve the Stage 2 stochastic dynamic programming problem first and characterize the full path of optimal control using backward induction.

Stage 2

At Stage 2, the social planner makes a planting decision at the wet year and takes an expectation over the length of following drought. The Bellman equation is:

$$V(K,H) = \max_I r^p K + r^a(S^H - K) - C^k I + (1+\mu)[r^p K - z(H)(K - S^L)] + (1-\mu)\rho V(K', H_1') + \mu\rho V(K', H_2') \tag{4.15}$$

with $K' = (1-\delta)K + I$, $H_1' = H - R + K - S^L$ and $H_2' = H - R + 2(K - S^L)$.

When I takes an interior solution, the first order condition with respect to I is:

$$\frac{\partial V(K,H)}{\partial I} = -C^k + (1-\mu)\rho V_K(K', H_1') + \mu\rho V_K(K', H_2') = 0 \tag{4.16}$$

By Envelope Theorem:

$$\begin{aligned} V_K(K,H) &= r^p - r^a + (1+\mu)[r^p - z(H)] + (1-\mu)\rho V_K(K',H_1')(1-\delta) + \mu\rho V_K(K',H_2')(1-\delta) \\ &\quad +(1-\mu)\rho V_H(K',H_1') + 2\mu\rho V_H(K',H_2') \qquad (4.17) \\ V_H(K,H) &= -(1+\mu)\alpha(K-S^L) + (1-\mu)\rho V_H(K',H_1') + \mu\rho V_H(K',H_2') \qquad (4.18) \end{aligned}$$

Equations (4.16)-(4.18) characterize the transition path of $\{H_t, K_t\}$ under optimal management when the newly planted permanent crops I_t takes an interior solution ($0 < I < \delta L^p$). Given the path of the interior solutions, we can identify the threshold H^i where the I starts to take the interior solution. The permanent crop stock $K^i = L^p$ when the stock starts to fall[3]. Then we can figure out the path before $\{H^i, K^i\}$ as $K = L^p$ for $H < H^i$. This completes the Stage 2 optimal transition path of $\{H, K\}$. Based on the Stage 2 result, we solve the Stage 1 problem to determine the threshold of water depth H^a when the dynamic problem transitions from Stage 1 to Stage 2.

Stage 1

When the annual crop is the marginal crop that uses groundwater, the permanent crop stock is $K = L^P$. The Bellman equation for determining $\{G^H, G_1^L, G_2^L\}$ is:

$$\begin{aligned} V(L^p,H) &= \max_{G^H, G_1^L} Y^w(L^p,H) + Y_1^d(L^p,H) + \mu Y_2^d(L^p,H) + (1-\mu)\rho V(L^p,H_1') + \mu\rho V(L^p,H_2') \\ \text{with} &\quad G_2^L = \arg\max Y^w(L^p,H) + Y_1^d(L^p,H) + Y_2^d(L^p,H) + \rho V(L^p,H_2') \qquad (4.19) \end{aligned}$$

where $K' = K = L^p$, $H_1' = H - R + G^H + G_1^L$ and $H_2' = H - R + G^H + G_1^L + G_2^L$. The pumping decisions in a wet year and the first dry year are made with the uncertainty of the second dry year, while when making the second dry year pumping decision, the decisions before are given and there is no uncertainty about the future.

When transitioning from Stage 1 to Stage 2, groundwater extraction takes a corner solution ($G = 0$ in wet year and $G = L^p - S^L$ in dry year). This could happen in any of the three years

[3]It is possible that I will takes a corner solution $I = 0$ when the permanent crop stock K falls. Here we assume the depreciation rate δ is large enough so I always take the interior solution when K declines.

during a period. As water depth and the pumping cost are non-decreasing when $K = L^p$, if it is not profitable to pump groundwater for annuals in the early years, it is not profitable to irrigate annual crops using groundwater in the years after either. I consider the case when $G = 0$ takes place in the wet year. The other two cases have similar solutions.

Since the transition takes place in the wet year, in the dry years following, the social planner only uses the surface water supply to irrigate existing crops and no permanent crop planting or pumping decision needs to make. The social planner will not pump groundwater for annual crops in the next drought. The value function is:

$$V(L^p, H) = \max_{I,G^H} Y^w(L^p, H) + Y_1^d(L^p, H) + \mu Y_2^d(L^p, H) + \rho(1-\mu)V(K', H_1') + \rho\mu V(K', H_2') \tag{4.20}$$

with $K' = (1-\delta)L^p + I$, $H_1' = H + G^H + (L^p - S^L)$ and $H_2' = H + G^H + 2(L^p - S^L)$.

The first order condition with respect to G^H is

$$\frac{\partial V(L^p, H)}{\partial G^H} = r^a - z(H) + (1-\mu)\rho V_H(K', H_1') + \mu\rho V_H(K', H_2') = 0 \tag{4.21}$$

As $\{K', H_1'\}$ and $\{K', H_2'\}$ are on the optimal path of Stage 2, the values of $V_H(K', H_1')$ and $V_H(K', H_2')$ are given. From Equation (4.21) and $G^H = 0$, we can identify the minimum water depth H^a where annual crops stop using groundwater.

Combining the the results at Stage 1 and Stage 2, the path of $\{H, K\}$ under optimal management is:

1. For $H \in [H_0, H^a]$: $K = L^p$; $H' = H - R + 1 - S^H + (1 - S^L)(1 + \mathbb{1}\{d = 1\})$ until $H = H^a$;

2. for $H \in [H^a, H^s]$: $K = L^p$ at the beginning, then it converges to an invariant distribution around K^s; $H' = H - R + K - S^H + (K - S^L)(1 + \mathbb{1}\{d = 1\})$ and it varies around H^s in the end.

The stochastic control problem does not have a closed form solution for H^a and H^s. However, we can solve for the two cases of the wettest possible history $\mathcal{H}^W$ and driest history $\mathcal{H}^D$ to infer the upper and lower bound of H^a and H^s.

Optimal path under extreme wet or dry condition

Suppose the probability of a second dry year μ is a parameter the agent draws from the history. If the history of weather realizations is $\mathcal{H}^W$, the social planner updates his belief and takes $\mu = 0$ to make the optimal extraction and crop decision. If the history of weather realization is $\mathcal{H}^D$, the social planner updates his belief and uses $\mu = 1$.

The outcome under extreme wet condition is:

$$H^{s,W} = \frac{2r^p - r^a - C^k(\frac{1}{\rho} + \delta - 1)}{\alpha} - \frac{\rho R}{1-\rho} \tag{4.22}$$

$$H^{a,W} \approx \frac{r^a}{\alpha} - \frac{\rho(L^p - S^L)}{\alpha(1-\rho)} \tag{4.23}$$

$$K^{s,W} = R + S^L \tag{4.24}$$

The outcome under extreme dry condition is:

$$H^{s,D} = \frac{3r^p - r^a - C^k(\frac{1}{\rho} + \delta - 1)}{2\alpha} - \frac{\rho R}{1-\rho} \tag{4.25}$$

$$H^{a,D} \approx \frac{r^a}{\alpha} - \frac{\rho(L^p - S^L)}{\alpha(1-\rho)} \tag{4.26}$$

$$K^{s,D} = \frac{R}{2} + S^L \tag{4.27}$$

Solutions to the two dynamic programming problems under extreme weather conditions can be found in Appendix 4.A. In each case, $H^{s,W}$ and $H^{s,D}$ are the corresponding steady state water depth. After H hits the steady state level, the water table only varies within a wet-dry cycle but not between cycles. Within the wet-dry cycle, the water table rises in the wet year and falls during the dry year(s).

Based on the outcomes under extreme conditions, with a $\mu \in (0, 1)$, the stock of permanent crops converges to a distribution around $K^s = K^{s,D}$, the water depth converges to a distribution around $H^s \in (H^{s,W}, H^{s,D})$ and the water depth where the social planner stops irrigating the annuals with groundwater is $H^a \approx \frac{r^a}{\alpha} - \frac{\rho(L^p - S^L)}{\alpha(1-\rho)}$. The social planner's minimum permanent crop stock is the same as the steady state level under extreme dry condition since that is the maximal acreage of permanent crops the social planner can grow without depleting the aquifer. Water depth varies between the extreme wet steady state and extreme dry steady state since at the upper bound, there is a chance water level will recover if only one dry year occurs and at the lower bound, there is a chance water table will fall if the second dry year occurs. The water depth where the social planner stops pumping groundwater for annual crops is similar under different weather histories[4]. When the water table is relatively high, the shadow price of groundwater is similar in all histories. The uncertainty of weather condition mainly affects the state towards which water depth and permanent crops converge when water scarcity binds.

Next, I will discuss the efficiency gain from optimal management, the issue of implementing the optimal regulation and artificial recharge based on the model results. For computational convenience, I assume $\mu = 0$ in the following discussion. This is the case under extreme wet condition. In theory, the gain from management should be even larger under worse weather conditions when water is scarcer.

When $\mu = 0$, under the optimal extraction plan, the path of changes of H, K, K^a, I and G is:

1. For $H \in [H_0, H^a]$: $H' = H - R + 2 - S^H - S^L$; $K = L^p$; $K^a = L^a$; $I = \delta L^p$; $G^H = L - S^H$; $G^L = L - S^L$;

2. for $H \in [H^a, H^s)$: $H' = H - R + L^p - S^L$; $K = L^p$; $K^a = S^H - L^p$ in wet years and $K^a = 0$ in dry years; $I = \delta L^p$; $G^H = 0$; $G = G^L = L^p - S^L$.

3. for $H = H^s$: $H' = H$; $K = K^s$; $K^a = S^H - K^s$ in wet years and $K^a = 0$ in dry years; $I = \delta K^s$; $G^H = 0$; $G = G^L = K^s - S^L$.

[4]The differences come from the difference in the steady state water depth and groundwater stock under the two extreme weather histories. Although the steady state may occur far into the future, it still affects the evolution of the groundwater stock after H^a, so H^a is slightly different under the two cases.

The details of characterizing the optimal path are in Appendix 4.A.

4.3 Open Access to Groundwater

To compare with the optimal management, I also characterize equilibrium groundwater extraction and crop choice when individual farmers have open access to groundwater. Unlike the social planner, individual farmers take future water depth as given and ignore the consequences of their behavior on the water level when making their pumping and planting decisions. I assume there is a surface water market so that the surface water will always be reallocated to high-value users when there is water scarcity. As discussed by Chapter 3, a well-functioning surface water market may lower total social welfare when there is heterogeneity in access to groundwater. I will discuss this issue in Section 4.4 when we relax the assumption that the aquifer is a bathtub. Here, however, I maintain the bathtub assumption and because all farmers have the same access to groundwater, a surface water market is efficient.

Suppose each individual farmer holds l units of farmland. Her per-acre surface water supply over a wet-dry cycle is $s = s^H + s^L$. If she is a Type-A farmer, she only grows annual crops. Her profit at period t is:

$$y_t^a(H_t) = r^a(g_t + s) - z(H_t)g_t \tag{4.28}$$

If annual crop farmers use groundwater, the surface water is infra-marginal and there is no surface water trade. As the individual ignores her own impact on groundwater depth, she solves the individual optimization problem for each period. Therefore, $g_t = 2l - s$ if $H_t < \frac{r^a}{\alpha}$ and $g_t = 0$ otherwise. Similar as H^a in the social planner's case, denote

$$h^a = \frac{r^a}{\alpha} \tag{4.29}$$

h^a is the water depth where annual crop farmers stop withdrawing groundwater in the open access regime.

For a Type-P farmer, she can grow both permanent and annual crops. For $H < h^a$, all permanent crop farmers grow permanent crops and fully irrigate their land. Once $H > h^a$, annual crop farmers no longer use groundwater. Type-P farmers purchase surface water rights from the Type-A farmers since the cost of extraction is larger than the return of the annual crops. In wet year, Type-P farmers can purchase enough water to irrigate all their land without groundwater extraction, while in a dry year, they need to pump groundwater as the total surface water supply cannot meet the demand for all permanent cropland.

I consider the optimization problem of a representative permanent crop farmer when the water depth is $H > h^a$. The price of surface water equals the return to annuals r^a in the wet year when water is abundant and it equals the pumping cost $z(H)$ in a dry year when water is scarce. The farmer's profit function at period t is:

$$y_t^p(k_t, H_t) = r^p k_t - r^a(k_t - s^H) + r^p k_t - z(H_t)(k_t - s^L) - i_t C^k \tag{4.30}$$

Because planting new permanent crops i_t affects future profits, the farmer chooses $\{i_t\}_{t=0}^{\infty}$ to maximize the sum of future profits: $\sum_{t=1}^{\infty} y_t^p(k_t, H_t)$. Like the social planner, the Type-P farmer will use all land to grow permanent crops($k = l$) as long as $H < h^s$ and only grow k^s acreage of permanents while using the surplus surface water in the wet year to grow annuals. h^s and k^s are the steady state of water depth and permanent crop acreage in the competitive case:

$$h^s = \frac{2r^p - r^a - C^k(\frac{1}{\rho} + \delta - 1)}{\alpha} \tag{4.31}$$

$$k^s = \frac{l}{L^p}(R + S^L) \tag{4.32}$$

Note that, in the equilibrium above the steady state stock of permanent crops k^s is identical for all permanent crop farmers. In fact, it does no have to be so; however, a necessary condition for the steady state is that the stock of permanent crops be $\sum k^p = R + S^L$. If $H < h^s$, i_t always takes a corner solution, so the permanent crop farmers fully use their land $k_t = l$.

Social planner vs. Open access

With an efficient surface water market, the inefficiency of the open access regime mainly comes from the commons problem. Individual farmers ignore the impact of their extraction on the water level in the aquifer and pump too much. Optimal management improves social welfare in two ways if we compare the key water level H^s and H^a with h^s and h^a.

First, $h^a - H^a \approx \frac{\rho(L^p - S^L)}{\alpha(1-\rho)} > 0$. The social planner stops applying groundwater to the annual crops earlier than the individual farmers. That not only delays depletion of the aquifer, but also reallocates some groundwater from annual crops now to higher-return permanent crops in the future.

Second, $h^s - H^s = \frac{\rho R}{1-\rho} > 0$. The social planner stops depleting the aquifer at a water depth shallower than the individual farmers. The savings from lower pumping costs are larger than the value of depleting extra stock of groundwater. However, individual pumpers deviate from the socially optimal extraction when $H = H^s$ because of the commons problem.

In theory, both channels of efficiency gain could be significant. Efficiency gain from the first channel is positively correlated to the scale of permanent crops L^p and negatively correlated with surface water supply in the dry year S^L. When L^p increases or S^L decreases, the gain from reallocating water from annual to permanent crops is larger since the permanent crops yield higher return. This channel is likely to be underestimated if people ignore the sharp difference between annual and permanent crops and estimate a smooth water demand function.

The second channel could have a huge influence if natural recharge R is large. Since the steady state permanent crop acreage equals to $R + S^L$, a larger natural recharge means a larger equilibrium permanent crop acreage and a larger amount of groundwater to be extracted at the steady state. That raises the social planner's incentive to maintain a higher water table and thus a lower pumping cost. On the opposite, when R is small enough, the equilibrium extraction is so low that even the social planner feels unnecessary to save water for a lower pumping cost. When $R = 0$, the socially optimal steady state water depth is the same as the competitive case. There is no gain from optimal management in this case.

The first channel of efficiency gain becomes significant when water depth approaches H^a and the second channel of efficiency gain is important when water depth is close enough to the steady state. For a water depth that is very low, the efficiency gain of groundwater management occurs in a far future so the discounted welfare improvement from optimal management is small.

However, for a water depth close to H^a, according to this model, the efficiency gain from optimal management can be significant as it reallocates groundwater from low-value annuals to high-value permanents. Studies that fail to consider the difference of the two types of crops will take a smooth water demand function and hence miss the efficiency gain from this channel. For example, in Knapp, Weinberg, et al. (2003), they estimated a water demand function using Kern County Water Agency 1998 report, when both annual and permanent crops were farmed in the county and the annual crops were always the marginal crops. The estimated water demand function then only captures the demand elasticity of annual crops and ignores the inflexible water demand from high-value permanent crops. That biases down the estimate of efficiency gain.

The second channel of efficiency gain usually does not add too much to the welfare improvement of optimal management. Even though the equilibrium recharge is significant and the difference of equilibrium water depth between optimal management and common access regime is large as in Knapp and L. J. Olson (1995), the time required to reach the steady state is so long that the discounted value of the efficiency gain is tiny. This is often the case for large aquifer with plenty of groundwater stock to deplete before water becomes scarce. For small aquifers, water is scarce; therefore, it is important to manage the steady state water depth as the efficiency gain is realized immediately.

4.4 Implementation of Optimal Aquifer Management

Since the benefit of managing the aquifer could be substantial with heterogeneous farmers, it is important to design a mechanism to implement the socially optimal groundwater use plan. The literature of natural resource management has discussed various mechanisms that improve social welfare. This chapter will focus on the institution that defines the property rights of groundwater. Other means such as pumping tax and restriction of land use may also achieve the optimal outcome. I will briefly talk about them when discussing the design of pumping rights.

Defining the property rights of groundwater includes two important aspects: the design of water rights, and an incentive compatible assignment of those rights. I assume that there will be an efficient water market where the agents could trade their water rights (both surface and ground water) without transaction costs. Thus the design of groundwater rights determines whether the market can induce a socially efficient outcome or not. How the water rights are assigned does not affect the efficient allocation according to Coase (1960). However, the assignment of water rights could affect whether the new policy will be approved by the voters.

Design of water rights

The water rights design that has been widely discussed or implemented including one-time groundwater stock rights and operating pumping rights. V. L. Smith (1977) proposes to create water rights for the stock of groundwater to solve the water valuation problem. According to Chapter 2, such an arrangement does not completely solve the commons problem as the agents tend to use more stock rights in the early period than is efficient because saving the stock rights creates positive externality as it raises the water table which also benefits others. Suppose the rights for natural recharge are negligible for this section[5]. Proposition 1 states the inefficiency result for stock rights.

Proposition 4.1 *If one-time stock rights of groundwater are created and distributed to a large number of pumpers, the total extraction per period will not match the socially optimal volume.*

Proof of Proposition 4.1 is in Appendix 4.B. Intuitively, when the return gap between annual and permanent crops is large enough, it takes a long time after annuals no longer

[5]The issues of distributing the flow rights are similar to the issues of stock rights as the main conflict of interests is always between farmers with access to groundwater and those without.

access groundwater before the permanent crop farmers stop mining the aquifer. At H^a, the marginal value of holding water rights is very small since the scarcity will arise far into the future. Therefore, the price of stock rights will be so tiny that the annual crop farmers will essentially ignore it and continue pumping groundwater until H approaches to h^a. As a result, assigning water rights for groundwater stock at once does not solve the commons problem.

To avoid the externality caused by unused water rights, individual farmers must not have discretion to choose extraction. Instead, each period's available water rights should equal the socially optimal extraction. Such varying water rights already exist and are called operating pumping rights as in Chapter 2. In that chapter, we have discussed how some Southern California basins set their pumping rights per period equal to the recharge to the aquifer. They do not issue pumping rights for the stock of water since their groundwater stock has been severely depleted. In this chapter, we have shown that the optimal aquifer management includes a period of depleting the groundwater stock and then maintaining the steady state water table by setting average pumping to equal average recharge to the aquifer. As the recharge is assumed to be constant, the operating pumping rights discussed in this chapter are designed for the stock of groundwater:

Operating Pumping Rights: For $H \geq H^a$, the pumping rights are 0 in wet years. In dry years, the pumping rights are $L^p - S^L$ for $H \in [H^a, H^s)$ and R for $H = H^s$.

Operating pumping rights assign exactly the same number of pumping rights to the farmers per period as the optimal extraction derived in the social planner's case. When there is a water market without friction, the water use is always efficient, so is the crop decision. Similar to pumping rights, a varying pumping tax such that the annual crop farmers stop pumping at H^a and the permanent crop farmers stop further depleting the aquifer at H^s generates the same result. Land use control that restricts growing annuals when water depth is beyond H^a may also work. The political issues to implement those policies could be different. In this chapter, we discuss the political conflict raised by water rights assignment.

Incentive compatibility of optimal management

The Bathtub Assumption Holds

Because of the heterogeneity among the farmers, the assignment of pumping rights should also be incentive compatible to make sure that the policy is approved by the agents. The following assignment rule is individually incentive compatible when the aquifer satisfies the bathtub condition.

Assignment 1: Pumping rights are shared by all farmers proportional to their land when $H \in [H^a, h^a]$ and pumping rights are only assigned to Type-P farmers proportional to their land when $H > h^a$.

When $H \in [H^a, h^a]$, under open access, all the farmers use groundwater proportional to their land. According to the Assignment 1, they hold exactly the same amount of water rights as under open access. Since the water market gives the farmers the option to trade, they all better off from the increased total social welfare.

When $H > h^a$, total social welfare under optimal management increases compared with the open access regime. Since the annual crop farmers sell their surface water rights to the permanent crop farmers in the dry year, there exists a price of surface water rights such that annual and permanent crop farmers share the increased social welfare.

Assignment 1 discriminates among farmers based on the crop they grow. Such arrangement exists in some water districts in the Central Valley of California. Those districts have the rule that in dry years, permanent cropland has the priority over annual cropland in receiving irrigation water. The political resistance to implement such regulation should be small when the aquifer satisfies the bathtub condition. Moreover, if the farmers are given a take-it-or-leave-it offer of Assignment 1, they will accept it, since they are all better off compared with the outside option. Of course, the annual crop farmers might seek a more even water rights arrangement. We discuss the political decision-making process in detail in next subsection[6].

[6] Assignment 1 satisfies the incentive compatibility for each individual since all farmers are better off

The Bathtub Assumption Fails

When the bathtub assumption does not hold, one consequence of depleting the basin is that some farmers lose their access to groundwater because they lie above the shallow part of the aquifer. The location of farmland creates another dimension of heterogeneity that affects the farmer's access to groundwater. With well-defined property rights, and if groundwater rights can be traded separately from land, the location of farmland does not matter as the rights holders could exercise their water rights in remote wells and convey water to their land. However, before establishment of the property rights, groundwater extraction and use are usually attached to the land where it is pumped. Therefore, under the open access regime, some farmers may no longer be able to farm with groundwater if the water table falls to a level beyond their reach. The remaining farmers benefit from their exit because total extraction falls, and depth to water grows more slowly.

It is then not surprising that Assignment 1 might not be approved by all the farmers. Farmers may not want to share pumping rights with others if they lie above the deep part of the aquifer and are the only users who can pump when water table falls to certain level. They may vote against the policy to delay the groundwater management.

To characterize the political conflicts caused by Assignment 1, I consider an aquifer with a "V" shape. The share of land that has access to groundwater when water depth is H is given by:

$$L(H) = 1 - \tau(H - H_0) \tag{4.33}$$

where τ is the slope of the aquifer. The bottom of the aquifer corresponds to water depth $\bar{H} = \frac{1}{\tau} + H_0$.

I also use $L(H)$ to denote the group of farmers with access to groundwater when the water depth is H. I call those farmers "groundwater users" and those without access to groundwater "non-groundwater users." At the beginning, $H = H_0$ so all land has access

compared with the open access regime. A proposal that allocates all water equally may also win if the annual crop farmers form a winning coalition given the specific political decision rule.

to groundwater. When water depth increases, farmland at the edge of "V" loses its access. Suppose $\bar{H} > h^s$ so the aquifer will never be completely mined.

Individual farmers' payoff differ between the optimal management and open access region. The main source of variation is the usage of groundwater which is affected by their location on the aquifer. The value of their surface water rights also differ depending on the equilibrium water value under the two regimes. To illustrate the political difficulty to implement the optimal management plan, I will focus on groundwater use by agents over different parts of the aquifer. I will discuss the influence of the price of surface water and how it affects the political issue at the end of this section.

Political decision-making problem

In this subsection, for simplicity, I assume surface water supply is starkly uncertain $S^H = L$ and $S^L = 0$ so we do not need to consider the farmers' payoff in wet years as there is abundant surface water to farm all land. Moreover, groundwater is the only source of irrigation water in dry years, and we do not need to consider the impact from surface water trade. I also assume the permanent crop return r^p has already captured the fixed cost of planting and the depreciation of crops, so we do not need to consider them in this section.

The political decision-making process to decide whether or not to implement the optimal groundwater management plan (operating pumping right and assignment rule 1) runs as follows. Suppose the political process starts at water depth $H_t < H^a$. All farmers in $L(H_t)$ have voting rights and they will share the pumping rights as defined by the assignment rule 1. The voters will vote for a policy H^r which is the level of water depth where the regulation goes into place. The farmers can propose and vote for multiple H^r's within a period. If no H^r is passed by the voters, the groundwater aquifer remains open access and the political process is repeated at $t + 1$. The questions are whether there is an H^r that will be supported by a vote of the majority of the farmers and if yes, what is the highest H^r?

The farmers' preference over the policy is determined by their payoff under two regimes.

Denote the farmers' payoff under open access by w and under optimal management by v. I use $\mathbf{H}$ to denote a farmer who loses her access to groundwater when water depth hits H. Denote H_t as period 0.

Under open access, for a farmer $\mathbf{H} \in [\mathbf{H_t}, \mathbf{h^a}]$, her payoff is:

$$w_1^a(\mathbf{H}) = \sum_{t=0}^{t(H)} \rho^t [r^a - z(\frac{H_t + H}{2})] \text{ or } w_1^p(\mathbf{H}) = \sum_{t=0}^{t(H)} \rho^t [r^p - z(\frac{H_t + H}{2})] \tag{4.34}$$

where $t(H) = H - H_t$ is the number of periods before the water depth hits H and the farmer loses access to groundwater[7]. $z(\frac{H_t+H}{2})$ is the average pumping cost. Note, w_1^a denotes the payoff for an annual farmer and w_1^p denotes the payoff for a permanent farmer.

For a permanent crop farmer $\mathbf{H} \in (\mathbf{h^a}, \mathbf{h^s}]$, her payoff is:

$$w_2^p(\mathbf{H}) = \sum_{t=0}^{t(h^a)} \rho^t [r^p - z(\frac{H_t + h^a}{2})] + \sum_{t(h^a)}^{t^*(H)} \rho^t [r^p - z(\frac{h^a + H}{2})] \tag{4.35}$$

where $t^*(H) = t(h^a) + \frac{H-h^a}{L^p}$. Groundwater depletes slower (at rate L^p) when annual crop farmers are out.

For an annual crop farmer $\mathbf{H} > \mathbf{h^a}$, her payoff is:

$$w_2^a(\mathbf{H}) = \sum_{t=0}^{t(h^a)} \rho^t [r^a - z(\frac{H_t + h^a}{2})] \tag{4.36}$$

The annual crop farmers only farm when $H \leq h^a$.

For a permanent crop farmer $\mathbf{H} > \mathbf{h^s}$, her payoff is:

$$w_3^p(\mathbf{H}) = \sum_{t=0}^{t(h^a)} \rho^t [r^p - z(\frac{H_t + h^a}{2})] + \sum_{t(h^a)}^{t^*(h^s)} \rho^t [r^p - z(\frac{h^a + h^s}{2})] \tag{4.37}$$

The payoff at steady state is 0 because the return r^p equals the pumping cost $z(h^s)$.

Given a proposal to regulate the aquifer at water depth H^r, the farmers calculate their payoff under regulation. H^r is always no smaller than H^a since for water depth $H < H^a$, there is

[7]The amount of groundwater at each water depth level reduces when water depth increases because the aquifer becomes narrower. However, this farmer's use of groundwater at each water depth level is unchanged since other farmers also lose their access to groundwater because of the falling water table.

no gain from regulation. After regulation, all farmers share the pumping rights for water stock between $[\min\{H^r, h^a\}, h^a]$, and only the permanent crop farmers share the pumping rights for water stock between $[\max\{H^r, h^a\}, H^s]$.

If $H^r < h^a$, an annual crop farmer's payoff after regulation is:

$$v_1^a(H^r) = L^p \sum_{t=t(H^r)}^{T(H^r)} \rho^t [r^p - z(\frac{H^r + h^a}{2})] \tag{4.38}$$

where $T(H^r) = t(H^r) + (h^a - H^r)\frac{L(h^a)+L(H^r)}{2L^p}$. Groundwater stock is depleted slower than under open access because total extraction is limited to L^p per period. Given the fixed amount of extraction, groundwater depletes faster when water is deeper because of the "V" shape. $\frac{L(h^a)+L(H^r)}{2}$ measures this change. The farmer shares $\frac{L^p}{L} = L^p$ fraction of the payoff that equals her share of pumping rights.

A permanent crop farmer's payoff is:

$$v_1^p(H^r) = L^p \sum_{t=t(H^r)}^{T(H^r)} \rho^t [r^p - z(\frac{H^r + h^a}{2})] + \sum_{t=T(H^r)}^{T_1^*(H^s)} [r^p - z(\frac{h^a + H^s}{2})] \tag{4.39}$$

where $T_1^*(H^s) = T(H^r) + (H^s - h^a)\frac{L(H^s)+L(h^a)}{2L^p}$. The groundwater depletion when $H > h^a$ is faster than under open access since in that case, only a fraction of permanent crop farmers can use groundwater.

If the regulation $H^r > h^a$, the annual crop farmers' payoff is 0 after regulation. A permanent crop farmer's payoff is:

$$v_2^p(H^r) = \sum_{t=t^*(H^r)}^{T_2^*(H^s)} [r^p - z(\frac{h^a + H^s}{2})] \tag{4.40}$$

where $T_2^*(H^s) = t^*(H^r) + (H^s - H^r)\frac{L(H^s)+L(H^r)}{2L^p}$.

Now I derive each farmer's preference over the policy choice H^r. First of all, for any farmer **H**, she prefers earlier regulation (a smaller H^r) if $H^r > H$. That is because after the farmer loses her access to groundwater, she can only benefit from the pumping rights which are assigned by regulation.

For an annual crop farmer $\mathbf{H} < \mathbf{h^a}$, her payoff from the regulation $H^r < H$ is:

$$\begin{aligned} W_1^a(\mathbf{H}) &= w_1^a(\mathbf{H^r}) + v_1^a(H^r) \\ &= \sum_{t=0}^{t(H^r)} \rho^t [r^a - z(\frac{H_t + H^r}{2})] + L^p \sum_{t=t(H^r)}^{T(H^r)} \rho^t [r^p - z(\frac{H^r + h^a}{2})] \end{aligned} \tag{4.41}$$

As long as $r^a < L^p r^p$, the annual crop farmer always prefers a smaller H^r. This condition holds in this model since we assume the return of permanent crops is much larger than annual crops. The same argument holds for any annual crop farmer $\mathbf{H} \geq \mathbf{h^a}$. For the annual crop farmers, although they can use more groundwater under open access than the pumping rights assigned to them, the return from their land is much smaller than the return from selling the pumping rights to permanent crops farmers. As a result, the annual crop farmers always prefer earlier regulation (smaller H^r).

For a permanent crop farmer $\mathbf{H} < \mathbf{h^a}$, her payoff from the regulation $H^r < H$ is:

$$\begin{aligned} W_1^p(\mathbf{H}) &= w_1^p(\mathbf{H^r}) + v_1^p(H^r) \\ &= \sum_{t=0}^{t(H^r)} \rho^t [r^p - z(\frac{H_t + H^r}{2})] + L^p \sum_{t=t(H^r)}^{T(H^r)} \rho^t [r^p - z(\frac{H^r + h^a}{2})] + \sum_{t=T(H^r)}^{T_1^*(H^s)} [r^p - z(\frac{h^a + H^s}{2})] \end{aligned} \tag{4.42}$$

The permanent crop farmer needs to make a trade-off when choosing the optimal H^r. The regulation slows groundwater depletion, but after regulation, the permanent crop farmer needs to share pumping rights with farmers who have already lost their access to groundwater. This is different from the bathtub case when the permanent crop farmers are strictly better off after regulation because their total water consumption does not change. In this model, the larger H^r is, the more farmers have lost their access to groundwater. Therefore, the permanent crop farmer's loss from sharing pumping rights with others is larger and she is more likely to prefer regulation delay (larger H^r). Let H^* be the threshold where the permanent crop farmer gains more from unlimited extraction than regulation. For $H^r < H^*$, the farmer prefers a smaller H^r; for $H^r \geq H^*$, the agent prefers a larger H^r.

Without loss of generality, I assume $H^* < h^a$. For permanent crop farmers $\mathbf{H} \geq \mathbf{h^a}$, H^* also applies if the permanent and annual crop farmers are randomly distributed over the aquifer.

The trade-off for permanent crop farmers when choosing an H^r above h^a is the same.

As a result, for annual crop farmers and permanent crop farmers $\mathbf{H} \leq \mathbf{H}^*$, they always prefer a smaller H^r and their ideal point to implement optimal management plan is H^a. For permanent crop farmers $\mathbf{H} > \mathbf{H}^*$, they prefer a smaller H^r for $H^r < H^*$ or $H^r > H$ and a larger H^r for $H^* \leq H^r \leq H$. Their ideal point to implement optimal management plan is H^a or H. H^* must be smaller than H^s since at H^s, permanent farmers $\mathbf{H} > \mathbf{H^s}$ always want a later regulation than H^s:

Proposition 4.2 *Farmers over the deep part of the aquifer prefer a deeper steady-state water level H_v^s than the socially optimal level H^s.*

A formal proof is in Appendix 4.C.

There is another threshold $H^{**} > H^*$ where the agent $\mathbf{H}^{**}$ is indifferent between H^a and H^{**}. For all permanent farmers $\mathbf{H} > \mathbf{H}^{**}$, their payoff from regulation at H^a and H^{**} are the same as farmer $\mathbf{H}^{**}$, so they have a unique ideal point at H which yields higher payoff to them than H^{**}.

The preference of agents in this model is similar to single-peaked preference, except for permanent farmers $\mathbf{H} > \mathbf{H}^*$ whose preference has two local maximums (H^a and H). The majority rule still generates a unique winning policy, that is H^a if the median voter is an annual crop farmer or permanent crop farmer $\mathbf{H} \leq \mathbf{H}^{**}$, or H if the median voter is a permanent crop farmer $\mathbf{H} > \mathbf{H}^{**}$.

Other super-majority voting rules are more likely to delay the implementation of optimal management than the majority rule. For instance, if unanimous consent is required for passing the vote, then there will be no regulation until water depth hits H_v^s, the steady state preferred by permanent crop farmers over the deep part of the aquifer. For other thresholds $100\% > \theta > 50\%$, if more than θ agents prefer H^a, then the policy choice is H^a, otherwise the policy will be the ideal point of agent $\mathbf{H}$ where a fraction θ of voters prefer a regulation $H^r \leq H$. The policy will be always settled in the political decision making process considered in this problem. Because water depth will keep increasing if no regulation is implemented, ideal points smaller than H will pass and at H, the fraction θ of voters will have to accept the regulation otherwise the results will only be worse.

Under the simple majority rule, the optimal policy point H^a does not necessarily pass the vote. That leads to delay of optimal aquifer management and loss of social welfare. One way to solve this issue is to enfranchise farmers $\mathbf{H} < \mathbf{H_t}$. By sharing voting rights and pumping rights with those agents, as shown by this model, they will vote for implementing the regulation at H^a. As a result, the enfranchisement can lead to a winning coalition for H^a and hence the socially optimal outcome.

Of course, the proposal to grant more agents with voting power might be rejected by current voters if the median voter realizes the consequence of an enlarged voting group. However, politicians usually take the advantage to setting the agenda of the political decision-making process. For example, they can define the group of voters as everyone lying over the aquifer. The state legislation, although it hesitates to intervene local groundwater management, also exercises its authority to define the local body of regulation (SGMA 2014). This rationalizes the inclusion of all landowners within a basin when deciding the groundwater management rules, even though some of the land has lost its access to groundwater.

Impact from surface water market

In the last subsection, we have discussed the political issue when there is heterogeneity among the farmers' access to groundwater. Another mechanism that influences the farmers' incentive for groundwater management is the surface water market. According to Chapter 3, with the surface water market, non-groundwater users can purchase surface water from groundwater users, and the sellers will pump groundwater to compensate the amount of water sale. The surface water market in fact grants the non-groundwater users a means to use groundwater. If the surface water supply is enough to cover all farmland without groundwater access, water use in the open access regime will be the same whatever the shape of the aquifer. If the surface water supply can not fulfill the demand from all the high value land, water sellers can grab the economic rent generated from the high-value crops by pricing at the permanent crop farmers' willingness to pay. In this section, I focus on the dry years to discuss the issue with surface water market. Without loss of generality, I assume the surface water supply is abundant in wet years so there is no need to trade surface water.

Although it is not the focus of this chapter, we can notice that the surface water market could lower social welfare when water depth $H \in [H^a, h^a]$, the same as the conclusion in chapter 3. With the surface water market, all farmers will irrigate their land and the groundwater extraction is larger than the socially optimal level. However, if there is no surface water market, groundwater extraction is capped by the groundwater access. Although some high value permanent cropland may not be farmed due to lack of groundwater accessibility, total social welfare can still be larger if the saved groundwater is more valuable than the extra permanent crops[8].

As the farmers supply and demand for surface water change during the water pumping process, I assume perfect competition in the surface water market. Depending on their groundwater accessibility and type, the farmers are in four categories. Each category's cost and return for surface water is:

Permanent Farmer, Groundwater User (PG):	Cost: $\min\{z(H), r^p\}$;	Return: r^p
Annual Farmer, Groundwater User (AG):	Cost: $\min\{z(H), r^a\}$;	Return: r^a
Permanent Farmer, Non-groundwater User (PN):	Cost: r^p;	Return: r^p
Annual Farmer, Non-groundwater User (AN):	Cost: r^a;	Return: r^a

For groundwater users, at water depth H the cost of selling surface water is either the replacement cost by pumping groundwater, $z(H)$, or the opportunity cost to fallow the land.

The price or value of surface water is determined by the competitive equilibrium in the surface water market. Denote it as p^w. There are three thresholds of water depth, H^1, H^2

[8]For example, consider the extreme case when all the groundwater users are permanent crop farmers and all the non-groundwater users are annual crop farmers. Without the surface water market, water use is socially optimal but with the market, the groundwater users will sell surface water to annual crop farmers at price $z(H)$ and pump groundwater to compensate.

and H^3. H^1 is the water depth where the irrigation water demand from non-groundwater users equals total surface water supply in the economy; H^2 is the water depth where the irrigation water demand from non-groundwater permanent crop farmers equals total surface water supply from annual crop farmers; H^3 is the water depth where the irrigation water demand from non-groundwater permanent crop farmers equals total surface water supply in the economy.

Assume $H^1 < H^2$. As the number of non-groundwater users increases with H, $p^w = z(H)$ for $H \leq \min\{h^a, H^1\}$, $p^w = r^a$ for $\min\{h^a, H^1\} < H \leq \min\{h^a, H^2\}$, $p^w = z(H)$ for $\min\{h^a, H^2\} < H < H^3$ and $p^w = r^p$ for $H \geq H^3$.

As for the value of water when groundwater pumping is regulated, it always equals r^p since the regulation creates scarcity of water and only permanent crops are farmed. Therefore, the value of surface water is always smaller under open access than under the optimal management, except for $H \geq H^3$ when total surface water supply in the economy could not satisfy the irrigation water demand from non-groundwater permanent crop farmers. If we consider the gain from potential surface water trade, the farmers' payoff from groundwater management increases because the value of their surface water rights increases. Therefore, allowing surface water trade generates extra incentive for the farmers to vote for the optimal groundwater management.

4.5 Artificial Recharge

Besides managing the existing groundwater stock, one should consider artificial recharge to control the water table in the aquifer and enhance the efficiency of groundwater use. The recharge has two positive effects. First, it raises the water table therefore lowering future cost of pumping. The impact on pumping cost lasts until the economy hits the steady state. Therefore, the cost effect is larger when water depth is low as the saved pumping cost can apply to a larger amount of groundwater to be extracted.

The second benefit to recharge is to save water for use on higher value crops. This occurs when water is scarce. In this model, it only happens at the steady state. The social planner may want to save water in the wet year and use it in the dry year to maintain a larger acreage of permanent crops.

Next, we modify the model by introducing artificial recharge Q to the social planner's problem. When Q takes a positive value, it is not profitable to pump groundwater for annual crops since otherwise the surface water should be directly applied to the annual crops to save the pumping and recharge cost. Denote the cost of recharge as c. The Bellman equation including the recharge decision is:

$$V(K,H) = \max_{Q,I} r^p K + r^a(S^H - K - Q) - cQ - C^k I + r^p K - z(H)(K - S^L) + \rho V(K', H') \quad (4.43)$$

where $K' = K(1-\delta) + I$ and $H' = H - R - Q + K - S^L$.

The first order conditions with respect to I and Q are:

$$\frac{\partial V(K,H)}{\partial I} = -C^k + \rho V_K(K', H') = 0 \quad (4.44)$$

$$\frac{\partial V(K,H)}{\partial Q} = -r^a - c - \rho V_H(K', H') = 0 \quad (4.45)$$

and by Envelope Theorem:

$$V_K(K,H) = r^p - r^a + r^p - z(H) + \rho V_K(K', H')(1-\delta) + \rho V_H(K', H') \quad (4.46)$$

$$V_H(K,H) = -\alpha(K - S^L) + \rho V_H(K', H') \quad (4.47)$$

According to Equation (4.45), artificial recharge to the aquifer occurs when the discounted next period shadow price of groundwater stock $\rho V_H(K', H')$ is equal to or larger than the opportunity cost r^a plus the cost of recharge c: $\rho V_H(K', H') \geq r^a + c$.

In this model, if artificial recharge occurs at the steady state, $K^s = R + S^L + Q^s$. Equations (4.45) and (4.47) imply $V_H(K^s, H^s) = -\frac{\alpha(R+Q^s)}{1-\rho} = -\frac{r^a+c}{\rho}$. If Q takes an interior solution, $Q^s = \frac{(r^a+c)(1-\rho)}{\alpha\rho} - R \leq \frac{S^H - R - S^L}{2}$. According to (4.47), as K declines when H increases, the shadow price of groundwater stock $-V_H(K,H)$ decreases as H increases. Therefore, Q takes a corner solution $Q = S^H - L^p$ before the steady state. It is never profitable to use groundwater on annual crops.

If $\frac{(r^a+c)(1-\rho)}{\alpha\rho} - R > \frac{S^H - R - S^L}{2}$, the shadow price of groundwater stock is so low at he steady state even when the natural recharge reallocates all water from annual crops to permanent crops. Similar to equation (4.47), the change of shadow price is $V_H(K, H) = -\alpha(L - S^L) + \rho V_H(K', H')$ when both annual and permanent crops use groundwater; the shadow price change is $V_H(K, H) = -\alpha(L^p - S^L) + \rho V_H(K', H')$ when only permanent crops use groundwater before the steady state.

As a result, if $r^a + c \geq \frac{\rho\alpha(L-S^L)}{1-\rho}$, natural recharge never happens since the saved pumping cost does not cover the cost of recharging; if $\frac{\rho\alpha(L^p-S^L)}{1-\rho} \leq r^a + c < \frac{\rho\alpha(L-S^L)}{1-\rho}$, natural recharge only occurs at stage 1; if $r^a + c < \frac{\rho\alpha(L^p-S^L)}{1-\rho}$, natural recharge occurs at both stages and stops before the water table getting close to the steady state.

In this model, the benefit from artificial recharge mainly comes from the cost saving effect (channel 1). Saving water into the aquifer returns a value equals to the discounted shadow price of groundwater stock, which is the present value of saved pumping cost over an infinite horizon. The benefit of reallocating water from annual crops to permanent crops (channel 2) occurs only at the steady state as the scarcity of water only occurs then. As shown in the case when $Q > 0$ at the steady state, natural recharge increases the equilibrium acreage of permanent crops by the same amount Q. This effect is larger when the opportunity cost r^a and the recharge cost c are smaller.

Notice that, in this chapter, we show that there is natural recharge when $r^a + c \leq -\rho V_H$. While according to results in Section 4.2, it is profitable to irrigate annual crops with groundwater if $r^a - z(H) \geq -\rho V_H$. Since $r^a + c > r^a - z(H)$, usually only one of the two things is predicted by the model. Either both annual and permanent crops consume groundwater, or positive natural recharge occurs. This is consistent with the findings in Knapp and L. J. Olson (1995) that the optimal management includes no artificial recharge under a large set of parameter values.

4.6 Conclusion

Groundwater depletion has been widely observed in dry regions like California. In 2014, the state of California issued the Sustainable Groundwater Management Act, which for the first time in its history provided a framework for sustainable groundwater management. However, despite its goal to achieve sustainability, the law was passed in a context where very little is known about the desired groundwater management, thus very few practical actions were suggested by the law. In general, the state pushed the responsibility of developing groundwater management institution down to local agencies, in the hope that the local users can find a way to achieve sustainable groundwater management.

For both the state government and the local water management agencies, figuring out the socially optimal groundwater extraction is the very first step to implement proper management. Knowing the optimal outcome removes the uncertainty of groundwater users over the impact of the policy and helps when they have to come to a vote. It also sets up the standard for the policy makers to evaluate different policy outcomes. In this chapter, I solve the dynamic optimization problem for the social planer's groundwater extraction and base all the following discussion of optimal groundwater management on the optimal pumping plan.

In an agricultural economy with both annual and permanent crops, the socially optimal extraction requires the water users to stop applying groundwater on low-value annual crops at a water level higher than the individuals' stopping point. To implement such pumping scheme, assigning water rights of the remaining groundwater stock to the farmers and letting them trade will not help. Since pumping cost increases as the water table declines, the pumpers tend to take their water out of the aquifer too fast. To avoid the externality, groundwater pumping rights need to be assigned to the users per period at a volume equal to the socially optimal extraction.

The design of groundwater rights can lead to optimal outcome if there is an efficient water market. However, the water rights allocation may not be individually incentive compatible so the regulation may not be approved by the voters. The political issue is severe when there is heterogeneity among the farmers' access to groundwater. Farmers over deep part of the aquifer may prefer to delay regulation so they can use more groundwater under the open access. To resolve the political conflict, sometimes the policy maker should enlarge the group of decision makers and share the pumping rights with more agents to get the optimal regulation to pass the vote.

In the literature of groundwater aquifer management, the optimal groundwater extraction has been well studied, while the issue of implementing the optimal management generally remains untouched. This chapter, by revealing the potential problems in groundwater rights design and allocation, shows that it may not work if we just assign property rights to groundwater and share the rights to the users based on a *pro rata* rule. Each period's pumping rights should be carefully calculated to induce the optimal outcome. To do so, better knowledge of the aquifer hydrology, the farmers' value of water and prediction of surface water delivery are required. Given that information, this chapter generates prediction on the policy choice under different voting rules. Specifically, I identity the condition when the optimal regulation can get approval by the voters. Since it is possible that the regulation always delays under the majority voting rule, this chapter suggests to expand the voting group to share with more agents the welfare gain from optimal management so they will become supporter of the regulation. That requires a change of political agenda which demands efforts from politicians and law makers. Only by collaboration from different intellectual communities, we can implement the sustainable groundwater management.

4.A Solution to the Dynamic Programming Problem under Extreme Weather Conditions

I solve the problem for the extreme wet case ($\mathcal{H}^W$). The solution to the extreme dry case follows the same procedure. The Stage 2 problem is solved first:

Stage 2

At Stage 2, the Bellman equation is:

$$V(K,H) = \max_I r^p K + r^a(S^H - K) - C^k I + r^p K - z(H)(K - S^L) + \rho V(K', H') \quad (4.48)$$

with $K' = (1-\delta)K + I$ and $H' = H - R + K - S^L$.

When I takes an interior solution, the first order condition with respect to I is:

$$\frac{\partial V(K,H)}{\partial I} = -C^k + \rho V_K(K', H') = 0 \quad (4.49)$$

By Envelope Theorem:

$$V_K(K,H) = r^p - r^a + r^p - z(H) + \rho V_K(K',H')(1-\delta) + \rho V_H(K',H') \quad (4.50)$$

$$V_H(K,H) = -\alpha(K - S^L) + \rho V_H(K', H'_1) \quad (4.51)$$

When I takes the interior solution, we have the Euler equation by combining equations (4.49, 4.50, 4.51) and substituting out K' from the transition equation of H:

$$2r^p - r^a - z(H) - C^k(\frac{1}{\rho} - 1 + \delta) = \alpha\rho(H'' - H' + R) + \rho[2r^p - r^a - z(H') - C^k(\frac{1}{\rho} - 1 + \delta)] \quad (4.52)$$

Let $c_1 = r^p - r^a + r^p - C^k(\frac{1}{\rho} - 1 + \delta)$, then the Euler equation could be written as:

$$c_1 - z(H) = \alpha\rho(H'' - H' + R) + \rho[c_1 - z(H')] \quad (4.53)$$

This equation gives the transition of water depth along the optimal path when I takes an interior solution at Stage 2. Since at the steady state, $I = \delta K^{s,W}$ which is an interior solution, the steady state $H^{s,W}$ satisfies Equation (4.53). Therefore, the steady state stock of water depth is:

$$H^{s,W} = \frac{c_1}{\alpha} - \frac{\rho R}{1-\rho} \quad (4.54)$$

The steady-state stock of permanent crops that stabilizes the water depth is:

$$K^{s,W} = S^L + R \quad (4.55)$$

Next, we figure out the path before $H = H^{s,W}$. Suppose I takes a series of interior solutions before the steady state. Based on the Euler equation (4.53), we substitute out H'' and H' using the transition equation of H:

$$H = H^{s,W} - \frac{\rho}{(1-\rho)}(K' - K) \tag{4.56}$$

For $K' \leq K$, $H \geq H^{s,W}$. That means if the stock of permanent crops declines along the optimal path when I takes an interior solution, it could be either the steady state or water depth going beyond the steady state $H^{s,W}$. That guarantees the existence of steady state as when $H > H^{s,W}$, the stock of permanents will keep falling until water table recovers.

The equation above also suggests along the path where the stock of permanent crops falls and the water depth increases, I must take a corner solution before hitting the steady state. Due to the discontinuity, H could rise above $H^{s,W}$, which will converge to $H^{s,W}$ eventually. Here we consider a simple situation when H falls right at $H^{s,W}$. This will always hold if we consider a continuous time model.

It depends on the size of L^p and δ whether the corner solution is $I = 0$ or $I = \delta L^p$. If $(1-\delta)L^p < K^{s,W}$, the size of permanent crops $K = L^p$ before the steady state. We can derive the path of H correspondingly. If $(1-\delta)L^p > K^{s,W}$, then the size of permanent crops first stays as L^p, then falls at a rate $K' = (1-\delta)K$ until it hits K^s. We can also derive the path of H correspondingly.

From now on, we assume the parameter values satisfies $(1-\delta)L^p < S^L + R$ so the path of I is $I = \delta L^p$ before hitting the steady state. The analysis based on the other case is the same. Until now, we have characterized the path after H^a based on which we can derive H^a using backward induction.

$H^{a,W}$: When Annual Crops Stop Using Groundwater

When the annual crops are the marginal crop that uses groundwater, the Bellman equation is:

$$V(K,H) = \max_I r^p K + r^a(S^H - K) + r^p K + r^a(S^L - K) + r^a G - z(H)G - C^k I + \rho V(K', H') \tag{4.57}$$

with $K' = (1-\delta)K + I$ and $H' = H + G - R$.

The first order condition with respect to G^H is

$$\frac{\partial V(L^p, H)}{\partial G} = r^a - z(H) + \rho V_H(K', H') \geq 0 \;\; (= 0 \textit{ if G takes an interior solution}) \quad (4.58)$$

We want to know $H^{a,W}$, the lowest H such that $r^a - z(H) + \rho V_H(K', H') < 0$ or equivalently $G = 0$.

At $H^{a,W}$, no groundwater is used for annuals, then the optimal path is in stage 2: $H' = H + L^p - S^L - R$ until $H = H^{s,W}$. Let $c_2 = L^p - S^L - R$ denoting the drop of water table each period when $K = L^p$. It takes $T = \frac{H^{s,W} - H^{a,W}}{c_2}$ periods to reach the steady state.

According to the Envelope Theorem (4.50), $V_H(K,H) = -z'(H)(K - S^L) + \rho V_H(K', H')$. Starting from $H^{a,W'}$, $K = L^p$ for $T-1$ periods and $K = K^{s,W}$ for the remaining time. So:

$$\begin{aligned} V_H(K^{a\prime}, H^{a,W\prime}) &= \sum_{t=0}^{T-2} -\rho^t \alpha (L^p - S^L) + \sum_{t=T-3}^{\infty} -\rho^t \alpha (K^{s,W} - S^L) \\ &= -\frac{1-\rho^{T-1}}{1-\rho}(L^p - S^L) - \frac{\rho^{T-3}}{1-\rho}(K^{s,W} - S^L) \end{aligned} \quad (4.59)$$

Note that $\frac{\partial V_H(K^{a\prime}, H^{a,W\prime})}{\partial H^{a,W}} = \frac{\log\rho \cdot \rho^{T-1}}{1-\rho}[L^p - S^L - \rho^2(K^{s,W} - S^L)](-\frac{1}{c_2}) < 0$, so there is a unique $H^{a,W}$ such that $r^a - z(H^{a,W}) + \rho V_H(K^{a\prime}, H^{a,W\prime})\frac{1-\beta}{L} = 0$ and for all $H > H^{a,W}$, $r^a - z(H^{a,W}) + \rho V_H(K^{a\prime}, H^{a,W\prime})\frac{1-\beta}{L} < 0$. The $H^{a,W}$ is the water depth where the farmers stop irrigating the annual crops with groundwater. Assume T is large enough so $V_H(K^{a\prime}, H^{a,W\prime}) \approx -\frac{L^p - S^L}{1-\rho}$. Then

$$H^{a,W} \approx \frac{r^a}{\alpha} - \frac{\rho(L^p - S^L)}{\alpha(1-\rho)} \quad (4.60)$$

This also implies that for the period before $H = H^{a,W}$, $r^a - z(H) + \rho V_H(K^a, H^{a,W})\frac{1-\beta}{L} > 0$. So all annual cropland is farmed. The optimal path is illustrated at the end of Section 4.2.

4.B Proof of Proposition 4.1

When individual farmers hold water rights and trade, the equilibrium market price for water at period t is p_t, which satisfies the no arbitrage condition:

$$p_t = \rho p_{t+1}, \quad (4.61)$$

If $p_t < \rho p_{t+1}$, an agent can purchase water rights at period t and resell it at next period to earn a positive present value. If $p_t > \rho p_{t+1}$, an agent holding unused water rights can sell the rights at period t and buy back at period $t+1$ to earn a positive present value. As there is unused water rights until the steady state, this condition holds for all the time before the steady state.

At the steady state, as the groundwater supply binds at the amount of flow rights, the price of water $p(H^s) = r^p + \frac{(1-\delta)C^k}{\rho} - z(H^s)$, which is the return of permanent crops in a dry year, plus the saved planting cost if the tree dies due to lack of water, minus the cost of pumping. The price of water remains at that value in the steady state since the water supply does not change.

As $p(H^s)$ is finite, together with the no arbitrage condition, when water depth is at H^a, the price of water $p(H^a) = \rho^T p(H^s)$ where T is the number of periods it takes for water depth to change from H^a to H^s. According to (4.21), the price of water such that the annual crop farmers stop pumping is $p = \rho V_H(H^{a\prime}, K^{a\prime})$. Based on equation (4.18)

$$\begin{aligned} V_H(K^{a\prime}, H^{a\prime}) &= \sum_{t=0}^{T-2} -\rho^t \alpha (L^p - S^L) + \sum_{t=T-3}^{\infty} -\rho^t \alpha (K^s - S^L) \\ &= -\frac{1-\rho^{T-1}}{1-\rho}(L^p - S^L) - \frac{\rho^{T-3}}{1-\rho}(K^s - S^L) \end{aligned} \tag{4.62}$$

For a T large enough, $p(H^s) < p$, so the annual crop farmers do not stop pumping at H^a. The one-time stock rights do not produce socially efficient groundwater use.

4.C Proof of Proposition 4.2

Without loss of generality, I assume the farmers $\mathbf{H} > \mathbf{H^s}$ are homogeneous with respect to groundwater accessibility (This is purely for computational convenience. But we can imagine that farmers in that group are able to redistribute profits to form a coalition against the regulation). Under Assignment 1, at $H = H^s$, the individual permanent crop farmer's return per period is:

$$y_r^p(H^s) = r^p k_r^s - z(H^s)(k_r^s - s^L) \tag{4.63}$$

$k_r^s = K^s \frac{l}{L^p}$ because the groundwater pumping rights are assigned to the permanent crops farmers proportional to their land.

Without the regulation, the permanent crop farmers $\mathbf{H} > \mathbf{H^s}$ continue to withdraw groundwater and irrigate all their land. They are able to grow more permanent crops than those without access to groundwater $\mathbf{H} \leq \mathbf{H^s}$. Denote the groundwater user's permanent crop acreage at the competitive equilibrium h^s be k_v^s. $k_v^s > k^s$. The individual permanent crop farmer's return per period is:

$$y_v^p(h^s) = +r^p k_v^s - z(h^s)(k_v^s - s^L) \tag{4.64}$$

Here we consider the case when $k_v^s < l$ so the permanent crop farmers do not sell their surface water rights at the steady state.

The return of depleting the aquifer from H^s to h^s is:

$$y(H^s, h^s) = (r^p - z(H^s, h^s))W(H^s, h^s) \tag{4.65}$$

where $z(H^s, h^s)$ is the average pumping cost when pumping water from H^s to h^s and $W(H^s, h^s)$ is the amount of groundwater between the two water levels.

The difference of the individual return under two different regimes is:

$$\Delta(H^s) = \frac{y_r^p(H^s)}{1-\rho} - \frac{(r^p - z(H^s, h^s))W(H^s, h^s)}{L^p L(H^s)} - \lambda \frac{y_v^p(h^s)}{1-\rho} \tag{4.66}$$

λ is a parameter capturing the time difference as the competitive steady state occurs later. Let $H_v^s = \arg\max \Delta(H)$. When the aquifer is a bathtub, $L(H^s) = L$ and $k_v^s = k^s$. $H_v^s = H^s$ since H^s is the socially optimal steady state.

Note that, $\Delta_{HL(H^s)} < 0$ and $\Delta_{HH} < 0$. Therefore when $L(H^s) < L$, $H_v^s > H^s$. Namely, the permanent crop farmers in $L(H^s)$ prefer a steady-state water depth H_v^s higher than the socially optimal H^s. They will vote against the regulation in the hope to delay the steady state at $H = H_v^s$.

BIBLIOGRAPHY

Agrawal, Arun (2001). "Common property institutions and sustainable governance of resources." In: *World Development* 29.10, pp. 1649–1672.

Anselin, Luc and Raymond Florax (2012). *New directions in spatial econometrics*. Springer Science & Business Media.

Atkinson, Giles et al. (2014). *Handbook of sustainable development*. Edward Elgar Publishing.

Berkes, Fikret (1986). "Local-level management and the commons problem: A comparative study of Turkish coastal fisheries." In: *Marine Policy* 10.3, pp. 215–229.

Berkes, Fikret et al. (1989a). "The benefits of the commons." In: *Nature* 340.6229, pp. 91–93.

– (1989b). "The benefits of the commons." In: *Nature* 340.6229, p. 91.

Bithas, Kostas (2008). "The sustainable residential water use: Sustainability, efficiency and social equity. The European experience." In: *Ecological Economics* 68.1-2, pp. 221–229.

Bjornlund, Henning (2003). "Efficient water market mechanisms to cope with water scarcity." In: *Water Resources Development* 19.4, pp. 553–567.

Blomquist, William (1992). *Dividing the waters: governing groundwater in Southern California.* ICS Press Institute for Contemporary Studies.

Brewer, Jedidiah et al. (2008). "Law and the New Institutional Economics: Water Markets and Legal Change in California, 1987-2005." In: *Washington University Journal of Law & Policy* 26.1, pp. 183–213.

Brozovic, Nicholas, Janis M. Carey, and David L. Sunding (2002). "Trading activity in an informal agricultural water market: an example from California." In: *Journal of Contemporary Water Research and Education* 121.1, p. 2.

Carruthers, Ian D. and Roy Stoner (1981). *Economic aspects and policy issues in groundwater development*. Vol. 494. World Bank Staff working paper No. 496. Washington, DC.

Casari, Marco (2007). "Emergence of endogenous legal institutions: Property rights and community governance in the Italian alps." In: *The Journal of Economic History* 67.01, pp. 191–226.

Chong, Howard and David Sunding (2006). "Water markets and trading." In: *Annu.Rev.Environ.Resour.* 31, pp. 239–264.

Coase, Ronald H. (1960). *The problem of social cost*. Springer.

Cooley, H., P. Gleick, and R. Wilkinson (2014). "Agricultural water conservation and efficiency potential in California." In: *Issue Brief*, pp. 14–05.

Culp, Peter W., Robert J. Glennon, and Gary Libecap (2014). *Shopping for water: How the market can mitigate water shortages in the American West*. Springer.

Dale, Robert H., James J. French, and Harry Dennis Wilson (1964). *The story of ground water in the San Joaquin Valley, California*. Vol. 459.

Gisser, Micha (1983). "Groundwater: focusing on the real issue." In: *Journal of Political Economy* 91.6, pp. 1001–1027.

Gisser, Micha and David A. Sanchez (1980). "Competition versus optimal control in groundwater pumping." In: *Water Resources Research* 16.4, pp. 638–642.

Gordon, H. Scott (1954). "The economic theory of a common-property resource: the fishery." In: *Journal of political economy* 62.2, pp. 124–142.

Grafton, R. Quentin et al. (2012). "Comparative assessment of water markets: insights from the Murray-Darling Basin of Australia and the Western USA." In: *Water Policy* 14.2, pp. 175–193.

Guilfoos, Todd et al. (2013). "Groundwater management: The effect of water flows on welfare gains." In: *Ecological Economics* 95, pp. 31–40.

Hanak, Ellen (2003). *Who should be allowed to sell water in California? Third-party issues and the water market*. Public Policy Instit. of CA.

– (2005). "Stopping the drain: Third-party responses to California's water market." In: *Contemporary Economic Policy* 23.1, pp. 59–77.

Hardin, G. (1968). "The tragedy of the commons. The population problem has no technical solution; it requires a fundamental extension in morality." In: *Science* 162.3859, pp. 1243–1248.

Heath, Ralph C. (1983). *Basic ground-water hydrology*. Vol. 2220. US Geological Survey.

Holmes, Thomas J. and Sanghoon Lee (2012). "Economies of density versus natural advantage: Crop choice on the back forty." In: *Review of Economics and Statistics* 94.1, pp. 1–19.

Hornbeck, Richard and Pinar Keskin (2014). "The historically evolving impact of the ogallala aquifer: Agricultural adaptation to groundwater and drought." In: *American Economic Journal: Applied Economics* 6.1, pp. 190–219.

Howitt, Richard E. (1994). "Empirical analysis of water market institutions: The 1991 California water market." In: *Resource and energy economics* 16.4, pp. 357–371.

Howitt, Richard and Ellen Hanak (2005). "Incremental water market development: The California water sector 1985-2004." In: *Canadian Water Resources Journal* 30.1, pp. 73–82.

Karamouz, Mohammad, Azadeh Ahmadi, and Masih Akhbari (2011). *Groundwater hydrology: engineering, planning, and management*. CRC Press.

Klier, Thomas and Daniel P. McMillen (2008). "Clustering of auto supplier plants in the United States: generalized method of moments spatial logit for large samples." In: *Journal of Business & Economic Statistics* 26.4, pp. 460–471.

Knapp, Keith C. and Lars J. Olson (1995). "The economics of conjunctive groundwater management with stochastic surface supplies." In: *Journal of Environmental Economics and Management* 28.3, pp. 340–356.

Knapp, Keith C., Marca Weinberg, et al. (2003). "Water transfers, agriculture, and groundwater management: a dynamic economic analysis." In: *Journal of environmental management* 67.4, pp. 291–301.

Koundouri, Phoebe (2000). "Three approaches to measuring natural resource scarcity: theory and application to groundwater." In:

– (2004). "Current issues in the economics of groundwater resource management." In: *Journal of Economic Surveys* 18.5, pp. 703–740.

Lam, Wai Fung (1998). *Governing irrigation systems in Nepal: institutions, infrastructure, and collective action.* Institute for Contemporary Studies.

Laukkanen, Marita and Phoebe Koundouri (2006). "Competition versus cooperation in groundwater extraction: a stochastic framework with heterogeneous agents." In: *Water Management in Arid and Semi-Arid Regions: Interdisciplinary Perspective*, pp. 188–198.

Lee, Lung-fei and Jihai Yu (2010). "Estimation of spatial autoregressive panel data models with fixed effects." In: *Journal of Econometrics* 154.2, pp. 165–185.

Li, Man, JunJie Wu, and Xiangzheng Deng (2013). "Identifying drivers of land use change in China: a spatial multinomial logit model analysis." In: *Land Economics* 89.4, pp. 632–654.

Libecap, Gary D. (2007). "The assignment of property rights on the western frontier: lessons for contemporary environmental and resource policy." In: *The Journal of Economic History* 67.2, pp. 257–291.

– (2008). "Chinatown revisited: Owens Valley and Los Angeles–bargaining Costs and fairness perceptions of the first major water rights exchange." In: *The Journal of Law, Economics, & Organization* 25.2, pp. 311–338.

Lipsey, Richard G. and Kelvin Lancaster (1956). "The general theory of second best." In: *The review of economic studies* 24.1, pp. 11–32.

Marshall, Alfred (1895). "Principles of economics." In:

Martin, Ralf et al. (2014). "Industry compensation under relocation risk: A firm-level analysis of the EU emissions trading scheme." In: *American Economic Review* 104.8, pp. 2482–2508.

Messick, David M., Scott T. Allison, and Charles D. Samuelson (1988). "Framing and communication effects on group members' responses to environmental and social uncertainty." In: *Applied behavioral economics* 2, pp. 677–700.

Mohammadian, Abolfazl and Pavlos S. Kanaroglou (2003). "Applications of spatial multinomial logit model to transportation planning." In: *Proceedings of the 10th international conference on travel behaviour research*.

Moran, Patrick AP (1950). "Notes on continuous stochastic phenomena." In: *Biometrika* 37.1/2, pp. 17–23.

Munshi, Kaivan (2004). "Social learning in a heterogeneous population: technology diffusion in the Indian Green Revolution." In: *Journal of Development Economics* 73.1, pp. 185–213.

Murphy, James J. et al. (2000). "The Design of 'Smart' Water Market Institutions Using Laboratory Experiments." In: *Environmental and Resource Economics* 17.4, pp. 375–394.

Nylen, Nell Green et al. (2017). "Trading sustainably: Critical considerations for local groundwater markets under the Sustainable Groundwater Management Act." In:

Olson, Mancur (1965). *The logic of collective action*. Vol. 124. Harvard University Press.

Ostrom, Elinor (1990). *Governing the commons*. Cambridge university press.

– (2002). "Common-pool resources and institutions: Toward a revised theory." In: *Handbook of agricultural economics* 2, pp. 1315–1339.

Ostrom, Elinor, Roy Gardner, and James Walker (1994). *Rules, games, and common-pool resources*. University of Michigan Press.

Ostrom, Elinor and James Walker (2000). "Neither markets nor states: Linking transformation processes in collective action arenas." In: *Polycentric games and institutions: readings from the Workshop in Political Theory and Policy Analysis*. Vol. 427. University of Michigan Press.

Pinkse, Joris and Margaret E. Slade (1998). "Contracting in space: An application of spatial statistics to discrete-choice models." In: *Journal of Econometrics* 85.1, pp. 125–154.

Rahman, HM Tuihedur, Gordon M. Hickey, and Swapan Kumar Sarker (2012). "A framework for evaluating collective action and informal institutional dynamics under a resource management policy of decentralization." In: *Ecological Economics* 83, pp. 32–41.

Sawyers, G. (2005). "A primer on California water rights." In: *University of California Agricultural Issues Centre 2005 Spring Outlook Forum*.

Sax, Joseph L. (2002). "Review of the Laws Establishing the SWRCB's Permitting Authority Over Appropriations of Groundwater Classified as Subterranean Streams and the SWRCB's Implementation of Those Laws." In: *California State Water Resources Control Board*, p. 1.

Smirnov, Oleg A. (2010). "Modeling spatial discrete choice." In: *Regional science and urban economics* 40.5, pp. 292–298.

Smith, Adam (1776). *The wealth of nations*. Courier Dover Publications (2019).

Smith, Vernon L. (1977). "Water deeds: a proposed solution to the water valuation problem." In: *Arizona Review* 26.1.

Squires, Dale et al. (1998). "Individual transferable quotas in multispecies fisheries." In: *Marine Policy* 22.2, pp. 135–159.

Srivastava, SK, Ranjit Kumar, and RP Singh (2009). "Extent of Groundwater Extraction and Irrigation Efficiency on Farms under Different Water-market Regimes in Central Uttar Pradesh." In: *Agricultural Economics Research Review* 22.1.

Taeb, Armeen et al. (2016). "California Reservoir Drought Sensitivity and Exhaustion Risk Using Statistical Graphical Models." In: *preprint*.

Tang, Shui Yan (1992). *Institutions and collective action: Self-governance in irrigation*. ICS press.

Tsur, Yacov and Theodore Graham-Tomasi (1991). "The buffer value of groundwater with stochastic surface water supplies." In: *Journal of Environmental Economics and Management* 21.3, pp. 201–224.

Walker, James M. et al. (2000). "Collective choice in the commons: Experimental results on proposed allocation rules and votes." In: *The Economic Journal* 110.460, pp. 212–234.

Walras, Leon (1874). *Elements of pure economics*. Routledge (2013).

Yu, Jihai, Robert De Jong, and Lung-fei Lee (2008). "Quasi-maximum likelihood estimators for spatial dynamic panel data with fixed effects when both n and T are large." In: *Journal of Econometrics* 146.1, pp. 118–134.

Zilberman, David and Leslie Lipper (2002). "Ch 10: The economics of water use." In: *Handbook of environmental and resource economics*, p. 141.